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# Modeling competing free-floating carsharing operators – A case study for Zurich, Switzerland[☆]

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ABSTRACT

A considerable amount of research has been devoted to understanding and modeling carsharing services in the past. However, a research question that has not been investigated yet is how carsharing companies affect each other in a competitive market. This paper presents a methodology, based on the MATSim framework, for investigating the interaction of carsharing competitors and uses it to analyze the possible competition of two free-floating carsharing companies in the city of Zurich, Switzerland. It further provides a first attempt to allow agents to make mode-choice decisions based on a discrete choice model that includes carsharing alternatives on a whole plan level. Relocation capabilities are added to the carsharing module that allow for testing of various relocation algorithms.

The paper investigates the competition of carsharing operators on two levels. First, by investigating the impact of different price levels, and second, by allowing one or both of the competitors to perform relocations. The obtained results show that (1) with fixed market rate, operators can obtain the highest profit by offering the service at 0.41 CHF/min, (2) offering different pricing schemes can lead to a higher cumulative payoff, although one of the competitors is left with a reduced profit and (3) performing relocations is unprofitable for the company tasked with the burden of doing it, whilst a competitor may enjoy a free-rider effect with an increasing number of rentals and higher profit.

## 1. Introduction

The carsharing industry has seen a highly dynamic development in the past 20 years. In addition to an exponential growth in fleet sizes and membership, the business model has evolved (Shaheen et al., 2018). Free-floating carsharing, the most recent and fastest-growing segment, has even become a prototype for novel forms of bike- and even scooter-sharing services. It is particularly attractive to customers as it offers the flexibility of one-way trips without fixed destination stations or pre-arranged rental durations. However, since demand is not homogeneously distributed in space and time, this flexibility comes at the cost of lower reliability (and potentially efficiency) of the service (Jorge and Correia, 2013).

So far, such operational challenges have not kept operators from increasing fleet sizes and expanding into new cities. As a result, there is now direct competition between multiple operators in various European and North American cities. Hence, the schemes try to distinguish themselves also through their branding and vehicle types. Apart from those attributes, service characteristics such as availability

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and prices play a key role (Ciari et al., 2015). Thus, competition makes optimization of such service characteristics even more important. Although various strategies have already been devised to improve service levels of free-floating carsharing, be it through optimizing service areas, fleet sizes, pricing, or even relocation strategies (Jorge and Correia, 2013), they have all considered a single operator only.

In general, two different paths have been used to address such issues so far. The first stream mainly consists of mathematical optimization models. Such models support operational planning by providing optimal fleet sizes or relocation strategies (Deng and Cardin, 2018). However, they mostly rely on strong assumptions such as constant network travel times or a fixed demand (mostly taken from earlier transactions). The second approach is based on agent-based simulations of the whole transport system, in which carsharing is integrated (Balac et al., 2017). In such models, carsharing is in direct competition with other modes. They provide a dynamic demand as well as load-dependent network travel times. This approach is computationally more complex and does not necessarily provide globally optimal, but plausible near-optimal solutions.

In this research, a framework to model competition between multiple carsharing operators has been developed for the agent-based transport simulation tool MATSim (Horni et al., 2016). The framework allows to study, how service characteristics of different operators affect their profitability. Since vehicle relocations are a widely suggested means to increase service availability (Weikl and Bogenberger, 2013), a relocation framework for free-floating carsharing was also implemented into MATSim as part of this research. The tool is then applied to study the case of two hypothetical competing operators in the city of Zurich.

The remainder of this paper is organized as follows: Section 2 provides an overview of the related literature. The simulation framework is introduced in Section 3. Section 4 presents the results. Finally, Section 5 discusses the results of this paper and summarizes the contribution of this research.

## 2. Background

### 2.1. Station-based carsharing

Carsharing services emerged as station-based services, to provide their customers short-term access to vehicles at designated stations. These systems mostly required reservations and vehicles have to be returned to their original station. In some cases, one-way trips between stations are allowed. From an operational perspective the systems are relatively similar - in both cases the economic success depends on station locations, fleet sizes and price structures. Due to spatiotemporal imbalances in their demand one-way services require (efficient) redistribution of vehicles and additional empty parking spots at sharing stations.

Methods used to optimize station-based carsharing operations can be grouped into two families. The majority of studies applied mathematical optimization techniques to optimize fleet sizes and distributions (Barrios and Godier, 2014; Hu and Liu, 2016; Li and Petering, 2018) or relocation strategies (Kek et al., 2009; Febbraro et al., 2012; Jorge et al., 2014), also taking into account electric vehicles and their charging requirements (Boyaci et al., 2017). Furthermore, methods to improve operator efficiency by dynamic pricing or even declining unfavorable one-way trips were tested (Correia and Antunes, 2012; Jorge et al., 2015). However, those mathematical optimization approaches have so far not accounted for the two-way relationship between supply and demand. Instead, they mostly rely on a static travel demand derived from historical booking data or synthesized from travel surveys. Although approaches using stochastic demand (Brandstätter et al., 2017; Deng and Cardin, 2018) can capture some natural randomness in the model, they still do not account for latent demand, potentially biasing model results towards the OD-patterns observed before optimization.

The second family of methodologies has used agent- and activity-based modeling approaches, which considered carsharing as part of the whole transport system and thus in competition with other modes (Ciari et al., 2012, 2016). Optimization was mostly done with respect to fleet sizes, pricing structures or station locations. Although possible, no fleet redistribution algorithms were developed based on this kind of models so far.

### 2.2. Free-floating carsharing

Despite its long and steady growth, station-based carsharing has never evolved beyond a niche service for a very specific customer group (Becker et al., 2017c). Only the recently introduced free-floating carsharing has been able to attract larger customer groups (Shaheen et al., 2015). Free-floating carsharing schemes operate without fixed stations and reservations; instead, customers can locate the closest available vehicle using a smartphone app at the start of their trip and reserve it for a short period, for example, during their access to the vehicle. Moreover, at the end of the rental they can return the vehicle to any eligible parking space[1] within a pre-defined service area. The different structure of the service not only results in other customer groups and usage patterns (Becker et al., 2017a,b), but also comes with new operational challenges (Weikl and Bogenberger, 2013), because supply and demand are not homogeneously distributed.

A flip side of the larger flexibility of free-floating schemes is their reduced reliability compared to station-based carsharing. This uncertainty may translate into lower customer satisfaction (Kim et al., 2017) and a lower impact on car-ownership (Becker et al., 2018). Moreover, the resulting fleet distribution may be different every day, so multi-day models are needed to model demand and supply patterns (Heilig et al., 2017).

Given the increased complexity, only a few approaches modeling and optimizing free-floating carsharing schemes have been introduced so far. As an early example Febbraro et al. (2012) used a discrete event systems approach to study the optimal fleet size of a carsharing scheme in Turin, Italy. However, their approach relied on a fixed demand (taken from an existing station-based scheme),

[1] In Switzerland, this generally includes all on-street parking in residential areas.

which was aggregated to rather large zones. Barrios and Godier (2014) used an agent-based approach to address the same question. While they partly addressed the problem of spatial aggregation through randomized trip origins and destinations, demand was still independent of supply and no representation of the transport network (and thus variable travel times) was included in the model. Only recently did Huang et al. (2018) present a first optimization approach that incorporated elastic demand (with a car being the alternative to carsharing).

Ciari et al. (2015) addressed the above limitations by incorporating free-floating carsharing into the agent- and activity-based transport simulation MATSim. In this approach, free-floating carsharing is part of a transport network, competing with other modes for each trip. Furthermore, all cars are dynamically routed on a transport network, hence also delays through congestion are included in the model.[2] (Balac et al., 2017) used a similar approach to study the effects of parking policies on demand for free-floating carsharing. Li et al. (2018) suggested an alternative, more abstract formulation via multi-modal supernetworks. However, none of the modeling approaches so far has covered the case of competing operators, which has become a common situation in many North American and European cities in recent years (e.g. Berlin, Munich, Milan, Vancouver).

Vehicle relocation processes for station-based carsharing have been devised using mathematical optimization techniques only. To balance realism (complete spatial disaggregation) with methodological requirements (limited number of stations/zones), Weikl and Bogenberger (2013) divided the service area into a grid of smaller elements (e.g. hexagons) and even refined it using a two-layered zoning approach (Weikl and Bogenberger, 2015). A field trial confirmed that their solution could increase the profitability of a free-floating carsharing service in Munich, Germany.

While Weikl and Bogenberger (2015) propose to perform relocations during the night, other researchers suggest a moving-horizon approach to monitor vehicle imbalances throughout the day and to act whenever necessary (Barrios and Godier, 2014). Apart from operator-based relocation strategies (using their employees), user-based approaches also appear to be promising in which users receive discounts for ending trips in high-demand areas (Herrmann et al., 2014).

Competition in carsharing markets has been steadily increasing in recent years as more organizations are entering already existing markets (Shaheen et al., 2006). However, research on how carsharing companies affect each other when operating in the same market is nearly non-existent. One of the rare publications on the topic finds that in competitive markets, operators tend to adjust prices frequently and to vary the price between regions and cities (Schwieterman and Bieszczat, 2017). Some insights from the ride-sourcing market could be drawn from the work by Zha et al. (2016). The authors' findings suggest that the competition in the ride-sourcing market does not necessarily lower the price level and that a monopoly platform will maximize the joint profit.

This research aims to contribute additional insights on this important issue. A methodology is presented, for investigating competitive carsharing markets, in which operators can pursue different price structure and perform relocation strategies to differentiate their service. It also aims to create a test-bed for different algorithms and provide an alternative to expensive field trials.

## 3. Modeling framework

The main methodological contributions of this work are:

- MATSim Carsharing Framework (MCF) is further modularized and extended to incorporate competitive carsharing operators.
- MCF is further extended to support the use of mode-choice models that include carsharing alternatives in the re-planning phase of the MATSim loop.
- For the first time agents can make carsharing mode decisions on a level of their complete daily agenda. Previous research only included trip-based mode choice decisions that do not take into account future trips and rarely take into consideration restrictions imposed by the choices made for the previous trips in the agent's daily agenda.
- Relocation capabilities are added to the MCF which allow to investigate the potentials of carsharing services.

They will be presented in more detail in the following subsections.

### 3.1. MATSim

The basis for the framework developed for modeling and optimizing of carsharing services is the multi-agent transport simulation MATSim. MATSim infrastructure allows to model car, public transport, walk and bike modes. In the mobility simulation, car and schedule-based public transport are directly simulated on the network and are therefore affected by congestion.

MATSim simulates the daily behavior of people, who pursue activities in a given study area. Each person in this study area is represented by an agent, who through the iterative process of a single MATSim simulation interacts with other agents on the network and aims to optimize its daily schedule. Through an iterative process, agents aim to maximize their utility by randomly changing parts of their plan (departure time from an activity, transportation mode) or re-route their trip to avoid congestion. The utility an agent obtains from its daily plan is calculated using utility functions defined for each transportation mode and activity. Performing activities typically increases the utility while traveling decreases it. Therefore agents aim to minimize their travel costs and maximize the time they spend performing activities.

[2] Given the current low market penetration and small fleets of carsharing schemes, the current effects can be assumed negligible at this point. However, carsharing impacts on network travel times may become relevant with larger fleets and higher utilization.

**Table 1**
Multi-nomial logit model used in the re-planning phase of the MATSim simulation (Hörl et al., 2018b).

| Mode | Variable | Parameter | Robust-t test |
|---|---|---|---|
| Walking | Constant | 0.431 | 0.32 |
| | Travel time [min] | −0.141 | −2.30 |
| Cycling | Constant | 0.344 | 0.46 |
| | Travel time [min] | −0.080 | −3.94 |
| | Age (>17) | −0.049 | −2.85 |
| Car | Constant | 0.827 | 2.00 |
| | Travel time [min] | −0.067 | −7.61 |
| Public Transport | Travel time [min] | −0.019 | −3.33 |
| | Access/egress time [min] | −0.080 | −3.23 |
| | Waiting time [min] | −0.038 | −1.50 |
| | Number of transfers | −0.170 | −1.10 |
| Cost | [CHF] | −0.126 | −10.60 |
| $\lambda_{distancecost}$ | | −0.400 | −6.74 |
| Number of decision makers: | | | 317 |
| Number of observations: | | | 1875 |
| LL(null): | | | −2266.287 |
| LL(final): | | | −1450.840 |
| Rho2: | | | 0.360 |
| Estimated parameters: | | | 20 |

While this replanning approach has proven useful in previous research using MATSim (Joubert et al., 2010; Waraich and Axhausen, 2012; Ciari et al., 2015; Agarwal and Kickhöfer, 2018; Horni et al., 2016; Balac et al., 2017), it was observed that it imposes several hurdles when simulating carsharing. The approach in which agents randomly try out transportation modes requires a substantial number of iterations to reach equilibrium for the usage of a carsharing service. This effect arises because the size of the carsharing supply is small compared to the number of agents allowed to use it even if membership is explicitly modeled. Therefore, if many new agents are allowed to try out carsharing in each iteration, most of them will be dissatisfied because not enough vehicles are available to serve such a large demand. To allow faster and more robust convergence in each iteration, only a small number of new agents are allowed to try out carsharing.

Instead of the replanning approach described above, we propose using the methodology described by Hörl et al. (2018a) that assigns the transportation mode for each trip of the agents based on a discrete choice model. Agents learn through the iterations by interacting with other travelers and thus affecting their mode and route choice in the replanning phase, assessing changes in travel times, availability of modes and perceived costs.

The methodology, to the best knowledge of the authors, presents the first attempt to incorporate carsharing in a mode choice on a plan-level. Adding plan-level decisions is crucial since trip level mode-choice decisions do not take into account the restrictions that the agent might encounter in the subsequent trips on its agenda.

### 3.2. Mode choice model

The mode choice model used in this study is a multinomial logit model based on stated preference data (Table 1). Since free-floating carsharing was not included in the survey, the travel time parameters for private cars were used as an approximation. This assumption is supported by a recent study on free-floating carsharing in Lisbon, Portugal (Martnez et al., 2017) indicating that the values of travel time for these two modes are the same. Moreover, for valuation of access times, the parameters for public transport were used.[3] Although an important variable for carsharing use (see Becker et al., 2017a), personal income was not included in the model, because the synthetic MATSim population does not yet contain personal income information. The utility functions of different alternatives are:

$$U_{walk} = \alpha_{walk} + \beta_{traveltime,walk} \cdot t_{traveltime,walk} \tag{1}$$

$$U_{cycling} = \alpha_{cycling} + \beta_{traveltime,cycling} \cdot t_{traveltime,cycling} + \beta_{age,cycling} \cdot (age - 18) \tag{2}$$

$$U_{car} = \alpha_{car} + \beta_{traveltime,car} \cdot t_{traveltime,car} + \beta_{cost} \cdot \left(\frac{distance}{40\ \text{km}}\right)^{\lambda_{distancecost}} \cdot price_{car} \tag{3}$$

[3] Egress times are not included. In standard MATSim, carsharing trips (like car trips) end directly at the respective destination.

$$U_{pt} = \alpha_{pt} + \beta_{traveltime,pt} \cdot t_{traveltime,pt} + \beta_{accesstime,pt} \cdot t_{accesstime,pt} + \beta_{egresstime,pt} \cdot t_{egresstime,pt} + \beta_{numtransfers,pt} \cdot numtransf + \beta_{cost} \cdot \left(\frac{distance}{40\text{ km}}\right)^{\lambda_{distancecost}} \cdot price_{pt} \tag{4}$$

$$U_{ffcs} = \alpha_{ffcs} + \beta_{traveltime,ffcs} \cdot t_{traveltime,ffcs} + \beta_{accesstime,pt} \cdot t_{accesstime,pt} + \beta_{cost} \cdot \left(\frac{distance}{40\text{ km}}\right)^{\lambda_{distancecost}} \cdot price_{ffcs} \tag{5}$$

Since travelers are known to ignore fixed and sunk cost in their mode choice decisions, the *price* attributes were adjusted as follows:

- public transport: $price_{pt}$ corresponds to the full fare of public transport. The fare is reduced by 50% for agents who hold a discount card (Halbtax). For agents holding a season ticket covering the trip, the fare is set to zero (in case the season ticket only covers part of the trip, the reduction is applied pro rata).
- private car: $price_{car}$ is set to 0.27 CHF/km. This corresponds to the variable cost of a car. The full costs including costs for car ownership, insurance and maintenance amount to about 0.70 km/h, according to a Swiss association of car owners.[4]

Modifications were already applied to the choice sets presented in the original survey. The same procedure is followed in MATSim. For carsharing, the full rental charge was considered as a mode choice attribute.

### 3.3. MATSim Carsharing Framework

An open-source Carsharing Framework using MATSim as a platform was developed to simulate carsharing services with a high level of detail on both the operator and user side. Even though MATSim has been used previously to study carsharing services, earlier implementations had several limitations which have now been addressed. The most important features of the current approach which were not available previously are:

1. the ability to model competition between different operators,
2. a service area can be defined,
3. carsharing operators can be represented as agents each following different business strategies,
4. relocation algorithms can be investigated.

The modularity of the CF is achieved by using the Guice software for dependency injection. The description of the extension points in MATSim and the implementation of the plug-in system developed using the dependency injection can be found in Zilske and Nagel (2016).

The high-level architecture of the MCF is presented in Fig. 1. CF consists of several independent submodules:

- **Carsharing Manager**: Main communication unit between CF and MATSim.
- **Supply**: Information on all available carsharing operators, their services and price structures.
- **Membership**: Information on the membership of all agents for each operator and each carsharing option.
- **Operations**: Contains information on all currently rented vehicles.
- **Models**: Contains decision models (vehicle preferences, company preferences, if/when the vehicle should be kept during activities) that provide information to the Carsharing Manager.
- **Routers**: Routes the current carsharing leg. Routers are flexible and can also create intermodal trips.
- **Analysis**: Keeps information on all completed rentals and provides output information for later analysis.
- **Relocation**: Responsible for computing relocation jobs based on the provided algorithm and dispatching relocation workers.

The MCF provides the ability to include different carsharing operators, each with individual service characteristics and cost structures, enabling investigation of competitive markets. Moreover, each agent can be a member of multiple services.

Agents choose one of the vehicles offered by the competing companies based on the utility function:

$$U_i = \alpha_{ff} + \beta_{traveltime,ff} \cdot t_{invehicletime,i} + \beta_{cost} \cdot t_{invehicletime,i} \cdot price_i + \beta_{accesstime,ff} \cdot t_{accesstime,i}, \quad \text{where } i \in Company1, Company2 \tag{6}$$

implemented in the Choose The Company model. Both companies pursue the same strategy upon receiving the request from the agent by providing the closest possible vehicle to the agent.

Additionally, the MCF also provides estimates of the expected travel times and carsharing availability for each operator in the service area. The estimates are grouped in 30 min time bins and based on the results of previous iterations.

A detailed explanation of additional sub-modules in MCF is given in Appendix A.

[4] Compare https://www.tcs.ch/de/testberichte-ratgeber/ratgeber/kontrollen-unterhalt/kilometerkosten.php.

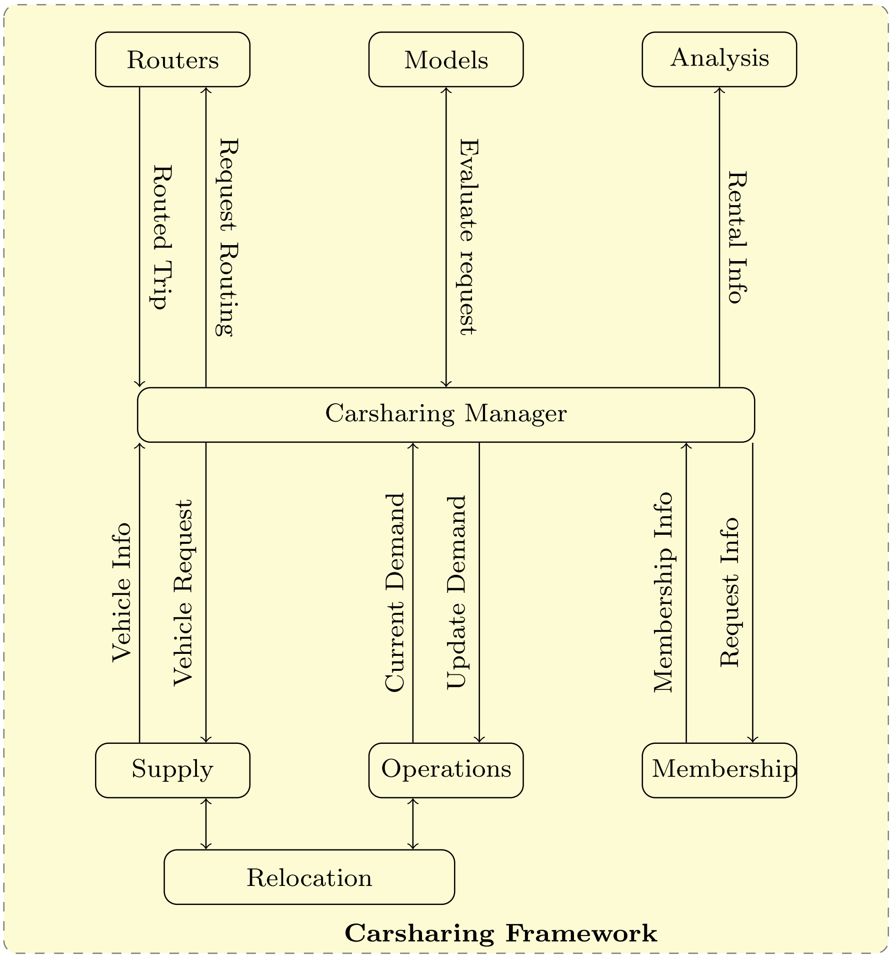



**Fig. 1.** High level architecture of the Carsharing Framework.

### 3.4. Relocation module

The relocation module is part of the MCF and is responsible for dispatching agents to perform vehicle relocations based on the relocation algorithm provided. Once the dispatcher gets a request for vehicle relocations, it dispatches relocation agents to the corresponding vehicles.

#### 3.4.1. Relocation agents

The relocation agents represent employees of the carsharing operators and are entirely controlled by a dispatch center. In particular, they do not have a daily plan like other agents in the simulation and are only used at certain points in time when they are assigned relocation tasks, which are then executed during the ongoing simulation.

Agents performing relocations travel to the vehicle that has to be relocated by either walking, cycling or by using public transport services, enter the vehicle (which becomes unavailable for rental during relocation), drive it to the destination as assigned by the dispatcher, and return to their original location.

The current implementation of the relocation agents provides the ability to combine several relocation tasks into one journey before returning to its base location.

#### 3.4.2. Relocation strategy

The distribution of free-floating carsharing requests over the course of one day reflects the different purposes of the rentals. Different distribution patterns of rentals in space and time can cause imbalances in the fleet distribution and reduces the quality of service provided to the users.

Some of the resulting imbalances can be tackled by relocating vehicles once daily, typically overnight. This strategy would mean “resetting” the vehicle fleet, by returning it to an ideal starting position. However, if the relocations were to be performed several times a day, or even continuously, the resulting gain in vehicle accessibility, and thereby, the number of rentals, should be even higher.

Real-world relocation strategies typically use historical data to estimate the demand. Since MATSim simulations usually cover a single day, such information is not available within one run of the simulation. Instead, the work presented uses booking requests from previous iterations as estimates of the future demand, thus allowing for a highly dynamic model of supply and demand, where the agents cannot only adapt their behavior to the supply, but the supply can also be adapted to the agents' behavior.

In order to better estimate the demand and organize the relocation activities, the carsharing service area is partitioned into non-overlapping polygons, referred to as relocation zones. They should not contain obstacles that would prevent access to a vehicle location in the real world, such as rivers, railway yards or freeways. Near the city center, vehicle density is higher, and the dimensions of the polygons are roughly equivalent to the maximum acceptable walking distance (750 m according to Weikl and Bogenberger (2013)). In the suburbs, where fewer vehicles are available, they are slightly larger. The service area is divided into 208 polygons.

Before the start of each iteration, the free-floating carsharing requests and returns from the previous iteration are analyzed and stored. Request data contains the time and position of the booking requests, as well as the start and end times of actual bookings. Requests are assigned to a relocation zone based on the booking location (not the location of the reserved vehicle). This way, latent demand in each of the relocation zones is taken into account.

We propose the following mechanism for the operators to receive information on latent demand: Instead of allowing users to reserve any vehicle within the service area, the user sends a request for a vehicle at a given location. In response, the operator suggests possible vehicles to the user, along with the locations, fuel level, costs and vehicle characteristics. The user then either chooses one of the vehicles or declines the offer. Declining an offer would give information to the operator that there is unserved demand at the particular place and time.

### *3.5. Relocation algorithm*

The expected demand for each of the relocation zones is determined at the predefined times. Relocations are performed once an hour between 7 am and 7 pm. The dispatcher calculates the required relocations in the following way:

- The expected number of requests and returns is estimated for each relocation zone.
- Based on the currently available vehicles in the zone and the number of potential requests and returns in the following hour, the zones are divided into shortage and surplus zones. Shortage zones are those where the number of expected requests is higher than the number of vehicles available. Surplus zones are those where the sum of currently available vehicles is higher than the potential requests. Similar approaches can be found in Weikl and Bogenberger (2015) and Fagnant and Kockelman (2014).
- The number of vehicles that can be relocated from a surplus zone is defined as:

$$V_{curravail} - V_{requests} \tag{7}$$

  where $V_{curravail}$ is the number of vehicles currently available in the relocation zone and $V_{requests}$ is the expected amount of requests.
- The shortage zones are then prioritized by shortage.
- For the vehicle relocation the priority is given to the highest shortage zones. In order to minimize the relocation distance the vehicles are first relocated from the closest surplus zones to the shortage zones. The shortage zones list is continuously updated in order to always have the largest shortage one on the top of the list. If the zone has no more need for vehicles, it is removed from the list.
- Finally the relocation agents are assigned a relocation job with the location and vehicle details. As the purpose of the study was not to optimize the initial location of the relocation agents, it is assumed that the agent needs 10 min using a bicycle to reach the vehicle. As Zurich is not a large city and the agents could be dispatched earlier to the areas where the surplus zones are expected to be, this is a reasonable assumption.

The presented algorithm is used to maximize the number of rentals while keeping the relocation distance at its minimum. It must be stressed that the goal of this research is not to develop or use a sophisticated algorithm, but to show the implementation features of the framework and to take a glimpse at how relocations could affect the competitive carsharing market. In later applications, more efficient algorithms can be implemented in this framework. Both the framework and the relocation algorithm are developed in Java and are available as open source software in the MATSim GitHub repository (MATSim, 2018).

### *3.6. Cost estimates for carsharing operators*

Estimating the profitability of the carsharing service is not an easy task since carsharing operators keep their operational costs confidential. The operational costs used in this paper are based on the work of Bösch et al. (2018) and are as follows: fixed costs per vehicle (acquisition, interest, insurance, tax, parking and toll) total of to 8.4 CHF/vehicle/day; variable costs totaling to 0.223 CHF/km, overhead costs (including injuries and damages, safety, personnel administration, legal services, data processing, finance and accounting, engineering, real estate management, office management and services, customer services, promotion, market research, and planning) totaling to 14 CHF/vehicle/day. While the fixed and variable costs are well documented, the estimation of overhead costs is based on limited available data, and should be considered with caution. Since the fleet size is constant, fixed costs always sum up to 840 CHF/day and overhead costs to 1400 CHF/day.

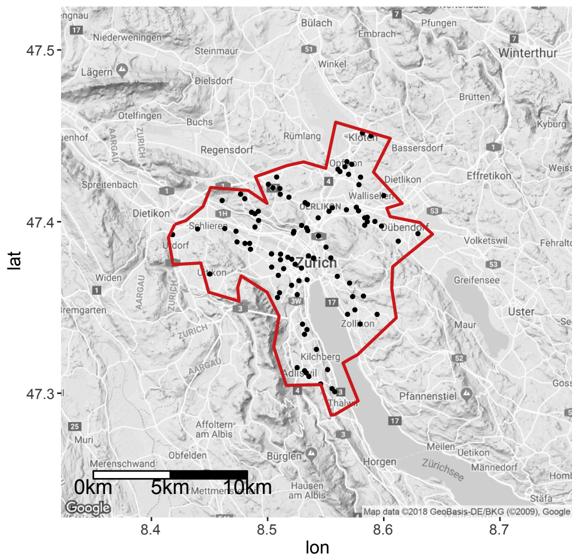



**Fig. 2.** Initial distribution of the carsharing vehicles and the boundaries of the service area.

## 4. Results

The framework described above has been used to investigate possible competitive free-floating carsharing operators in the city of Zurich, Switzerland. The study area is defined by a circle with a 30 km radius centered around Bellevue, Zurich. The simulated population is around 1.6 million people who either live or perform at least one of their activities in the study area. The agents in the simulation are allowed to change their modes of transport and their route. Available modes are privately owned car, bike, walk, public transport and free-floating carsharing. Details on the generation of the scenario, including the calibration and validation procedures can be found in Bösch et al. (2016). The free-floating carsharing service area is set to include the city of Zurich along with the nearby airport (Fig. 2), containing around 400 000 residents. In order to reduce the computational burden, the simulated scenario is scaled down to 10%, meaning that population, network capacities and carsharing supply are all scaled down in order to realistically represent the transportation system around Zurich. Therefore, through the remainder of the paper, all values on the supply and demand correspond to the 10% sample.

The carsharing supply consists of two competing services, from now on referred to Company 1 and Company 2. Both companies offer the same number of cars (100) and use the same initial distribution of vehicles (see also Fig. 2).[5] Placing the vehicles at the right locations at the start of each day is a viable research topic as discussed previously, but out of the scope of this study. The initial distribution of vehicles follows the population densities in the service area. Therefore, more populated areas have more vehicles available initially. The round-trip service is not simulated here since studies show that these two services are substantially different with respect to both customer groups and usage patterns (Becker et al., 2017a) and therefore would not have a direct impact on free-floating usage.

Each simulation was run 5 times with different random seeds for 100 iterations. The results presented here are the averages over these simulations.

### 4.1. Baseline scenario

In the baseline scenario (from now on Scenario 1), both companies offer the service for the same price - 0.37 CHF/min[6] which was inspired by the original price structure of the free-floating service launched in Basel in 2014.

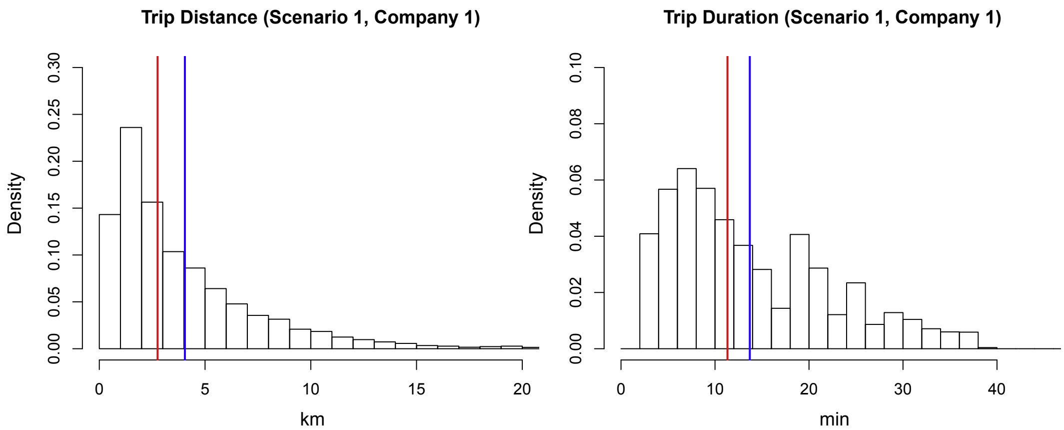
Companies perform similarly well with slight variations - as is expected. The whole market profit is around 1650 CHF per day for a 10% sample (see also Table 2) with the given overhead assumptions. As all attributes are equal (for customers), one can also interpret the service as being offered by only one company. This would mean that the operation would be profitable at this level of costs.

Most users perform only one trip per day with a carsharing vehicle. However, there are some with 2–3 rentals per day. The average distance per trip is around 3.9 km and the rental time is approximately 12.5 min. These values are reasonable taking into the account the size of the service area (Fig. 3). In almost all simulations, each vehicle was utilized at least once, meaning that there are only few vehicles placed in areas without demand.

[5] Based on our investigation this fleet size can achieve a good mixture of high user satisfaction and profit for the operator.
[6] 1 CHF corresponds to 0.81 USD at purchasing power parity for 2016 (OECD, 2018).

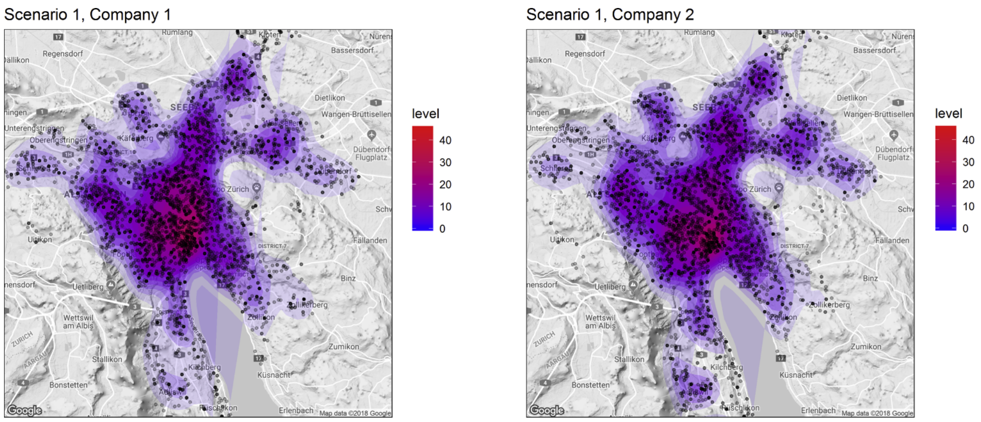
**Table 2**
Main results for the scenario 1 where both companies offer the service for 0.37 CHF/min.

| | Company 1 | | Company 2 | |
|---|---|---|---|---|
| | mean | sd | mean | sd |
| # of rentals | 784.4 | 15.5 | 801.6 | 5.7 |
| # of unique users | 745.6 | 15.0 | 761.6 | 5.7 |
| # of unique vehicles | 99.6 | 0.3 | 99.4 | 0.3 |
| Mean access time [sec] | 165.7 | 1.5 | 168.3 | 1.2 |
| Mean distance traveled [m] | 3826.2 | 63.5 | 3866.8 | 68.4 |
| Mean trip duration [sec] | 762.2 | 27.2 | 770.7 | 24.7 |
| Total turnover [CHF] | 3697.5 | 172.7 | 3815.5 | 143.7 |
| Total operation costs [CHF] | 2919.2 | 17.0 | 2941.9 | 17.0 |
| · variable and fixed costs [CHF] | 1519.2 | 17.0 | 1541.9 | 17.0 |
| Revenue [CHF] | 778.7 | 171.9 | 874.4 | 142.7 |




(a) (b)

**Fig. 3.** Company 1 in Scenario 1 (a) Trip distances and (b) Trip durations. Red line represents the median and blue the mean. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)




(a) (b)

**Fig. 4.** Rental start locations in Scenario 1: (a) Company 1 and (b) Company 2.

Pickup locations of both Company 1 and Company 2 are almost the same (see Fig. 4), since all service characteristics are the same. Most of the pick-up locations are situated in the central districts of the city with a high density of amenities. Areas towards the edges of the city experience lower level of rentals except for the area around the airport located in the north-northeast part of the city center.

**Table 3**
Scenarios description.

| | Price Level Company 1 | Price Level Company 2 |
|---|---|---|
| Scenario 1 | 0.37 CHF/min | 0.37 CHF/min |
| Scenario 2 | 0.33 CHF/min | 0.33 CHF/min |
| Scenario 3 | 0.41 CHF/min | 0.41 CHF/min |
| Scenario 4 | 0.37 CHF/min | 0.33 CHF/min |
| Scenario 5 | 0.37 CHF/min | 0.41 CHF/min |
| Scenario 6 | 0.29 CHF/min | 0.29 CHF/min |
| Scenario 7 | 0.45 CHF/min | 0.45 CHF/min |

### 4.2. Sensitivity to price

Possible competition among carsharing operators is investigated first by introducing different price levels. Besides the price level from Scenario 1 to 0.37 CHF/min, the companies could offer the service for two additional price levels - 0.41 CHF/min (it resembles the previous price for carsharing in the city of Basel) and 0.33 CHF/min which represents again the same absolute reduction in price from 0.37 CHF/min, as from 0.41 to 0.37 CHF/min (please reference Table 3 for the description of all scenarios).

Tables 4 and 5 show the most important statistics for the scenarios in which both companies have the same fleet size and distribution, but with different competing price structures (as explained above).

When both companies offer the service for the same price (Scenarios 2 (0.33 CHF/min) and Scenario 3 (0.41 CHF/min) - Tables 2 and 4) their performance is very similar. However, the market profits for these three level of prices is different. Highest market profit is achieved with the prices equal to 0.41 CHF/min (Scenario 3), a price previously used by the carsharing operator in Basel and Geneva. As competition is nonexistent, one can observe the service as offered by one company and conclude that this level of pricing is close to optimal, considering the fleet size and service area.

Scenarios 4 and 5 show two cases where the competition between the operators occurs when the companies offer the same fleet, but with different price levels. In both Scenario 4 and 5, Company 1 offers the service for the price of 0.37 CHF/min while Company 2 enters the market with the price of 0.33 CHF/min in Scenario 4 and 0.41 CHF/min in Scenario 5. In Scenario 4, Company 2 is a big winner as it manages to attract many users that would have otherwise chosen Company 1 (as can be seen in the Scenario 1, when both companies offer the service at the same price) and even though is offering the service with the lower price it increases its profit. Company 1 on the other side loses some of its turnover. In Scenario 5 we can see a similar effect. Even though Company 2 loses some of its turnover because of the higher prices, the market profit is higher than in Scenario 1. Company 1, on the other hand, increases its turnover, because it attracts many users that would have chosen Company 2 if both companies offered the service at the same price (Scenario 1). All other statistics like trip duration, distance, access time very only slightly between the different fare setups.

To further explore the effects of price on the profitability of competitive free-floating carsharing operators two more price levels are simulated: 0.29 CHF/min and 0.45 CHF/min. In both scenarios, where operators offer the service at the same price the turnover and revenue for the operators are further reduced from their optimal values as seen in Table 6.

### 4.3. Relocations effects in the competitive markets

In order to capture demand in the areas that are not well served by the carsharing vehicles throughout the day, an operator might decide to perform vehicle relocations. Here, we allow only one company to perform relocations - Company 2. The relocation effects are first presented for the baseline scenario (Scenario 1) and for Scenario 3 which produces the highest market profit. The results are presented in Table 7.

In each scenario, Company 2 has 10 relocation workers. A lower number of workers did not provide enough relocation movements to substantially affect the demand. The workers performed an average of 129 relocations per day in both Scenario 1 and

**Table 4**
Main results for the Scenario 2 where both companies offer the service for 0.33 CHF/min and Scenario 3 where both companies offer the service for 0.41 CHF/min.

| | Scenario 2 | | | | Scenario 3 | | | |
|---|---|---|---|---|---|---|---|---|
| | Company 1 | | Company 2 | | Company 1 | | Company 2 | |
| | mean | sd | mean | sd | mean | sd | mean | sd |
| # of rentals | 891.8 | 12.3 | 869.2 | 8.2 | 746.8 | 7.3 | 723.4 | 6.1 |
| Total turnover [CHF] | 3939.8 | 167.5 | 3884.8 | 135.4 | 3922.7 | 162.8 | 3765.4 | 147.6 |
| Total operation costs [CHF] | 3028.5 | 16.3 | 3020.9 | 11.5 | 2887.7 | 10.5 | 2853.6 | 9.3 |
| · var. + fixed costs [CHF] | 1628.5 | 16.3 | 1620.9 | 11.5 | 1487.7 | 10.5 | 1453.6 | 9.3 |
| Revenue [CHF] | 911.8 | 166.7 | 864.2 | 134.9 | 1035.9 | 162.5 | 912.2 | 147.3 |

**Table 5**
Main results for the Scenario 4 (company 1–0.37 CHF/min and company 2–0.33 CHF/min) and Scenario 5 (company 1–0.37 CHF/min and company 2–0.41 CHF/min).

| | Scenario 4 | | | | Scenario 5 | | | |
|---|---|---|---|---|---|---|---|---|
| | Company 1 | | Company 2 | | Company 1 | | Company 2 | |
| | mean | sd | mean | sd | mean | sd | mean | sd |
| # of rentals | 691.8 | 16.0 | 989.2 | 21.1 | 922.0 | 13.9 | 655.6 | 8.9 |
| Total turnover [CHF] | 3390.5 | 139.1 | 4413.5 | 200.7 | 4351.3 | 161.2 | 3366.7 | 99.7 |
| Total operation costs [CHF] | 2824.2 | 13.3 | 3125.4 | 23.9 | 3041.1 | 21.6 | 2777.0 | 7.9 |
| · var. + fixed costs [CHF] | 1424.2 | 13.3 | 1725.4 | 23.9 | 1641.1 | 21.6 | 1377.0 | 7.9 |
| Revenue [CHF] | 566.7 | 138.5 | 1288.2 | 199.3 | 1310.2 | 159.8 | 610.3 | 99.4 |

**Table 6**
Main Results for the Scenario 2 where both companies offer the service for 0.29 CHF/min and Scenario 3 where both companies offer the service for 0.45 CHF/min.

| | Scenario 6 | | | | Scenario 7 | | | |
|---|---|---|---|---|---|---|---|---|
| | Company 1 | | Company 2 | | Company 1 | | Company 2 | |
| | mean | sd | mean | sd | mean | sd | mean | sd |
| # of rentals | 944.6 | 12.2 | 971.0 | 18.4 | 652.2 | 11.7 | 655.2 | 8.7 |
| Total turnover [CHF] | 3772.4 | 120.9 | 3834.3 | 162.6 | 3668.3 | 180.4 | 3603.2 | 163.8 |
| Total operation costs [CHF] | 3087.2 | 9.4 | 3090.6 | 24.2 | 2810.4 | 19.7 | 2798.1 | 17.2 |
| · var. + fixed costs [CHF] | 1687.2 | 9.4 | 1690.6 | 24.2 | 1410.4 | 19.7 | 1398.1 | 17.2 |
| Revenue [CHF] | 686.8 | 120.5 | 744.3 | 160.8 | 857.9 | 179.3 | 805.1 | 162.9 |

**Table 7**
Relocation results for the scenario 1 (both companies offer the service for the same price - 0.37 CHF/min) and scenario 3 (both companies offer the service for the same price - 0.41 CHF/min).

| | Scenario 1 | | | | Scenario 3 | | | |
|---|---|---|---|---|---|---|---|---|
| | Company 1 | | Company 2 | | Company 1 | | Company 2 | |
| | mean | sd | mean | sd | mean | sd | mean | sd |
| # of rentals | 791.8 | 13.1 | 873.8 | 10.5 | 741.6 | 16.7 | 772.6 | 8.7 |
| Total turnover [CHF] | 3892.0 | 171.2 | 4179.2 | 160.4 | 3790.7 | 180.8 | 3996.7 | 162.9 |
| Total operation costs [CHF] | 2927.9 | 15.2 | 2981.7 | 19.7 | 2871.2 | 20.6 | 2912.9 | 13.5 |
| · var. + fixed costs [CHF] | 1527.9 | 15.2 | 1581.7 | 19.7 | 1471.2 | 20.6 | 1512.9 | 13.5 |
| # of relocations | | | 129.2 | 0.3 | | | 129.4 | 0.4 |
| Mean relocation trip time [min] | | | 7.5 | 0.2 | | | 7.1 | 0.3 |
| Total relocation cost [CHF] | | | 794.2 | 9.4 | | | 775.3 | 9.3 |
| Revenue [CHF] | 965.9 | 160.2 | 403.4 | 157.7 | 919.5 | 178.5 | 308.6 | 161.3 |

Scenario 3 using the relocation strategy described in the previous section. The average in-vehicle time was 7.5 min and 7.1 min respectively. Access time for relocation workers to the vehicle that has to be relocated was assumed to be on average 10 min using a foldable bike. By performing this straightforward relocation strategy, the operator gained around 72 more rentals per day in Scenario 1 and 49 in Scenario 3.

Relocation costs include a 20 CHF/hour salary for relocation workers (paid for access and relocation movement duration) and depreciation, maintenance, fuel and tire costs. Even though relocations did increase the number of rentals, the increase in turnover was substantially lower than the expenses for relocations, rendering it unprofitable.

In contrast, Company 1 manages to attract more users in Scenario 1 but not in the Scenario 3 and increases its profit (however only in the 0.37 CHF/min price level scenario). This indicates that if only one operator performs relocations, the other operator benefits from a “free-rider effect”, but only under certain circumstances. There are two main reasons for this effect: First, while relocating vehicles, Company 2 makes them unavailable to customers, thus temporarily decreasing the availability of its fleet, which makes the fleet from Company 1 more attractive. Second, by moving the vehicles from areas with expected lower demand, Company 2 decreases its presence in some neighborhoods and at certain times of the day. However, the demand is not known a priori. Therefore, when the demand occurs, Company 1 benefits, because it usually has the best offer in such areas. Therefore, two opposing forces occur for the operator that does not perform relocations. Such an outcome is difficult to predict without simulation.

**Table 8**
Relocation results for the Scenario 4 (company 1–0.37 CHF/min and company 2–0.33 CHF/min) and Scenario 5 (company 1–0.37 CHF/min and company 2–0.41 CHF/min).

| | Scenario 4 | | | | Scenario 5 | | | |
|---|---|---|---|---|---|---|---|---|
| | Company 1 | | Company 2 | | Company 1 | | Company 2 | |
| | mean | sd | mean | sd | mean | sd | mean | sd |
| # of rentals | 728.0 | 11.7 | 1047.0 | 12.0 | 906.4 | 18.2 | 701.8 | 8.3 |
| Total turnover [CHF] | 3557.4 | 140.5 | 4686.3 | 196.9 | 4330.6 | 204.1 | 3667.3 | 139.7 |
| Total operation costs [CHF] | 2851.0 | 8.7 | 3165.6 | 14.7 | 3049.7 | 22.5 | 2812.8 | 11.5 |
| · var. + fixed costs [CHF] | 1451.0 | 8.7 | 1765.6 | 14.7 | 1649.7 | 22.5 | 1412.8 | 11.5 |
| # of relocations | | | 129.0 | 0.3 | | | 129.8 | 0.1 |
| Mean relocation trip time [min] | | | 7.8 | 0.1 | | | 6.2 | 0.1 |
| Total relocation cost [CHF] | | | 807.0 | 5.8 | | | 733.7 | 4.9 |
| Revenue [CHF] | 706.5 | 140.2 | 713.7 | 195.9 | 1281.0 | 202.9 | 120.8 | 138.7 |

This finding is further investigated in Scenarios 4 and 5 (Table 8). In Scenario 4, it is clear that the company that does not do relocations has a substantial benefit and increases its turnover, whereas in Scenario 5 the opposite happens. A possible reason can be that Company 1 when initially has comparably lower demand, can acquire additional demand with the given fleet and price. However as the demand rises, the ability to attract additional users diminishes. This finding is important, as we observe that changes in distributions of one company can change rental patterns of its competitor.

Destinations of relocation activities in different parts of the day are shown in Fig. 5. Most of the relocations end in areas of high (realized) demand as seen in Fig. 4. Interestingly, morning and evening relocation patterns are quite similar, while mid-day and early afternoon patterns are substantially different. Mid-day relocations are much more focused on the very core of the city where rentals

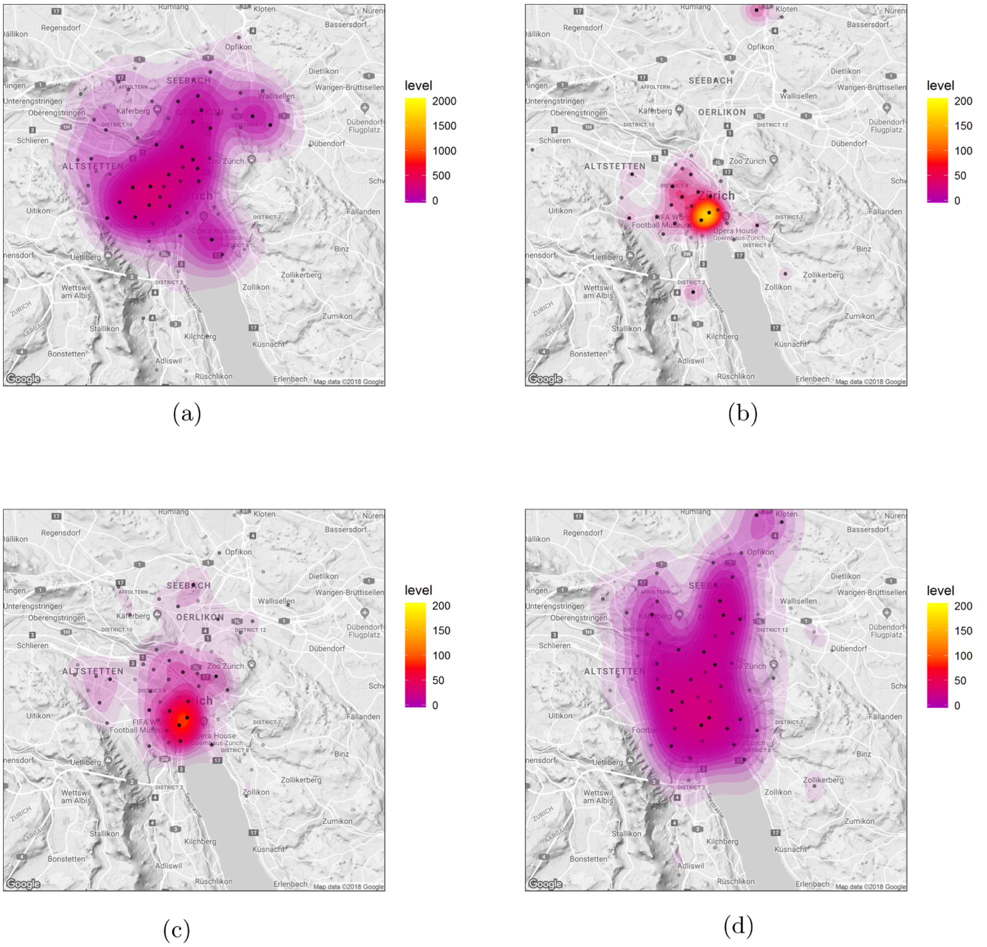
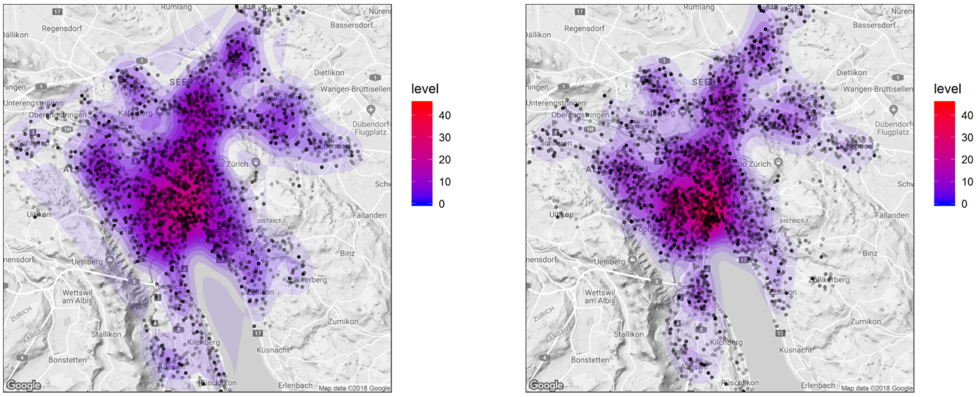



**Fig. 5.** Relocation drop-off locations: (a) 7–10 am; (b) 11 am to 1 pm; (c) 2–4 pm; (d) 5–7 pm.




(a) (b)

**Fig. 6.** Rental start locations in Scenario 2: (a) for Company not performing relocations and (b) for Company that is performing relocations.

are mostly expected to occur. The same applies for the early afternoon, but with less dramatic peaks in the city center and spreading slightly towards the airport and surrounding outskirts. Although most of the users use carsharing for only one trip per day, they are not using for the same type of trip. Instead, some use it in the morning, while others use it in the afternoon, which as a result creates similar global patterns throughout the day. Another reason for this behavior may be that activities are similarly spread around the city center.

However, the distribution of the pick up locations for Company 2 becomes visibly different from those of Company 1 (Fig. 6) when Company 2 performs relocations, as more vehicles are constantly moved towards the city core and away from the outskirts.

#### *4.3.1. Relocations by both companies*

Companies operating in a competitive market might simultaneously decide to perform relocations in order to serve the demand better. Simulations were run again for Scenarios 1 and 3 with each company having ten relocation workers. Table 9 summarizes the results.

Both scenarios have a much higher increase in total rentals per relocation movement than when only one company relocates their vehicles, even though the total number of relocations doubles. If the only purpose of relocations is to increase the demand, from a market perspective, it will be better for both companies to perform relocations.

## 5. Discussion and conclusions

Competition in free-floating carsharing markets has emerged as a new phenomenon due to the ongoing expansion of (new) operators. Moreover, while user groups and usage patterns have already been well-researched for the case of single operators (Becker et al., 2017a,b), it is still widely unclear how such patterns are affected by competition. Hence, it is hard to predict how these markets may evolve. Also, given that various car-manufacturers use free-floating carsharing as a field trial for new mobility services, insights gained by these systems may help to understand future services such as automated taxis.

The main contribution of this research is to provide a test-bed for the investigation of competitive carsharing markets. An important part of the framework is a first implementation of a carsharing relocation interface for MATSim. It is available as open-source software and can serve as the basis for various detailed analyses.

**Table 9**
Relocation results for the scenario 1 (both companies offer the service for the same price - 0.37 CHF/min) and scenario 3 (both companies offer the service for the same price - 0.41 CHF/min) with 10 relocation workers available.

| | Scenario 1 | | | | Scenario 3 | | | |
|---|---|---|---|---|---|---|---|---|
| | Company 1 | | Company 2 | | Company 1 | | Company 2 | |
| | mean | sd | mean | sd | mean | sd | mean | sd |
| # of rentals | 883.4 | 10.1 | 867.0 | 13.7 | 806.8 | 9.5 | 785.8 | 18.2 |
| Total turnover [CHF] | 4307.7 | 144.8 | 4214.2 | 177.5 | 4261.6 | 196.6 | 4189.0 | 229.0 |
| Total operation costs [CHF] | 2985.5 | 13.4 | 2987.2 | 13.7 | 2922.6 | 17.1 | 2906.7 | 18.3 |
| · var. + fixed costs [CHF] | 1585.5 | 13.4 | 1587.2 | 13.7 | 1522.6 | 17.1 | 1506.7 | 18.3 |
| # of relocations | 127.6 | 1.5 | 129.6 | 0.2 | 129.0 | 0.3 | 130.0 | 0.0 |
| Mean relocation trip time [min] | 6.4 | 0.1 | 7.0 | 0.3 | 6.5 | 0.1 | 6.3 | 0.1 |
| Total relocation cost [CHF] | 733.2 | 12.4 | 771.0 | 12.2 | 745.7 | 4.6 | 741.4 | 2.5 |
| Revenue [CHF] | 589 | 142.4 | 455.9 | 175.7 | 593.4 | 195.4 | 540.9 | 228.1 |

In this research, the framework is applied to analyze the case of two competing free-floating carsharing operators in the city of Zurich, Switzerland. It shows that different strategies and price levels can play a substantial role in defining the profitability of the service and usage levels. It confirms earlier research by Schwieterman and Bieszczat (2017) showing that when offering the same service level (same type of vehicles, fleet size and its distribution), competing companies can increase profit by adapting their price structures. The results show that adjusting the price levels unilaterally can lead to an increase in profit for a single company. Offering the service for 0.37 CHF/min as compared to the 0.41 CHF/min service offered by the competitor can lead to a substantial increase in profit. However, based on non-cooperative game theory, this is not a stable situation. The company which offers the service for a higher price can reduce its price in order to increase its profit. Therefore, unless being cooperative, companies may try adjusting their prices in order to increase their profits, but large differences will probably not occur (refer to Schwieterman and Bieszczat, 2017 for a practical example). As a side-note, the results show that different price structures attract different market segments (trip types), an effect, which has also been reported by Ciari et al. (2015). Companies that are non-cooperative might try to eliminate the competition by reducing the prices for their services forcing the competition to do the same in order to avoid higher loses. In this situation where both companies are operating at a loss only the one with stronger financial support would survive and corner the market.

Furthermore, the results show that relocations are unprofitable in a competitive carsharing market. The high cost of relocation workers, depreciation, fuel, maintenance and tire costs, even if every relocation would be turned into a rental, at best leads to a marginal increase in revenue. It is important to note that if the relocation workers would only be paid during the actual relocation movements, most of the scenarios with relocation would exhibit an increase in revenue for the operator performing relocations. This implies that relocation movements in the automated world would be highly efficient as their costs would be dramatically reduced. Finally, relocations result in a "free-rider" effect in some scenarios.

The application shown in this research is hypothetical because no free-floating carsharing schemes operate in the city of Zurich. To validate the results, it would be interesting to study a city where the competition already exists and to analyze potential operator strategies. However, this requires a calibrated MATSim scenario for the respective case study area.

In addition, the currently implemented relocation strategy is simplistic and even though it shows improvements in both turnover and usage, more sophisticated algorithms may result in higher gains. The incorporation of such algorithms could be a step forward to get even a better grasp of the potentials of relocations in competitive carsharing markets.

Another limitation of the this study, as is the case for most studies on carsharing, is the lack of a destination choice model. This additional choice dimension can affect the demand for carsharing services, since the agents could adapt their destinations as this new service could increase their accessibility. This means that their choice set of alternatives for secondary activities increases, so the OD pairs might change and affect the demand for carsharing. What we do not expect, however, is to see substantial change in the impacts of the competition, the main focus of this paper.

Despite such limitations, this research gives clear suggestions for operators in competing carsharing markets with respect to their pricing and relocation strategies. Moreover, since the framework is easily extendable, further research on the effects of fleet sizes, service areas or other characteristics is within reach.

## Appendix A. Modules of MATSim CarSharing Framework

### *A.1. CarSharing Manager*

CarSharing Manager (CM) is the *brain* of the Carsharing Framework. It receives inputs from the MATSim framework, processes them and sends back the results to the MATSim simulation. CM has access to the information provided by other modules of the Carsharing Framework (Supply, Membership, Models, Routers).

Upon receiving a request from MATSim that a carsharing trip needs to be routed for a specific agent, CM performs a set of instructions and returns the routed trip to MATSim. If it was not possible to route a trip, CM might offer a different transportation mode (like public transport). If the trip is replaced by a different mode the agent needs to add the changed plan to a set of plans that the agent keeps in its memory (usually this is 5 in standard MATSim) in order to maintain consistency. The booking of the carsharing vehicles is executed intentionally during the traffic simulation and not during the re-planning phase, for two reasons. First, only round-trip services in practice allow pre-booking of more than 15 min. Second, the pre-booking is in practice performed by different people at different times, which can be mimicked by allowing agents to book their vehicles at different points of time during the simulation (in this case at the end of their preceding activity). This allows for a certain randomness that one can experience in reality when one sometimes might or might not find a free vehicle when requested.

### *A.2. Supply module*

The supply module contains information about all available operators, their services and cost-structures. Supply information is provided to the CF via an XML file. The components of this module are:

1. **Vehicle** - contains the following information
   (a) Id - unique vehicle id
   (b) CompanyId - company to which the car belongs
   (c) Type - whether it is a sports car, hybrid, transporter, etc.

2. **Station** - contains all the vehicles that are currently available and total/available parking spaces (for station based services only).
3. **Service** - A carsharing service. Each service can have its own pricing structure, that is provided to the supply module.
4. **Company** - High-level module that contains all the services a company (operator) provides to its customers.

In addition, it is possible to define a service area so that at the end of the rental, carsharing vehicles can only be parked within this area.

Having **Supply** as a pluggable module provides a flexible way to provide necessary information on the location of the available vehicles to the relocation module (introduced later in this section). In this way, the relocation module can relocate vehicles based on a given optimization algorithm independently from the carsharing framework. The modularity of the supply instance makes it easily extendable to support vehicles and stations with additional information (i.e. charging stations or current level of charge for electric vehicles). Each operator in the supply module can act as a separate agent that can control the prices, available vehicles, their location, etc., according to its goals.

### *A.3. Decision Models Module*

Decision Models Module (DMM) can contain arbitrary number of decision models that the CM uses when requested to route a carsharing trip for an agent. Examples of currently implemented models are:

1. **Keep the Car** model decides if the agent should keep the rented vehicle while he is performing a certain activity or should he end the rental.
2. **Choose the Company** model lets agents decide from which company should they rent their carsharing vehicle.
3. **Choose Vehicle Type** model lets agents decide what type of vehicle they would prefer for their trip.

The decisions made by the agent are stored in its plan and can be retrieved in the subsequent iterations if the agent decides to execute the same plan.

Additional decision mechanisms can be provided to CM using the current infrastructure.

### *A.4. Operations module*

Operations module takes care of two types of demand:

1. Ongoing rentals - It provides information to the manager about the vehicles that are currently in use.
2. Finished rentals - It is used for analysis at the end and for scoring during the simulation.

### *A.5. Router module*

The router module provides routers for different kinds of carsharing services. Currently implemented are routers for free-floating, one-way and round-trip carsharing. During the simulation, the carsharing router receives a request to route a carsharing trip. Along with the request, the router receives the following information:

- Agent whose leg needs to be routed.
- The vehicle that will be used.
- Location of the vehicle.
- Parking location at the end of the trip.

The stages of the carsharing trips that the router sends back to the CM are as follows:

1. Access walk to the rented vehicle,
2. Carsharing Activity Interaction where the agent unlocks the vehicle and prepares for driving,
3. Vehicle trip that is routed on the network based on the congested travel times, using the carsharing vehicle,
4. Carsharing Activity Interaction where the agent parks the vehicle (and potentially ends the rental),
5. Egress walk to the next activity.

All these steps are subsequently simulated in the MATSim framework, meaning that the simulation of carsharing in MATSim does not require any structural change in the simulation. Router module is flexible and allows alternative ways of carsharing trip routings (i.e. combining carsharing with other modes). The agent that is using carsharing as a transport mode, can change his route in every iteration in order to adapt to the current state of the traffic. For free-floating carsharing, a parking-choice module (Waraich and Axhausen, 2012) can also be activated if parking information is provided to the simulation as described and implemented in Balac et al. (2017).

### A.6. Membership module

In the simulation, only agents that have a carsharing membership are allowed to use carsharing as a mode. Each agent can hold any number of membership cards for different operators and services. According to the particular scenario simulated membership can be assigned arbitrarily or according to a specific model. An example of assigning carsharing membership to agents in MATSim can be found in Ciari et al. (2016).

### A.7. Analysis module

The analysis module is responsible for collecting the information on the executed rentals during the simulation. It outputs the information on all rentals for external analysis.

### A.8. MATSim and Carsharing Framework communication

The most important part of the communication between MATSim and the Carsharing Framework is the request to route a carsharing trip for a certain agent at a certain time and place, from MATSim to the Carsharing Framework. The agents make decisions through the interaction with the operators and their personal preferences. If the outcome of this process is a success, the carsharing trip is routed, otherwise a fail confirmation is sent to MATSim. Upon routing the trip, the Carsharing Framework returns a fully routed trip between the origin and destination. These two frameworks also exchange information on the events that they are both generating. The events is the concept that MATSim uses in order to store information on every change of the state in the system (i.e. when an agent finishes his activity, enters a vehicle, enters a link on the network and so on). For Carsharing Framework some of these events are RentalStartEvent, RentalEndEvent, NoVehicleEvent (when there are no carsharing vehicles available), etc.

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