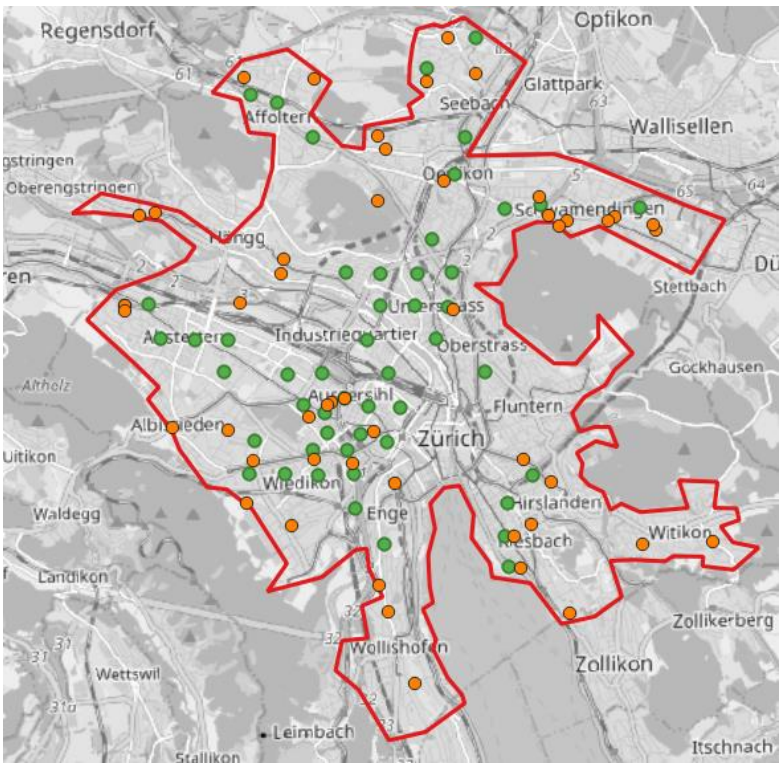


Free-floating carsharing vehicle placement and relocation

Carmen Buff

Bachelor Thesis
Institute for Transport Planning and Systems **June 2020**

Institut für Verkehrsplanung und Transportsysteme
Institute for Transport Planning and Systems

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Acknowledgements

First of all, I would like to express my thanks to Prof. Dr. Kay W. Axhausen who supported me during the work on my bachelor thesis and who gave me constructive advice for the further development of my thesis. Furthermore, I would like to thank Dr. Milos Balac, my supervisor during the whole progress of this thesis. He was available to discuss occurring questions and problems and gave me further inputs on how to improve my thesis.

Table of contents

List of tables

List of figures

Bachelor Thesis, Civil Engineering

Free-floating carsharing vehicle placement and relocation

Carmen Buff
ETH Zürich

CH-8093 Zürich

buffc@student.ethz.ch

June 2020

Abstract

The offer of free-floating carsharing services has grown in the past years and this service type has become present all over the world. As in this service, the carsharing users can end their trip on any public parking space, an imbalance between the vehicle supply and the user demand is likely to occur. Nevertheless, the influence of the initial vehicle placement in free-floating carsharing services has not been investigated yet. This thesis, therefore, analyses the performance of different initial vehicle locations. Furthermore, even if previous studies already focused on the relocation problem, most of them focused on relocations during the day. Additionally, many previous studies do not determine if relocations are profitable for the operator in terms of financial gains. In this thesis, simulations over five days are conducted and it is shown that in the best initial vehicle placement scenario the revenue decreases by 15% after the first day. Besides, the revenue never reached the value of the first day again, which means that night-time relocations might be profitable even if they produce additional costs.

Keywords

Carsharing; Free-floating; Relocation; Initial vehicle placement

Preferred citation style

Buff, C. (2020) Free-floating carsharing vehicle placement and relocation, *Bachelor Thesis*, Institute for Transport Planning and Systems (IVT), ETH Zurich, Zurich.

1 Introduction

One of the first professionally organized carsharing operators was the cooperative Sefage (Selbstfahrgemeinschaft). The community started its carsharing business in Zurich in 1948 (Shaheen and Cohen, 2007). At this time, mostly economical reasons were responsible for the introduction of carsharing as transport mode, as part of the population could not afford to own a car. With the introduction of the carsharing service, individuals could benefit from the use of a private vehicle without worrying about the maintenance and the occurring costs for an own vehicle (Shaheen and Cohen, 2007).

Since the first introduction of a carsharing operator, the business expanded all over the world and the fleet size, as well as the membership, increased. Furthermore, different carsharing service types were developed. In the last years, the free-floating service type has been introduced in different cities all over the world. For this carsharing system, no vehicle stations exist and the customers can pick up any vehicle next to their location. At the end of a carsharing trip, the vehicle can be parked on any public parking lot. Even if the implementation of this service brings more freedom and flexibility for the customers, the carsharing operator is confronted with higher complexity of the system. If the vehicles are parked in an area, where the demand for a carsharing trip is low, the vehicles may remain unused for a long time. Apart from that, a shortage of vehicle supply might exist in areas with high potential carsharing users. To avoid these vehicle imbalances, the providers should consider vehicle relocation processes. In the past, several studies focused on the optimization of the relocation processes and different algorithms have already been proposed. Most of these studies investigated the influence of relocation processes carried out several times during the day. Alternatively, relocations could be performed during the night, when the demand is lower and the vehicles could be placed at the optimal locations for the next day. This thesis thus examines whether relocations should be conducted over the night and if relocations can increase the profitability of the carsharing service.

In addition to the relocation processes, the initial vehicle placement might have an influence on the demand and profitability of a free-floating carsharing service. Therefore, the efficiency and profitability of the service might be maximised by applying the optimal initial vehicle placement. Previous studies focused on the optimal station location for one-way station-based carsharing services, where the vehicles need to be returned to an existing carsharing station. As, to the author's knowledge, no study investigated how the demand for free-floating carsharing is affected by the initial vehicle placement, this thesis examines different initial vehicle distributions to determine how the profitability of the service can be maximised. Thus, several

simulations are carried out with the Multi-Agent Transport Simulation MATSim (Horni, Nagel and Axhausen, 2016).

The following chapter provides an overview of the existing carsharing service types and describes some existing relocation strategies and algorithms as well as the influence of the station location for one-way station-based carsharing systems. Afterwards, the simulation framework, as well as the investigated scenarios, are described in chapter 3. The outcomes of the conducted simulations are presented in chapter 4. Finally, the results of this thesis are discussed in chapter 5.

2 Literature review

2.1 Carsharing service types

In typical carsharing systems, the system operator provides a vehicle fleet to a group of members. Maintenance, insurance and management of the vehicles are the tasks of the system provider, whereas users usually have a 24-hour self-service access to the vehicles. The existing carsharing services can be divided into three different models: round-trip carsharing, one-way carsharing and peer-to-peer carsharing. Furthermore, there exist two options to perform one-way carsharing, either station-based or free-floating (Shaheen, Chan and Micheaux, 2015).

2.1.1 Round-trip carsharing

Round-trip carsharing systems are station-based, which means that vehicles are only available at and need to be returned to a specific parking lot, a so-called station. For round-trip services, the user needs to return the used car to the station where he picked the vehicle up. Furthermore, a reservation is required before the customers can make use of a shared vehicle. These restrictions lead to a reduction in flexibility for the customers, as trips need to be planned before starting a journey. Nevertheless, the service is relatively simple and easy to provide, as vehicles are returned to their initial position and therefore the vehicle equilibrium can be maintained. Hence, the rates paid by the customers can usually be kept lower than in other carsharing service types.

In Switzerland, Mobility carsharing is the best-known operator of round-trip carsharing. Mobility provides a vehicle fleet of approximately 2390 cars at 1480 locations among the whole country of Switzerland (Mobility Genossenschaft, 2020c). Zipcar is another well-known provider of round-trip carsharing. Its main business is in the United States and Canada, but the company offers some locations in Europe as well, mostly in the United Kingdom (Zipcar, 2020).

In the past, most researchers examined station-based carsharing systems. Thus, multiple studies exist which analyse the demand for these services. An informative literature review on this can be found in Jorge and Correia (2013). Furthermore, some studies focused on the location of the stations and how they influence the membership or the profit of the carsharing service (e. g.: Ciari, Weis and Balac, 2015; Changaival, Danoy, Kliazovich, Guinand, Brust, Musial, Lavangnananda and Bouvry, 2019; Kumar and Bierlaire, 2012).

2.1.2 One-way station-based carsharing

In one-way station-based carsharing services, the access and return location can differ from each other, leading to higher flexibility for the customers. Nevertheless, the vehicles still have to be parked at a designated station. On the operational level, the system gets more complex if one-way rentals are allowed. As inequalities occur between the vehicle supply and demand within the operating area, relocation processes need to be performed by the provider. As in most cases, booking is still necessary before accessing a vehicle, the demand is easier to predict than for free-floating carsharing systems (Weikl and Bogenberger, 2015). Beside round-trip carsharing, Mobility carsharing offers one-way trips as well. Most stations are located in the Mittelland or Jura (Mobility Genossenschaft, 2020b).

Multiple studies examined the relocation problem for one-way station-based carsharing systems. A literature review concerning this topic can be found in Illgen and Höck (2019).

2.1.3 Free-floating carsharing

Free-floating carsharing is one of the most recent developed systems. The introduction of free-floating carsharing provides higher flexibility to the users. With this service, the shared vehicle can be parked on any public parking space in the operating area. Compared to the station-based option, the driver can park the car closer to his end destination. Thus, the customers' comfort is increased, as the walking distance before and after each trip can be minimized (Paschke, Balac and Ciari, 2016). Furthermore, in most cases no reservation is needed in free-floating carsharing systems, meaning that the customers can just access an available vehicle whenever desired (Weikl and Bogenberger, 2015). This opportunity turns the system more attractive to the users, but in contrast, the operation gets more complex. Like in one-way station-based services, vehicle imbalances occur in the system and relocation processes are needed. However, the system behaviour is now hardly predictable as customers do not need to book the vehicle nor define their destination before accessing it (Weikl and Bogenberger, 2015). Due to this additional relocation costs, the user prices are mostly higher than in station-based carsharing systems. Another reason for higher fees for free-floating carsharing is that the operator needs to pay the parking fees while a vehicle remains unused, as the cars can be parked on public parking spaces.

In Switzerland, free-floating carsharing only exists in two cities, namely in Basel and Geneva. It is a service provided by Mobility carsharing as well (Mobility Genossenschaft, 2020a). A well-known operator of free-floating carsharing in Europe is Share Now. They operate in eight

different European countries, namely in Germany, Italy, France, Austria, Spain, Denmark, Hungary and the Netherlands. (Share Now, 2020).

2.1.4 Peer-to-peer carsharing

In peer-to-peer (P2P) carsharing, members can temporarily convert their privately-owned vehicle into a shared vehicle which is then available for other users. In most cases, the network is provided by a third-party company, which covers insurance and enables the connection between users and suppliers. As any member can provide its vehicle as a shared car, the system is able to offer greater variability of vehicle types, access and end points than other carsharing services (Shaheen, Martin and Bansal, 2018). As no vehicle fleet needs to be provided by an operator, P2P systems show the potential to be used in lower-density areas, where the traditional carsharing models are not profitable (Hampshire and Gaites, 2011). The P2P service offers advantages for both, the suppliers and the clients: The owner of the privately shared vehicle gains part of the rate paid by the user, whereas the user does not need to own a car and to worry about maintenance and insurance. Unfavourably, access is sometimes not automated, but a transfer of the vehicle key from the owner to the client is necessary (Shaheen et al., 2018). Nevertheless, further technology developments allow offering key-less access to the vehicles, using an application or a member card.

In Switzerland, Sharoo provides peer-to-peer carsharing. In this system, all hirers and all suppliers need to register in the Sharoo app. Besides, each car is equipped with a box so that key-less access to the vehicles is possible and the whole booking and accessing system can be performed using the Sharoo app. Furthermore, Sharoo offers insurance that covers any possible damage of the shared car (Sharoo, 2020). Up to now, approximately 1700 different vehicles are registered at Sharoo and can be used by Sharoo members (Sharoo, 2020). Getaround is another company offering peer-to-peer carsharing. Getaround started its operations in the United States and expanded to Europe in 2019, as they acquired the peer-to-peer operator Drivy, the largest carsharing provider in Europe. Therefore, Getaround now operates in around 300 cities in the United States and six countries in Europe, namely in France, Germany, Spain, Austria, Belgium and the United Kingdom (Getaround, 2019).

2.2 Relocation strategies

For one-way station-based and free-floating carsharing systems, imbalances in the vehicle distribution are likely to occur among the operating area. These imbalances, on the one hand, lead to oversupplied areas, so-called cold spots, where more vehicles are available than needed to cover the demand. On the other hand, undersupplied areas exist, referred to as hot spots, in which the supply is lower than the demand. To balance this mismatch of the vehicle distribution, relocations need to be performed. In general, relocation strategies can be divided into operator-based and user-based approaches.

2.2.1 Operator-based relocation strategies

In operator-based relocation strategies, additional employees are hired to conduct vehicle relocations (Weikl and Bogenberger, 2013; Paschke et al., 2016). Weikl and Bogenberger (2013) suggest that each vehicle can be relocated separately or that a transporter could be used to relocate up to three cars at the same time. Operator-based relocations can easily be combined with vehicle maintenance and cleaning. Furthermore, it is possible to assure that each vehicle is relocated to the desired location, making this approach more reliable than user-based relocations. However, trips without customers are conducted, leading to additional costs for the staff and gas consumption. Weikl and Bogenberger (2013) further present a strategy, where vehicle depots are located in undersupplied areas. If the demand increases, additional vehicles can be released from the depot. By applying this strategy, no extra relocation rides are necessary as the vehicles are already located in undersupplied areas. On the downside, additional costs occur as more vehicles are required to fill the depots and as the depot generates additional costs itself.

Paschke et al. (2016) state more concretely, how operator-based relocations could be performed: First of all, the use of a service car is suggested where all employees work in teams of two. A service car is driven to the vehicle, which needs to be relocated. One worker then performs the vehicle relocation, while the second one uses the service car to arrive at the destination of the vehicle relocation. Once there, the first worker gets picked up and the team starts another relocation trip. Furthermore, it is suggested to use public transport or folding bikes to arrive at the relocation locations. Car transporters are mentioned as well and the study states, that in the future, autonomous vehicles could help to conduct these processes. A further proposal of this thesis is to combine relocations with refuelling.

Operator-based relocations can be carried out at different time intervals. Some approaches focus on relocations conducted once daily, mostly over-night, as the demand in the morning is

different than the vehicle distribution in the evening. In other approaches, relocations are performed several times per day to compensate the vehicle imbalances occurring during the day.

In 2017 car2go, a former free-floating carsharing operator in Europe, stated that they perform operator-based relocations. In 2019, car2go joined the previously mentioned Share Now company (Carsharing.at, 2019). To perform the relocations, different service teams moved the vehicles from oversupplied to undersupplied areas. The relocations were conducted several times a day and through them, additional customers made use of the carsharing service (Car2go, 2017).

2.2.2 User-based relocation strategies

If user-based relocations are pursued, the operator tries to influence the customers to start or to end their trips at other locations than initially planned. The user should access the vehicle in an oversupplied area and leave it at an undersupplied location. Weikl and Bogenberger (2013) suggest different user-based strategies. Lower rates or free trips could be offered to the user if he ends his trip in an undersupplied area. Furthermore, joint trips could be proposed to customers leaving an undersupplied area at the same time, resulting in lower costs for each joining person as the fees can be divided among the users. Weikl and Bogenberger (2013) state, that user-based strategies are cheaper and environmentally more sustainable, as there is no need for extra relocation rides without customers. Nonetheless, the customer reaction to these incentives is hardly predictable and a privacy loss for the customer occurs, as the destination needs to be indicated before departure. Moreover, the system operator still needs to maintain and clean its vehicles, as these tasks are difficult to combine with user-based relocations (Weikl and Bogenberger, 2013).

In 2018, car2go implemented a flexible rating system in Germany to compensate the imbalances in the vehicle distribution (Daimler, 2018). According to this system, a user has to pay less if he picks up a vehicle in an area, where the demand is low and the car remains unused for a long time. Similarly, the price rises, if a customer intends to pick up a vehicle in an area or at a time with high demand. Car2go justifies this rise in prices as they need to move additional vehicles to the undersupplied location, generating higher costs for the operator. The flexible rating system should help to move vehicles out of oversupplied areas with low requests and bring them to other locations with higher demand (Car2go, 2020). In 2019, car2go joined the Share Now company which took over the flexible rating system and even expanded it to other cities (Carsharing.at, 2019).

2.3 Relocation algorithms for free-floating carsharing systems

In free-floating carsharing systems, imbalances in the demand and supply of vehicles are likely to occur. To satisfy the existing demand and possibly maximising their profit, carsharing companies are willing to perform relocations. Several studies already focused on how to optimize relocation operations. Nevertheless, most of the discussed algorithms have not been applied yet in real-world by existing carsharing operators.

Weikl and Bogenberger (2013) provided a model, which allows operator-based as well as user-based relocations. The whole operating area of the free-floating carsharing service is divided into different segments. To plan the occurring relocations, a two-step model is designed. An offline demand module is used to predict future demand. Historical vehicle data of a running carsharing system, in this case from Munich (Germany), is used to identify some spatial-temporal demand patterns by combining different days with a similar demand. This demand pattern allows predicting the number of vehicle bookings during the next time period. In a second step, an online optimization module is developed. By measuring the actual demand and vehicle locations and combining these data with the results of the offline module, the optimal vehicle distribution for the next time slot can be determined. To decide whether and where relocations are necessary, a mesoscopic relocation algorithm is applied. Firstly, a macroscopic algorithm determines the number of vehicles to be relocated from and to which areas by comparing the actual vehicle locations with the optimal distribution. The following microscopic algorithm defines which car should be relocated to which exact location, including operator-based as well as user-based relocations. The whole two-step model has not yet been applied to real-life scenarios. However, the application of the mesoscopic relocation algorithm to some test scenarios produced promising results.

A free-floating carsharing system with traditional as well as electric vehicles is examined by Weikl and Bogenberger (2015). They focused on operator-based relocations which are conducted during the night. The study proposes to perform service trips during executed vehicle relocations. The service area of the free-floating carsharing is divided into macroscopic zones, and among them into microscopic zones. The model first focuses on the optimal number of vehicles in each zone before suggesting actual relocations on a microscopic level. The analysis of historical data allows to detect under- and oversupplied zones within the network. Furthermore, the optimal distribution of the available vehicles is proposed for specific periods. The macroscopic relocation step allows determining the zones, from or to which relocations are needed to maximise the profit for the system operator. The following microscopic relocation algorithm determines, which individual vehicles should be relocated, trying to combine as many service trips as possible with the relocations. Besides, the algorithm proposes intra zone

relocations, meaning that vehicles should be brought to a more attractive location within the zone. To test the proposed algorithm, some real-world field tests took place in Munich. The existing operating area of a free-floating carsharing service includes 79km^2 and the operating fleet consists of approximately 390 traditional vehicles and 20 electric vehicles. As previous studies detected most vehicle imbalances between the supply on Sunday evening and the demand on Monday morning, the relocation field test was conducted during the respective night. Six workers performed the proposed relocations, using public transport, service cars, folding bikes, bike-sharing or footpaths to reach the vehicles to relocate. In one night, 24 inter zone and 12 intra zone relocations were conducted, resulting in a total of 36 vehicle movements. The net profit increased at 5.8% compared to earnings on Mondays without previous relocations. As additional demand could be covered by the conducted relocations, the field tests had a positive outcome.

According to Herbawi, Knoll, Kaiser and Gruel (2016), a single shuttle might be used to perform operator-based relocations. Thus, all employees use one shuttle to approach the locations, where a vehicle needs to be relocated. Once such a location is reached, a worker gets out and performs the relocation, while the shuttle drives to the next oversupplied area. There, another worker starts conducting the next relocation trip. Once the employees reach the relocation destination, they are picked up by the shuttle again. The FIFO principle is applied, meaning that the first visited car is relocated to the first visited possible relocation destination. The algorithm proposed by Herbawi et al. (2016) maximises the number of conducted relocations within a given time period. To test the suggested algorithm, it is applied to four real-world cases, namely in the cities of Seattle, Twin Cities, Denver and Berlin. For each city, different travel time periods for the shuttle were tested. In most cases, the algorithm could perform a satisfying number of relocations. Furthermore, it is observed that the number of relocations per worker per hour decreases when the allowed operating duration for the shuttle is increased, leading to less efficient relocation processes. Therefore, a future investigation of a combination of operator-based and user-based relocation is suggested to maximise efficiency as well as the reliability of the system.

The strategy proposed by Herbawi et al. (2016) is further developed by Santos, Cândido, Balardino and Herbawi (2017). The use of multiple shuttles instead of one single shuttle is considered to reach more efficient relocation processes, resulting in the faster achievement of the optimal vehicle distribution among the area. In comparison to the algorithm developed by Herbawi et al. (2016), the new approach needs to decide which shuttle is used to visit which locations. In this first approach, the workers do not change the shuttle during a relocation period. The FIFO principle is applied again. Furthermore, some spots are prioritized over others. Therefore, each location is characterized by a profit which is received if a vehicle is allocated

to it. By maximising the total profit, a prioritization of locations is achievable. The proposed evolutionary algorithm maximises the profit-weighted sum of all locations assigned with a vehicle. As a secondary object, the total time needed to perform all proposed relocations is applied, if more than one possible solution reach the same weighted sum. These two parameters are used to form an objective function which needs to be maximised. To test the algorithm, different test scenarios are created. The locations and travel times used to create the test cases are the ones from the city Belo Horizonte in Brazil. By comparing the solutions generated by the evolutionary algorithms (EA) and the ones reached by an inter linear programming formation, the quality of the results of the EA can be determined. The test scenarios showed, that the EA can find accurate solutions even for bigger vehicle fleets.

Paschke et al. (2016) implemented relocation agents in the multi-agent transport simulation MATSim to simulate operator-based relocations which are carried out several times per day. In MATSim, agents can re-plan their activities. Therefore, one simulation consists of several iterations, each containing the execution of a modified plan, determining its utility and modifying the plan to maximise the utility (for more details, see chapter 3.1.2). In the implemented relocation strategy, the demand of previous iterations is used to predict the requested number of vehicles at specific locations. Furthermore, the service area of the free-floating carsharing system is divided into different relocation zones. The simulation day starts at 6.00 in the morning and is then divided into six time slots of three hours each. The number of vehicle deficit or surplus is determined for each time period and each zone. Therefore, the predicted demand is compared to the number of vehicles available, including the vehicles which are expected to be returned during the examined time slot. A list containing all relocation zones is made up by arranging the zones in a descending number of vehicle deficit, meaning the zone with the most vehicles required is at the top of the list. Relocations are then conducted from zones at the bottom of the list, which show a vehicle surplus, to the zones at the top of the list. Furthermore, relocations are only conducted if more than one vehicle is required in a specific zone. The system then assigns a relocation agent to conduct the determined relocation. The agent uses a bicycle to reach the vehicle to be relocated. The algorithm was applied to a simulation scenario in Zurich, consisting of a service area of approximately 150 km^2 and a vehicle fleet of 235 cars. During one day, 50 relocations are performed, leading to a gain in conducted carsharing trips of about 5%.

Many of the existing carsharing relocation algorithms focus on the aim to achieve a higher number of vehicle trips for one day. But even if a higher demand can be met through the performed relocation processes, it cannot be assumed that this is more profitable for the carsharing operator, as relocation itself cause additional costs. The mentioned study of Weikl and Bogenberger (2015) takes these costs into account and examines whether an additional

profit of the operator can be achieved through the relocations. Nevertheless, it can be said that the relocation costs in operator-based relocations mainly depend on the salary for the relocation agents. This value can vary quite strong between different countries. Thus, operator-based relocation processes might be more profitable in countries with lower salary level as the relocation costs can be kept in a lower frame. Moreover, further studies should be carried out to test whether relocations are also profitable for the operator in areas where the labour is quite expensive, as it is the case in Switzerland. Therefore, this thesis tries to estimate if the operator's benefit can be increased by the performance of relocations or if the relocation costs surpass the additionally gained revenue.

Furthermore, the analysed studies only focused on either relocation processes carried out at various times during the day or on relocations during the night. Further examinations should be made on the comparison of these two systems to investigate which kind of relocation process is more efficient and more profitable for the operator.

2.4 Initial placement of carsharing vehicles

Not only the choice of an appropriate relocation strategy influences the efficiency and performance of a carsharing system, but the initial placement of the vehicle at the start of the day might have an important effect on vehicle utilisation as well. The carsharing system provider needs to determine the optimal initial locations for the vehicles to maximise his profit, the users' satisfaction or the number of customers. An additional aim is to minimise the necessary relocations as much as possible. As free-floating carsharing is a rather new service type and no study analysing the optimal vehicle locations in the morning for this service type is found, the presented existing studies analyse the optimal station locations for one-way station-based systems rather than free-floating systems.

Awatshi, Breuil, Chauhan, Parent and Reveillere (2007) suggested an approach to select the optimal vehicle stations using multiple criteria. Apart from the population density and the occurring parking difficulties and costs, the mix of land use, including living space, employment as well as commercial and local facilities, form a decision criterion for the carsharing station locations. Furthermore, the presence of specific target groups, vehicle ownership and access to other transportation means are taken into consideration. A pair-wise comparison of the criteria and all possible stations is conducted to determine the weights of each factor. The overall weight for the stations is computed by taking all weights of the criteria into account. In a final step, all stations generating a weight value over a given threshold are possible new locations for the stations of a carsharing system. The presented approach is applied

in Angoulins-sur-mer (France) and its results are promising, as the applied process chose the same locations as stations than customers selected in a conducted survey.

In the research conducted by Efthymiou, Antoniou, Tyrinopoylos and Mitsakis (2011) another multi-criteria analysis technique is developed to determine the optimal locations for electric vehicle charging stations. The total population, the total number of points of interest, the average income as well as the distance from parking to attractions are used as decision variables. A specific weight is assigned to each variable and a map representing the weighted value for each area can be generated to support the selection of the optimal station locations. An important insight of this research is, that the population and the income have a large influence on the optimal locations of charging stations. However, the optimal locations are only slightly affected by the number of points of interest and the distance from parking is even less influencing.

Correia and Antunes (2012) applied a mixed-integer programming (MIP) model to find optimal station locations. This model aims to maximise the profit for the organization of a one-way carsharing service. The price rates paid by the users lead to revenues, while the expenses consist of maintenance costs for vehicles and the stations, depreciation costs of the vehicles and costs for vehicle relocations conducted over-night. Three different schemes are examined, in which the carsharing company partly has the possibility to control the service, meaning that requested trips can be accepted or refused. A case study of the model is carried out in Lisbon (Portugal). To apply the MIP model, the potential demand, possible station locations, driving and walking times among the network and the company's expenses need to be determined. Different simulations are carried out, varying in the price rate, the maximum number of stations and the minimum demand needed to be satisfied. It resulted in the fact, that the profit is higher if there is no constraint concerning the maximum number of stations as this leads to a wider distribution of the vehicles. Furthermore, it is not profitable to attend the total demand as a large number of vehicles is required to do so. The vehicles then remain unused for a long time, leading to a loss for the provider, as no new revenues can be generated but the costs still arise. Besides, the number and size of the stations have an evident impact on the trip selection of the users. Another insight is, that the choice of the optimal number, location and size of the stations can lead to reduced financial losses of the operators. Nonetheless, profit can only be generated by including a reservation system or by trip refusal in case of no available vehicle at the station, leading to an optimal selection of the performed trips.

An approach to determine the optimal location of carsharing stations based on customers' demand is proposed by Yu, Zhang and Li (2017). To predict the demand, GPS trajectories of occupied taxis are used to determine the accessing and descending points, leading to the

possible request of a one-way carsharing trip. To reach a well-arranged overview of the actual demand, the whole network is divided into regular grids and the taxi pick up and drop off points are cumulated within a grid. Optimal vehicle locations are then determined by clustering the travel demand through the application of a clustering algorithm. To test the proposed algorithm, some experiments with the GPS trajectories of taxis in Beijing are conducted. It results that more customers are served if the proposed proceeding is applied to select the vehicle stations. Furthermore, the distances covered by the customers to reach a vehicle is smaller than in other models.

A similar approach is developed by Li, Li, Fan and Deng (2017). They examined how different criteria influence the optimal carsharing station locations. The whole model is proposed for the city of Shanghai (China). As a first criterion, the number of potential users should be as high as possible, resulting to place a station in an area with high population density. In addition, the system should be able to cover a main part of the potential travel demand. The demand itself is again determined by analysing conducted taxi trips. Furthermore, the stations should be located in areas, where different activities can be carried out so that a lot of travel purposes like shopping, work or recreation can be covered. Moreover, the distance between two stations should at least be 1 km to receive an efficient system. An analytic hierarchy process is used to evaluate which indicator is the most influencing one. It turned out that the density of members is the most important criteria. It is further observed that carsharing is more often used to reach a social recreation area than for other purposes. It resulted that the most efficient vehicle locations are in central areas of the city, as not only the number of potential users but the potential travel demand are high in this area.

New research from Sai, Bi and Chai (2020) proposed a model to optimize the carsharing station locations for an electric carsharing network by maximising the number of users supplied with a vehicle. The chosen service type combines fixed stations, which generate construction costs, and free stations for which a parking fee needs to be paid. The research area consists of small grids, each representing the existing demand and a possible carsharing station. The user demand of each small grid is estimated, considering the population density, land use, leisure entertainment venues, tourist attractions, transportation hubs, ordinary interchange points and other factors. The objective function of the algorithm is to maximise the number of users who can be supplied with a vehicle. Additionally, a cost limit for the company can be defined. In this constraint, the car purchase costs, the costs to construct chargers, the land rent and the parking fee costs, are taken into account. A genetic algorithm is applied to find the optimal solution for the objective function under the cost constraint. The proposed model is tested in a case study in Lanzhou (China), were urban transportation problems are present due to the large number of cars used by the population. An area of 30 km x 12 km is chosen and the demand is

estimated by surveys conducted by a carsharing company. The genetic algorithm can provide a station distribution among the network which is able to cover most user demands. Therefore, the proposed model can be helpful to choose the optimal station location for a carsharing service.

In summary, most of the existing studies focused on the optimal station location for one-way station-based carsharing services. On the contrary, to the author's knowledge, no research is conducted on how the initial vehicle placement influences the demand for a free-floating carsharing service. Furthermore, many studies tried to determine the optimal station locations by estimating the existing demand or by analysing the demand of already operating transport modes. Nevertheless, a further way of proceeding would be to choose the initial vehicle placement according to socio-demographic variables.

2.5 Agent-based simulation models for carsharing systems

Different studies focus on the creation of agent-based simulation models which allow simulating the demand and supply of carsharing systems over time. In most studies, a discrete mode-choice model (see chapter 3.1.3) is used to determine the probability of choosing a specific transport mode. In the following subchapters, the three most known simulation models are described in more detail.

2.5.1 mobiTopp

In the travel demand model mobiTopp, each person is described by different attributes, like its age, sex, employment and car ownership. In mobiTopp, all persons have an activity schedule for each day and it is possible to perform a multi-day simulation. To determine the mode of transport for a trip between two activities, MobiTopp uses a discrete mode-choice model. This model is extended by Heilig, Mallig, Schröder, Kagerbauer and Vortisch (2017) by integrating station-based as well as free-floating carsharing into it. Through the analysis of real customer data of Karlsruhe, a customer model for carsharing is created which helps to determine which people might be possible members of a carsharing service. Furthermore, the trip lengths distribution of existing carsharing companies is applied to calibrate the mode-choice model for the two different carsharing modes. An advantage of this simulation model is, that the simulation period is one week. Therefore, demand and usage differences between weekdays and weekends can easily be determined. There again, the spatial resolution is not as high as in other simulation models, as only zones and not any specific coordinates are used as locations.

2.5.2 An agent-based model of one-way carsharing systems in Lisbon

Martinez, Correia, Moura and Lopes (2017) propose a model which simulates the daily activity of a station-based one-way carsharing service in Lisbon (Portugal). In their simulation model, a discrete mode-choice model is introduced to determine the probability of each transport mode chosen by the travellers. A Monte Carlo simulation then assigns a specific mode to each trip of a person. If in the following somebody wants to perform a carsharing trip, he will check if a vehicle station is available within a reasonable walking distance. If such a location is available, the user will walk there and pick up the shared vehicle. Otherwise, he will choose another mode of transport. Furthermore, the proposed simulation model includes vehicle maintenance and relocation by staff members. As the presented model allows to integrate operational strategies such as vehicle relocations during the day, the model provides an insight on what kind of effort by the operator is necessary to receive a well-balanced and efficient carsharing system. Nevertheless, at the moment, this model only offers simulations for one-way carsharing systems and not for free-floating carsharing services.

2.5.3 MATSim

The multi-agent transport simulation framework MATSim offers simulations of car traffic and public transport in consideration of the existing congestion. MATSim is further described in the following chapter (see chapter 3.1) and only a short insight is given here. In the proposed framework, people within the study area perform a daily activity schedule while interacting with other persons. A multinomial logit model is used to determine the transport mode of the conducted trips (see chapter 3.1.3). Balac, Becker, Ciari and Axhausen (2019) introduced a free-floating carsharing mode to the mode-choice model and enabled the competition of different carsharing operations. In this simulation framework, an operating area can be set for the carsharing service and additional operational strategies, like different relocation algorithms, can be implemented and analysed. MATSim allows to perform large-scale simulations and its spatial resolution is high, as the input and output data of vehicle locations, activity facilities, home buildings and further locations are available as geographic coordinates. MATSim is chosen as a simulation framework for this work as free-floating carsharing systems are integrated and it generates a high spatial resolution which is important in order to determine the influence of different initial vehicle placements.

3 Methodology

In this thesis, a closer look is taken at how the initial placement of vehicles in a free-floating carsharing system affects the user demand. Furthermore, it is investigated if night-time vehicle relocations are profitable for the provider and whether they should be performed or not. To do so, simulations are performed using the multi-agent transport simulation software MATSim. In the following sections, the fundamental concepts of MATSim, as well as the simulation processes, are described in more detail.

3.1 MATSim

3.1.1 The MATSim algorithm

MATSim is a multi-agent simulation framework coded in Java and designed for large-scale scenarios. The traffic occurring during one day is modelled by a population performing their daily activities. The existing road network, activity opportunities, land use and possible transportation services are represented in MATSim and available for the population's use. In the framework, people are able to choose between different transport modes to conduct their daily trips. The following paragraphs explain the most important components of the framework, namely the agents and the network. Furthermore, a closer look is taken at the queue-based approach which defines how the vehicles can use the provided network (Horni et al., 2016).

Agents

Agents represent the population and are described by different attributes, among them their age, sex, home location, occupation, car availability and a daily plan. The plan of an agent defines the activities to be performed during the simulation time as well as when and with what kind of transport mean the person plans to travel between two successive activity locations. Through the simultaneous performance of each agent's plan, the occurring traffic can be simulated by MATSim.

Network

In MATSim, the network represents the road and railway infrastructure that can be used by the agents. It can be described by nodes and links. Each node is characterized by its geodesic coordinates. A connecting segment between two nodes is called a link. Each link is described by its length, flow capacity, maximum allowed speed, number of lanes as well as the allowed vehicles on it.

Queue-based approach

To model large-scale scenarios, MATSim uses an efficient queue-based method. Each car, which wants to enter a road segment, is held back at the end of the existing waiting queue. The first vehicle of the waiting queue can enter the current road segment if there is enough capacity available. If the capacity limit of a segment is reached, the vehicles need to wait until other vehicles leave the current road segment and the necessary capacity is regained. The explained method is efficient, but of course, some simplifications are introduced (see Horni et al. (2016) for more details). Therefore, the traffic flow in MATSim depends mainly on the storage capacity and the flow capacity of a road segment. While the storage capacity determines how many vehicles can be stored in a network segment, the flow capacity defines the number of vehicles that are able to leave a specific segment in a given time step (Horni et al., 2016).

3.1.2 Iterations

The framework offers a simulation of one day, which is executed as an iterative process. One iteration consists of the simulation of one chosen plan per agent, scoring of each agent's plan and replanning. In the replanning part, some agents are allowed to adjust their daily plan to generate a higher score than in the previous iteration. Generally, the departure time, the route, as well as the transport mean, can be varied throughout an iteration. The score measures the utility of the daily plan for each person and MATSim aims to maximise the overall score generated by the whole population. Further iterations are carried out as long as the overall score increases. As soon as the score remains at a stable value, the user equilibrium is reached and the iterative process ends. Reaching the user equilibrium means, that the trip time on all routes used by the agents is the same and it is lower than on all unused routes. As the number of iterations needed to reach a reasonable output mainly depends on the scoring system, the scoring method influences the whole simulation process. To determine the score of an iteration, the Charypar-Nagel utility function is applied for basic MATSim simulations. A detailed discussion of this utility function can be found in Horni et al. (2016). Typically, the utility of an agent's plan can be increased if the travel cost and travel time are reduced.

3.1.3 Discrete mode-choice model

In discrete choice models, each possible alternative of a decision is assigned with its probability to be chosen among all the choices. In the case of MATSim, a discrete mode-choice model is applied in the replanning part of an iteration. To do so, the agents are only allowed to change their mode of transport within their daily plan while the order and time of the activities stay constant. Thus, the alternatives in the discrete mode-choice model are the different modes of

transport. For each alternative, some attributes need to be determined, for example, the travel time, the travel costs and the number of transfers needed. A utility function is then used to determine the benefit of each alternative. The following application of a Multinomial Logit Model allows determining the probability of choosing a specific mode of transport. A detailed explanation of the applied discrete mode-choice model can be found in Hörl, Balac and Axhausen (2018) and Hörl, Balac and Axhausen (2019). The introduction of a discrete mode-choice model allows faster termination of the iteration process, as no random mode choice decisions are taken as it can be the case if the scoring system described above is applied.

3.1.4 Carsharing in MATSim

In MATSim three different carsharing systems are implemented, namely round-trip carsharing, one-way station-based carsharing and free-floating carsharing. As the focus of this thesis lies in free-floating carsharing, only this service type is explained in detail.

If an agent uses a vehicle of the free-floating carsharing during his daily activities, MATSim simulates the agent's journey according to the following steps (Balac, Ciari and Axhausen, 2017):

1. Reserve the closest vehicle to the current location
2. Walk from the current location to the booked vehicle
3. Drive to the starting point of the next activity, while interacting with other traffic
4. Park the rented vehicle next to the starting point of the following activity
5. Terminate the car rental so that the vehicle is now available for other agents

During the simulation, not only the distance and time travelled with the shared vehicle is determined, but the access walk time as well. At the moment, no car parking restrictions are implemented in the used simulation framework. Therefore, the agent can park his car at the location of his next activity whereby no egress walk and time arise.

For the conducted simulations, the following parameters are applied to the discrete mode-choice model for the free-floating carsharing service:

- $\alpha = 0$
- $\beta_{\text{access time}} = -0.08$ [1/min]
- $\beta_{\text{travel time}} = -0.067$ [1/min]
- travel time cost = 0.40 CHF / min

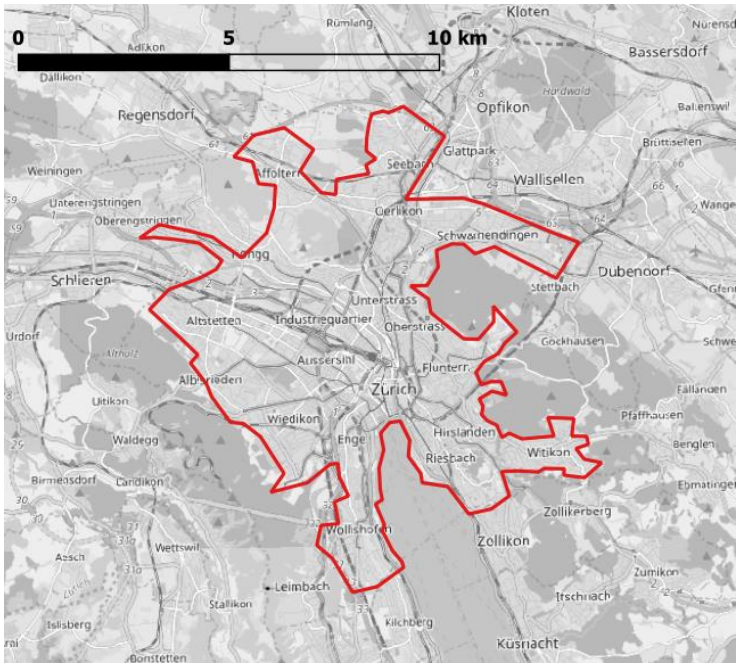
3.2 Simulation scenarios

3.2.1 General information

The simulations are conducted in the area of Zurich. For this thesis, the population and the simulation scenario developed by Hörl, Becker, Dubernet and Axhausen (2019) are used. The simulation area is defined as a circle with a radius of 30 km around Zurich Bürkliplatz. Furthermore, 10% of the entire population in this area are implemented and about 158’000 persons have a daily plan which needs to be conducted throughout the day. The agents are able to decide among driving their own car, cycling, public transport, walking and free-floating carsharing as a transport mode to reach their activity locations. A simulation day starts at midnight and lasts for 30 hours, leading to an end of the simulation at 6 am of the following day. Furthermore, 40 iterations are carried out during one simulation.

In all the proposed scenarios, only one carsharing operator is acting. Only free-floating carsharing service is provided and there is no operator of station-based carsharing services. The operating area of the free-floating carsharing provider is set to about 53km^2 and includes the main parts of the inhabited area of the city of Zurich. The boundaries of the operating area can be seen in Figure 1. The free-floating carsharing company offers 50 vehicles which the agents can access during the whole day. All agents holding a driving licence are able to use carsharing as transport mode, meaning that no membership is required. Riding a carsharing vehicle, the users are charged per minute with a fee of 0.40CHF/min.

Figure 1: Operating area of the free-floating carsharing service



Source: Background map: OpenStreetMap (2020)
Data: Hörl et al. (2019)

3.2.2 Initial vehicle placement

The initial placement of carsharing vehicles is an important factor which can influence the efficiency of the carsharing systems as well as the profit of the operating company. As mentioned in chapter 2.4, different strategies have been developed to determine the optimal locations. In this thesis, different vehicle locations at the start of a simulation day are tested in order to investigate how they influence the demand and how the use of carsharing vehicles can be maximised. The following six different criteria were used to assign a location to the vehicles:

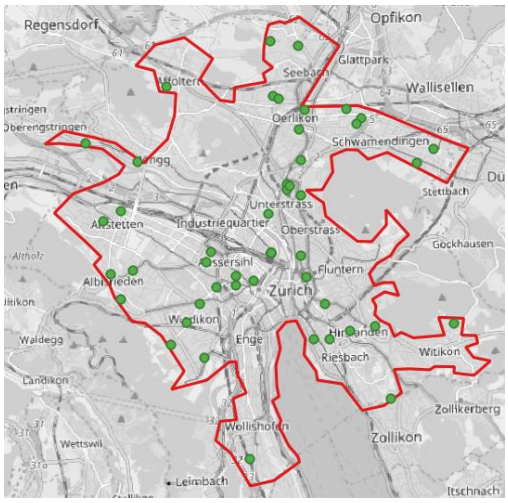
- Population density
- Income
- Population density of persons younger than 36 years
- All vehicles at Zurich main station
- Vehicles at the most used railway stations in Zurich
- Equal distribution among the area (regular grid)

Initially, the simulation is carried out according to a defined reference scenario, to which the subsequent scenarios can then be compared to. In the following sections, each scenario is briefly described.

Reference scenario

In the reference scenario, the vehicles are distributed according to the population density, but some parking restrictions are applied. For example, no vehicle is situated in the Kreis 1 of Zurich city (Figure 2), because there are no blue parking zones available in this area. As it is assumed that free-floating carsharing vehicles are parked at these public parking lots, the initial distribution excludes areas without such parking possibilities. Nevertheless, carsharing users can end their trips wherever they want, including zones without a public parking area, as no restriction is applied for trip's end locations. In the following scenarios, the vehicles can be initially placed everywhere and the above-mentioned restriction is neglected.

Figure 2: Initial vehicle distribution in the reference scenario



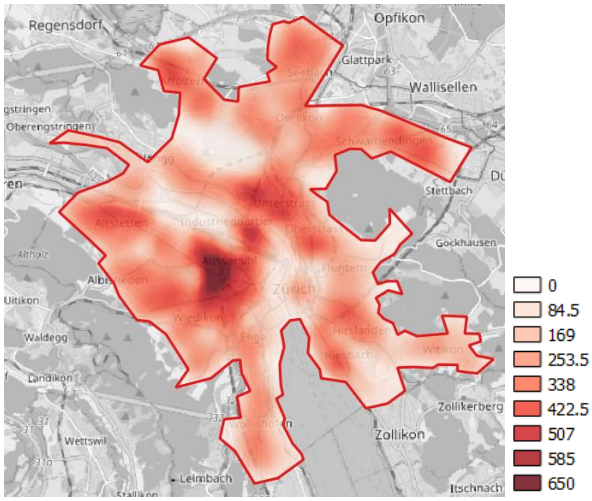
Source: Background map: OpenStreetMap (2020)
Data: Hörl et al. (2019)

Population density

In this scenario, the initial distribution of the carsharing vehicles is set according to the population density. This criterion is chosen, because the chance, that carsharing is used as transport mode increases with an increasing number of persons travelling in a given area. The distribution of the population density is illustrated in Figure 3, where a darker colour corresponds to a higher population density. The application of this criterion leads to more

vehicles in the centre of the operating area and fewer vehicles in other areas as the vehicles are initially parked at locations with high population density.

Figure 3: Population density in the operating area: number of people within a radius of 500m

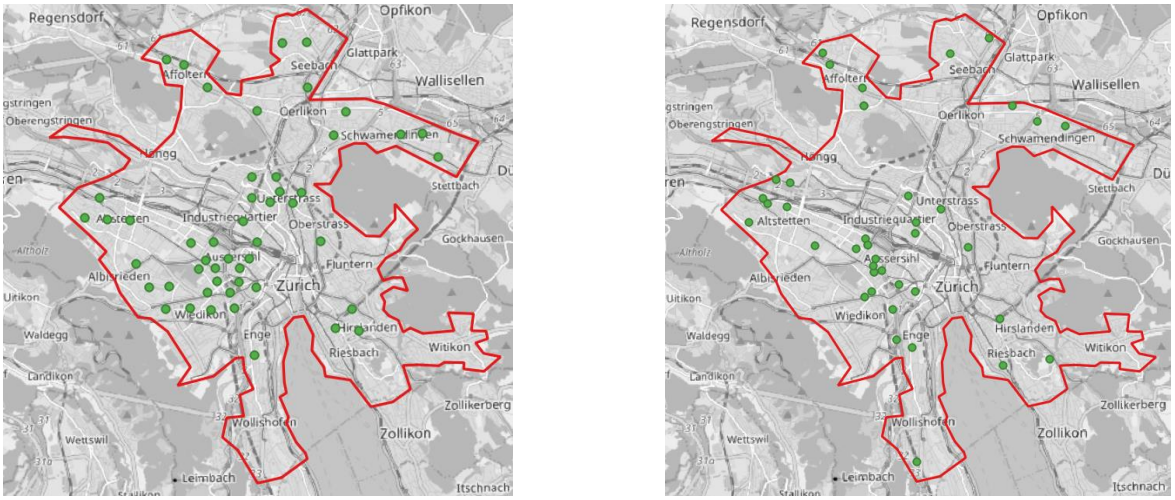


Source: Background map: OpenStreetMap (2020)
Data: Hörl et al. (2019)

Furthermore, two different approaches can be used to distribute the cars according to the population density. In the first approach, the operating area is divided into small rectangular zones while each zone covers the same area. The vehicles are then distributed among the zones with the highest numbers of persons living in it. The resulting initial vehicle locations are marked as green dots in Figure 4 (a). The zone size is set to 0.28 km^2. This size of the zones is chosen because if a vehicle is located in the middle of the zone, the access distance is less than 450m for each person living within a zone. Even if this approach reflects the population density of the area, the created zones do not consider any geographical borders and the actual distribution of the zones has an influence on the resulting vehicle distribution. To minimize this effect, the second approach tries to determine the points within the area which are accessible within 100m for the highest number of persons. If this approach is applied, the initial vehicle placement according to Figure 4 (b) results.

Figure 4: Initial vehicle placement based on the population density: (a) approach with zones and (b) approach with accessibility

(a) (b)

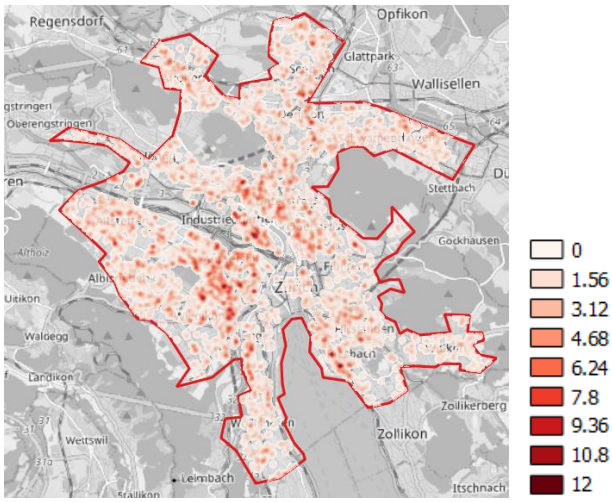


Source: Background map: OpenStreetMap (2020)

Income

The research of Efthymiou et al. (2011) states that the potential user's income highly influences the optimal location of charging stations for shared electric vehicles. Therefore, a scenario is created where the vehicles are initially placed at living locations of people with a high income. To do so, only the persons are considered who are in the top 10% of the income distribution of all people living in the investigated area. The resulting distribution is discernible in Figure 5, where a darker colour corresponds to a higher density of people with high income in the depicted location. Out of this data, the vehicle locations are chosen according to the spatial distribution of the living place of the individuals with high income. For completeness of the thesis, the two different approaches to determine the initial vehicle location are applied as in the previous scenario. The resulted placement for both approaches is illustrated as green dots in Figure 6.

Figure 5: Population density of people with the highest income: number of people living within a radius of 100m

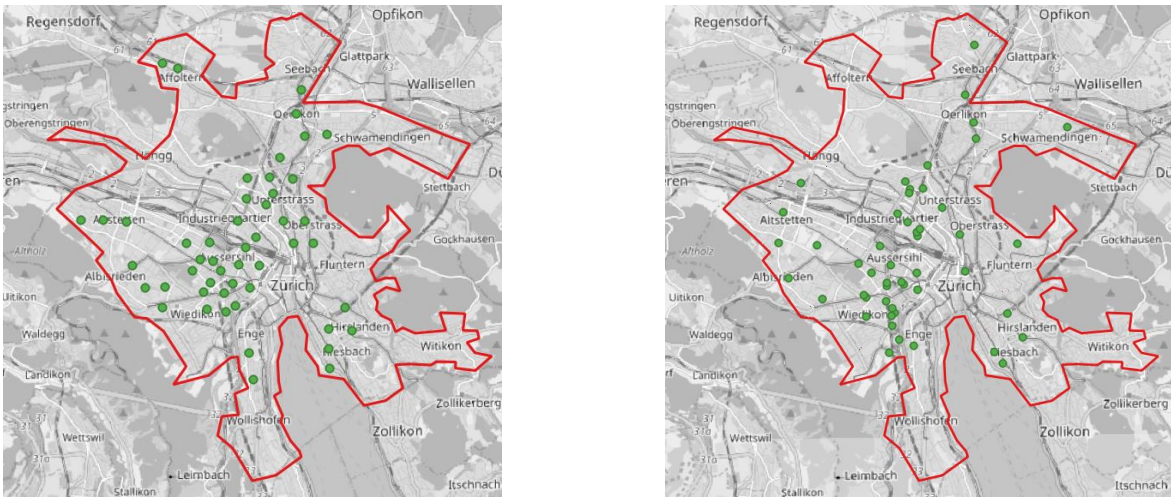


Source: Background map: OpenStreetMap (2020)

Data: Hörl et al. (2019)

Figure 6: Initial vehicle placement based on people's income: (a) according to zones and (b) according to accessibility

(a) (b)

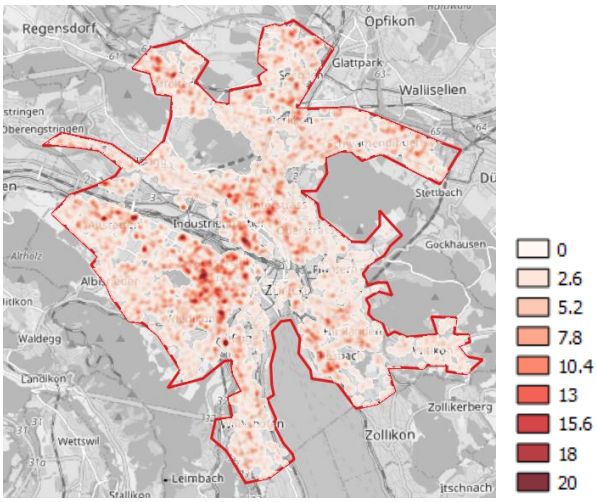


Source: Background map: OpenStreetMap (2020)

Population density of persons younger than 36 years

A previous study, which examined the user groups of different carsharing schemes in Switzerland, states that half of the users of the free-floating carsharing service in Basel are younger than 36 years (Becker, Ciari and Axhausen, 2017). Therefore, this scenario only considers persons younger than 36 years to investigate if the age influences the existing demand for carsharing vehicles. To exclude children, which obviously cannot use carsharing vehicles as a transportation mode, the possession of a driving license is set as a further criterion. By applying these restrictions, the places with the highest population density of these young people are detected (Figure 7) and the vehicles are placed at locations, where a high density is present. To do so and to stay consistent between the different scenarios, again the approaches with the zones and the one with the accessibility are applied (Figure 8).

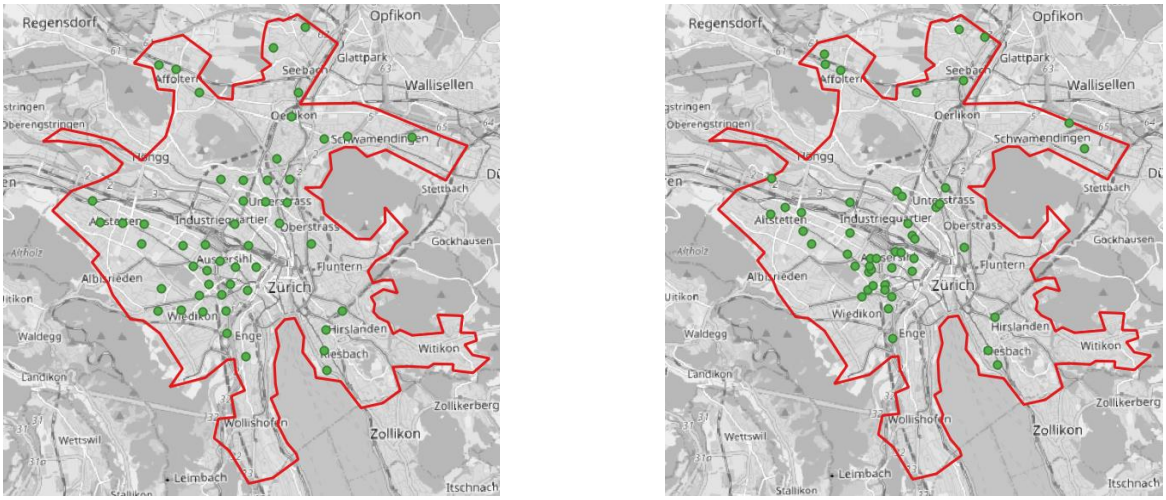
Figure 7: Population density of people under 36 years: number of people living within a radius of 100m



Source: Background map: OpenStreetMap (2020)
Data: Hörl et al. (2019)

Figure 8: Initial vehicle placement based on the population density of people under 36 years: (a) according to zones and (b) according to accessibility

(a) (b)

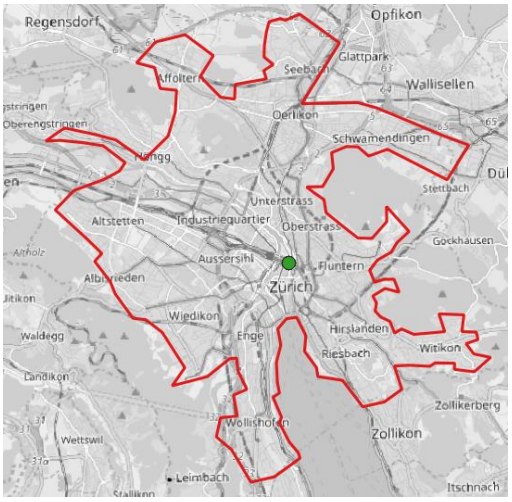


Source: Background map: OpenStreetMap (2020)

All vehicles at Zurich main station

In this scenario, all 50 vehicles of the carsharing company are initially located in front of the central station of Zurich (Figure 9). This scenario follows the recommendations of Li et al. (2017) and tries to initially place the vehicles in the central area of the city and at locations, where the travel demand is high. Both of these criteria are fulfilled at Zurich main station, therefore this location is chosen for the proposed scenario.

Figure 9: Initial vehicle location of all vehicles at Zurich main station

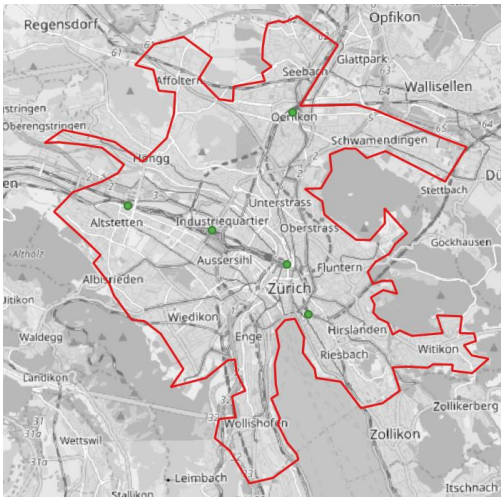


Source: Background map: OpenStreetMap (2020)

Vehicles at the most frequented railway stations in Zurich

This scenario focuses on the same criterion as the previous one and tries to place the vehicles initially at places, where the travel demand is high. Nevertheless, now the vehicles are located at five different places within the operating area and not all at the same place as in the previous scenario. Ten vehicles each are placed next to the most frequented railway stations in Zurich, namely Zurich main station, Altstetten, Hardbrücke, Oerlikon and Stadelhofen (Figure 10).

Figure 10: Initial vehicle placement at the most frequented railway stations in Zurich

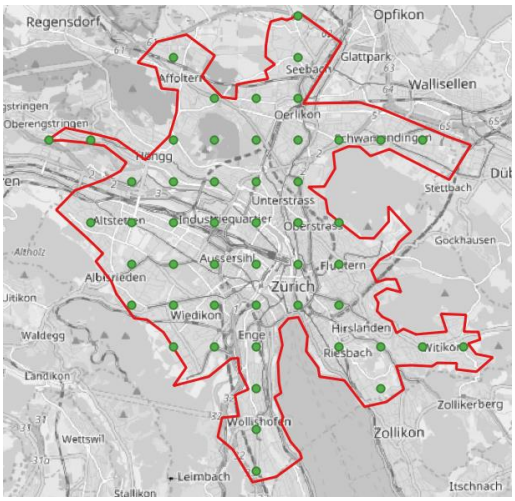


Source: Background map: OpenStreetMap (2020)

Regular grid

To test, if the initial vehicle distribution has any influence on the existing demand, the vehicles of the carsharing company are located according to a regular grid among the operating area. To receive a regular grid with 50 location inside the operating area, the distance between two locations is set 1020 m both in north-south and east-west direction. The resulting initial vehicle locations can be seen in Figure 11.

Figure 11: Initial vehicle placement according to a regular grid



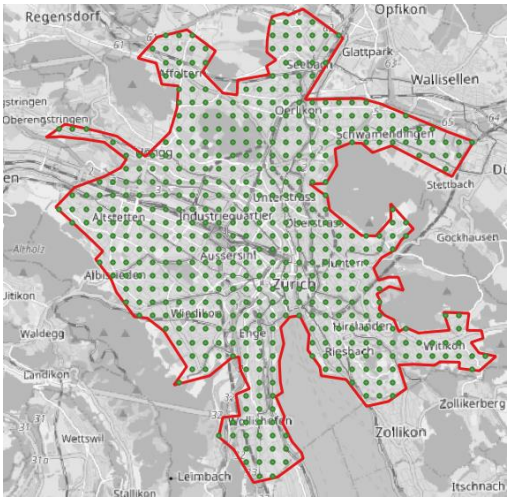
Source: Background map: OpenStreetMap (2020)

3.3 Initial vehicle placement with 500 vehicles

As in the simulation framework, all persons with a driving license have access to the free-floating carsharing service, the potential number of users is quite high and the 50 vehicles of the previous simulations may not be able to cover the demand. To test how the influence of the initial vehicle placement on the demand and the revenue changes with the carsharing fleet size, simulations are conducted for two scenarios with 500 free-floating carsharing vehicles. The aim of these simulations is to check whether the effect of the initial vehicle placement becomes larger with an enlarged fleet.

In the first scenario, the vehicles are initially ordered in a regular grid among the area. The distance between two vehicles is set to 325m in north-south and east-west direction. The resulting initial vehicle locations are depicted as green dots in Figure 12.

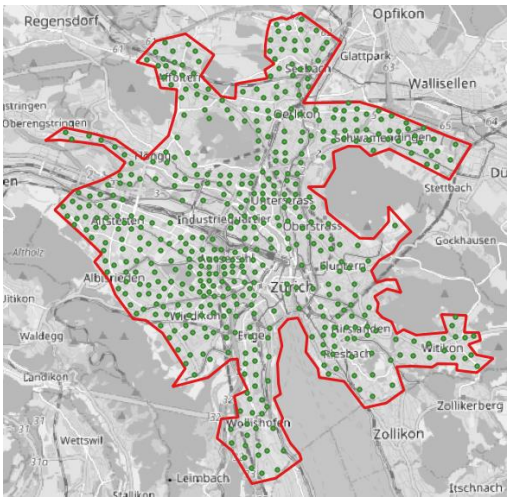
Figure 12: Initial vehicle placement according to a regular grid for 500 vehicles



Source: Background map: OpenStreetMap (2020)

In the second scenario with 500 shared vehicles, the initial locations are determined according to the population density. To do so, the operating area of the free-floating carsharing service is again divided into small zones. The vehicles are then placed according to the number of people living within each zone. The resulting initial vehicle distribution can be seen in Figure 13.

Figure 13: Initial vehicle placement based on the population density for 500 vehicles



Source: Background map: OpenStreetMap (2020)

3.4 Initial vehicle placement for less attractive free-floating carsharing service

For the previously described simulations, the free-floating carsharing service is rather attractive in comparison to other transport modes. This attractiveness is reflected by the parameters used for the discrete mode-choice model. In this model, a constant, which reflects all properties of a transport mode which are not covered through the travel time or the travel costs, influences the attractiveness of a specific transport mode. For example, this constant includes the comfort of a specific transport mode. For the previous simulations, this constant is set to zero for the carsharing service, meaning that the choice for or against the free-floating carsharing as a transport mode is only influenced by the travel costs and time. This may not reflect reality as some people might neglect to use a shared car because it is less comfortable than another transport mode. To examine how the influence of different initial vehicle placements behaves for a less attractive carsharing service, the value of the constant is set to -3.0. Furthermore, the fees of the free-floating carsharing service are slightly adjusted as the price of 0.40CHF/min is relatively low. Research shows that the price which Mobility applies for the free-floating carsharing users in Basel and Geneva is set to 0.45 CHF/min. Besides, the operator's costs in Zurich are higher than in the rest of Switzerland as, for example, the parking fees are more expensive. Therefore, a price of 0.60 CHF/min is applied in the following simulations, which seems more appropriate for the area of Zurich than the previously used fees.

The simulations with these adjusted parameters are conducted for the initial vehicle placement according to a regular grid, the population density and the population density of people younger than 36 years. These three initial vehicle placements are chosen because the results of the previous simulations of these scenarios only slightly deviated from each other even if the initial vehicle placement between the two population density scenarios and the regular grid are completely different. The simulations are carried out with a fleet size of 50 vehicles and the resulting initial vehicle placement corresponds to the one of Figure 11 for the regular grid, Figure 4 (a) for the population density scenario and Figure 8 (a) respectively for the population density of people under 36 years.

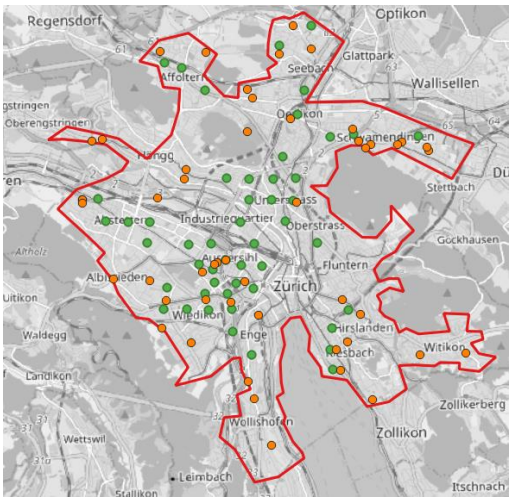
3.5 Simulations over one week

In the free-floating carsharing system the customers can park the used vehicle at any public parking space in the operating area. Therefore, at the end of the day, the vehicle locations do not correspond to the initial positions of the cars in the morning. As discussed in previous chapters, this can lead to an unbalanced system as the vehicles might be placed at locations where the demand for free-floating carsharing is low. This can then lead to a less profitable

carsharing service and relocations might be required to regain the balance between the supply and demand. To test, how the demand and the profitability of the carsharing service differ throughout a week if no relocation operations are carried out, simulations are conducted over five simulation days. The initial vehicle locations of the next day correspond to the vehicles' end positions of the previous day. The simulations are conducted with five different random seeds and for each random seed, a series over five simulation days is performed.

The simulations are conducted for the boundary conditions described in chapter 3.4, a fleet size of 50 vehicles and the regular grid as well as the placement according to the population density of people under 36 years are used as initial vehicle locations for the first day. In Figure 14, the initial vehicle locations for the population density scenario are marked as green dots while the locations of the vehicles at the end of a simulation day are depicted as orange dots. It can be seen that more vehicles are located in the outer regions of the operating area and that fewer vehicles are present in the centre of Zurich where the population density is high. Besides, it is visible that some vehicles are located very close to each other.

Figure 14: Vehicle locations at the start (green dots) and the end (orange dots) of a simulation day



Source: Background map: OpenStreetMap (2020)

Furthermore, an algorithm is developed to roughly estimate whether the performance of relocation is profitable for the operator or if the relocation costs would exceed the additionally gained revenue. In the algorithm, a vehicle is not relocated if it lays within a radius of 500 m to a vehicle location for the next morning and no other vehicle is located closer to the specific vehicle location. After the vehicles which need to be relocated are determined and the algorithm tries to minimise the total distance travelled to perform all relocations. Therefore, the distances

of all vehicles to all possible relocation destinations are calculated and the shortest distance available within any vehicle-location-pair is determined. In the following, the corresponding vehicle and relocation destination are matched and marked as used so that the vehicle is not relocated anymore and no other vehicle gets relocated to this specific location. Once all relocation start and end positions are determined, it is tried to minimise the distance travelled between a relocation destination and the next relocation start point. To do so, the distance from the current relocation destination to all possible next relocation start locations is calculated and the next relocation vehicle is determined by the minimal distance within the previous destination and its start location.

Thus, the total time needed to perform the relocations is calculated with the assumption, that the average speed during a vehicle relocation equals 40 km/h. This speed is chosen, as it is assumed that the main part of the relocations is carried out on links with a speed limit of 50 km/h and that the traffic volume is relatively low during the night. As the relocations are carried out during the night, where public transport is not available, it is suggested that the relocation agents would use a bicycle to travel from the previous relocation destination to the next relocation start point. It is assumed that they perform the distances with an average speed of 15 km/h. To determine whether relocations are profitable or not, the costs are determined by calculating the arising expenses. Therefore, it is assumed that the relocation agents earn 20 CHF/h and they get paid for the relocation movement duration as well as for the access time to the next vehicle. Furthermore, the fuel costs are taken into account with a price of 0.16 CHF/km (1.60 CHF/l petrol and 10 l/100 km).

4 Results

4.1 Initial vehicle placement

For each scenario, five simulations are conducted with varying random seed in order to minimize the coincidence within the simulation results. The outcomes of the single simulations are combined to calculate the mean and the standard deviation of each attribute. In the following paragraphs, the results of each scenario are briefly described and at the end, a summary of the main results is added.

4.1.1 Reference scenario

In the reference scenario, a mean of 1402.6 carsharing trips are conducted and an average total distance of 3967 km is covered by shared vehicle trips. On average, the distance travelled during one carsharing trip is approximately 2.8 km and the average trip time amounts to 8.7 min. In this scenario, it lasts about 7h 45min until each vehicle is picked up at least once and further, each vehicle is used for more than one vehicle trip during the simulation day. Table 1 provides an overview of these and further main results of the reference scenario.

Table 1: Main results for the reference scenario

Attribute	mean	standard deviation
Number of rentals	1402.60	30.92
Total distance travelled [km]	3967.06	208.06
Mean distance travelled [m]	2827.15	100.20
Total trip duration [s]	732927.80	32872.32
Mean trip duration [s]	522.55	20.49
Mean access time [s]	216.77	3.94
Mean time until each vehicle is at least used once [h]	7.73	1.24

The temporal distribution of the rental start times of the reference scenario is depicted in the histogram in Figure 15. More than 80% of the rentals start between 6.30 am and 8.30 pm. Besides that, 50% of the rentals are conducted before 1.30 pm. After 24 hours, the next day starts and the hours 25 to 30 correspond to the time between midnight and 6 am of the following day. It is visible, that during this time only few rentals are conducted.

Figure 15: Histogram of rental start times for the reference scenario

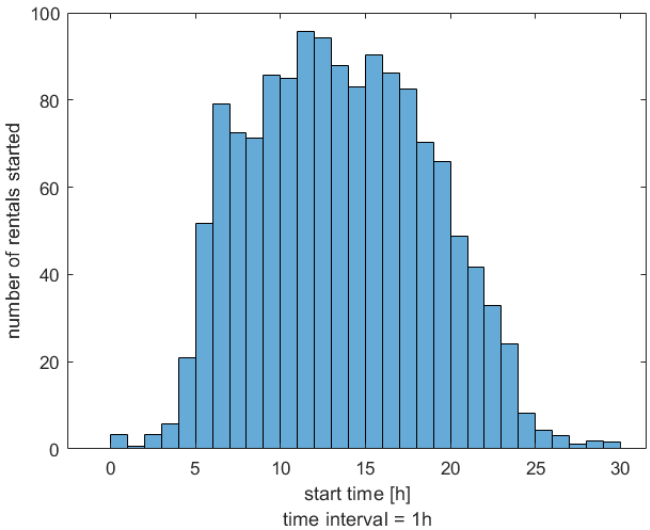
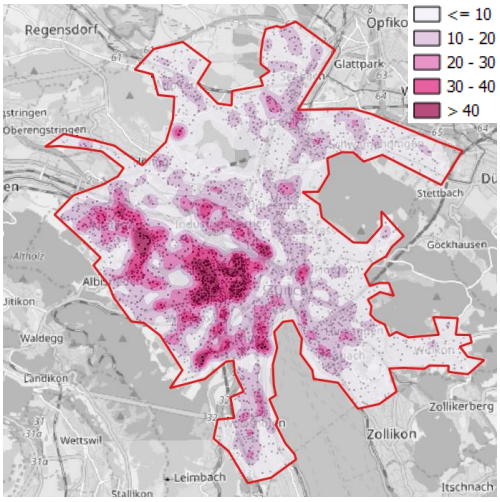


Figure 16 shows the spatial distribution of the pick-up locations of the conducted simulations for the reference scenario. Therefore, a radius of 300m is set and it is analysed how many vehicles are picked up in this area during all simulations for the corresponding scenario. The area with most rental starts is located in the quarter of Aussersihl, south-west of Zurich main station and extends to Zurich Hardbrücke. Another hot spot can be found next to Zurich Altstetten. Generally, the number of pick-ups is highest in the western part of the operating area whereas it is fairly low in the other parts.

Figure 16: Spatial distribution of pick-up locations in the reference scenario



Source: Background map: OpenStreetMap (2020)

4.1.2 Population density

The main results of the second scenario, where the vehicles are initially placed according to the population density, are listed in Table 2. Apart from the mean and the standard deviation, the percental deviation from the reference scenario is computed for each attribute. Furthermore, the data is analysed for both approaches explained in chapter 3.2.2. Nevertheless, the analysis of the simulations shows that the mean access distance to reach a vehicle lies within a radius of 285 m and that less than 11% of the user reach a vehicle within a radius of 100 m. Therefore, the approach where the number of potential users within 100 m is measured might be less appropriate than the one where the area is divided into different zones. Hence, the following analysis focuses on the results for the zone approach and its main results are visible in Table 2. For the completeness of the thesis, the results for the accessibility approach are listed in Table 18 in appendix A 1 and it can be seen that the revenue gained in the two different approaches only slightly diverges from each other.

For the approach, where the area is divided into different zones and the vehicles are placed accordingly, the number of rentals amounts to 1415.80 and increases 0.94% compared to the reference scenario. Besides, the total trip duration increases by 5.74%. This increase is significant for the profit of the carsharing operator, as the users pay fees according to their trip duration. Therefore, the revenue increases by the same percentage. Furthermore, the time until each vehicle is at least used once decreases by 17.95% and remains at a value of 6 h 20 min. In no other scenario all vehicles are picked up earlier. The decrease of this time, as well as the

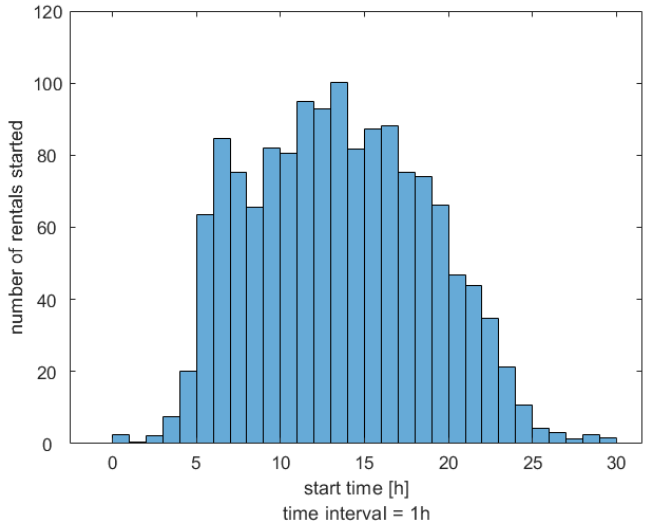
increase in the revenue, show that this initial vehicle placement might be more profitable for the operator than the one of the reference scenario. Besides, the mean access time remains more or less constant compared to the reference scenario while the mean distance travelled increases by 2.43%. It is remarkable, that even if the number of rentals does not increase largely compared to the reference scenario, the additional revenue reaches a notable value. This is explained by the fact that the mean trip duration increased compared to the reference scenario.

Table 2: Main results for initial vehicle placement according to the population density with zone approach

Attribute	mean	standard deviation	Deviation from reference scenario
Number of rentals	1415.80	12.26	0.94%
Total distance travelled [km]	4099.75	111.58	3.34%
Mean distance travelled [m]	2895.89	82.86	2.43%
Total trip duration [s]	775019.20	44882.25	5.74%
Mean trip duration [s]	547.40	30.94	4.75%
Mean access time [s]	214.81	2.64	-0.91%
Mean time until each vehicle is at least used once [h]	6.34	0.31	-17.95%
Revenue [CHF]	5166.79	299.22	5.74%

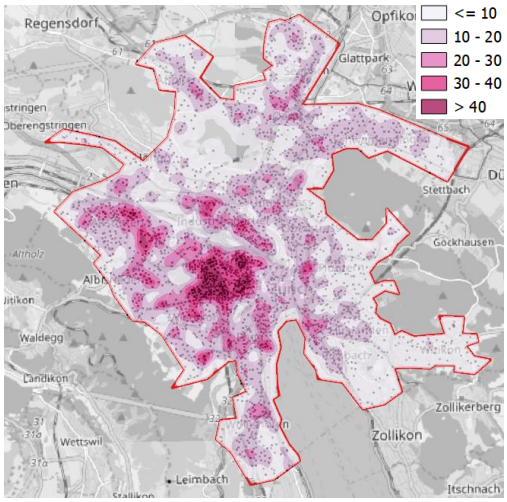
The temporal distribution of the rentals (Figure 17) is similar to the one of the reference scenario. Again, 80% of the rentals are conducted between 6.30 am and 8.40 pm and the median is reached at 1.20 pm. Between 1 pm and 2 pm the number of started free-floating carsharing trips reaches its maximum.

Figure 17: Histogram of rental start times for placement according to the population density



The pick-up locations do not vary significantly between the first two scenarios, as the similarity of Figure 16 and Figure 18 shows. The scale of the colour bar is the same for both figures, allowing a direct comparison of the two maps. The biggest hot-spot remains the same and is still located in the area of Aussersihl. Nevertheless, the number of started rentals in the other areas increases slightly in the second scenario, meaning that for example more rentals are started in the south-eastern part of the operating area than in the reference scenario. At the same time, fewer rentals are started in the area of Altstetten. For the following scenarios, the maps with the pick-up locations are added to the appendix as they do not differ significantly between the scenarios.

Figure 18: Spatial distribution of pick-up locations for vehicle placement according to the population density



Source: Background map: OpenStreetMap (2020)

4.1.3 Income

As in the previous scenario, two different approaches are used to place the vehicles initially according to the income. Nevertheless, as it again resulted that the access walk exceeds the radius of 100 m in more than 90%, the approach where the vehicles are located according to the zones is used for the comparison of the results. To reach the completeness of the thesis, the results for the second approach can be found in appendix A 1 (Table 19). For the third scenario, where the vehicles are initially distributed among the persons with the highest income, 1463.2 rentals are conducted on average which leads to an increase of 4.32% compared to the reference scenario. This number of conducted free-floating carsharing trips corresponds to the highest one reached in all scenarios. In contrast, the mean trip duration is lower than in other scenarios and therefore the revenue of 5217 CHF is not the maximal one of all scenarios. Besides, in this scenario, it takes about 6h 45min until each vehicle is used once. These and further main results of the third scenario are listed in Table 3.

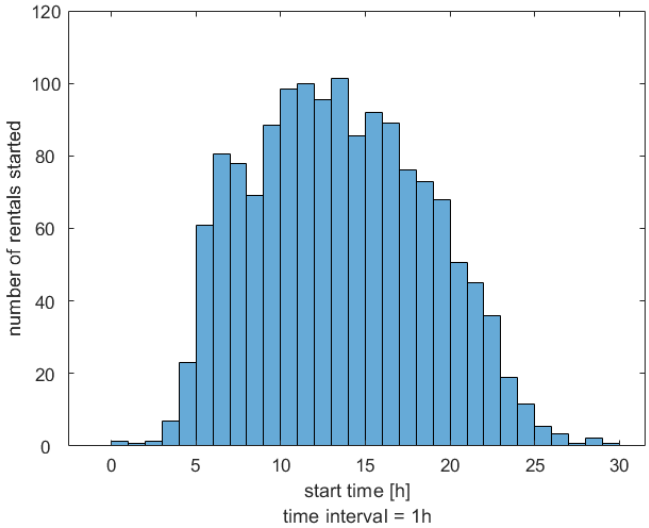
Table 3: Main results for initial vehicle placement according to the income for zone approach

Attribute	mean	standard deviation	Deviation from reference scenario
Number of rentals	1463.20	43.46	4.32%
Total distance travelled [km]	4118.21	66.73	3.81%
Mean distance travelled [m]	2816.64	98.99	-0.37%
Total trip duration [s]	782593.00	27697.73	6.78%
Mean trip duration [s]	535.01	17.94	2.38%
Mean access time [s]	215.73	0.57	-0.48%
Mean time until each vehicle is at least used once [h]	6.73	1.22	-12.98%
Revenue [CHF]	5217.29	184.65	6.78%

Nevertheless, on average, only for three out of 50 vehicles the first pick-ups during the simulation day are carried out by a person who belongs to the group of people with the highest income. A possible reason for this is, that the income is not considered in the mode choice decision of the agents. Therefore, the results of the income scenario need to be considered with attention as it cannot be detected how the income influences the mode decision and subsequentially the carsharing demand.

The histogram of the rental start times for the initial vehicle placement according to the income is visible in Figure 19. In this scenario, the 10% quantile is reached at 6.40 am and the 90% quantile at 8.32 pm, which means that 80% of the rentals are conducted within these times. Furthermore, 50% of the free-floating carsharing trips are carried out before 1.15 pm. These values are similar to the ones of the first two scenarios and no large differences can be detected between the different histograms. The hour during which the number of rentals reaches its maximum is detected to be between 1 pm and 2 pm.

Figure 19: Histogram of rental start times for placement according to the income



4.1.4 Population density of persons younger than 36 years

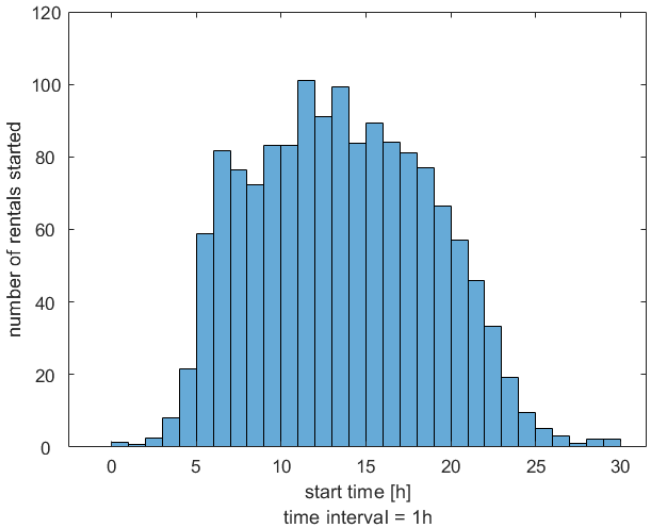
In the scenario, where the vehicles are initially placed according to the population density of people younger than 36 years, on average 1442.2 free-floating carsharing trips are conducted. Compared to the reference scenario, the total trip time increased by 7.88% and a total trip time of 220 min is reached. As this value corresponds to the highest one reached within all scenarios, the resulting revenue reaches the maximum for all scenarios with a value of 5271 CHF. Besides, at 6.23 am each vehicle is at least used once, which is only about 3 min later than in the population density scenario. In addition, the mean distance travelled increases slightly compared to the reference scenario, while the access time decreases by 0.8%. The main results for this scenario are presented in Table 4. Furthermore, the spatial distribution of the pick-up locations is added to appendix A 2, as no large differences to the previous scenarios can be detected.

Table 4: Main results for initial vehicle placement according to the population density of people under 36 years with zone approach

Attribute	mean	standard deviation	Deviation from reference scenario
Number of rentals	1442.20	45.49	2.82%
Total distance travelled [km]	4105.53	100.76	3.49%
Mean distance travelled [m]	2849.39	125.66	0.79%
Total trip duration [s]	790716.20	18120.84	7.88%
Mean trip duration [s]	548.73	22.23	5.01%
Mean access time [s]	215.02	3.90	-0.80%
Mean time until each vehicle is at least used once [h]	6.38	0.23	-17.46%
Revenue [CHF]	5271.44	120.81	7.88%

The temporal distribution of the rental start times is again similar to the previous scenarios (Figure 20). More than 80% of the rentals start between 6.35 am and 8.35 pm. Besides, half of the number of rentals are carried out before 1.21 pm. The time interval with the highest number of started free-floating carsharing trips is between 11 am and 12 pm.

Figure 20: Histogram of rental start times for placement according to the population density of people under 36 years



4.1.5 All vehicles at Zurich main station

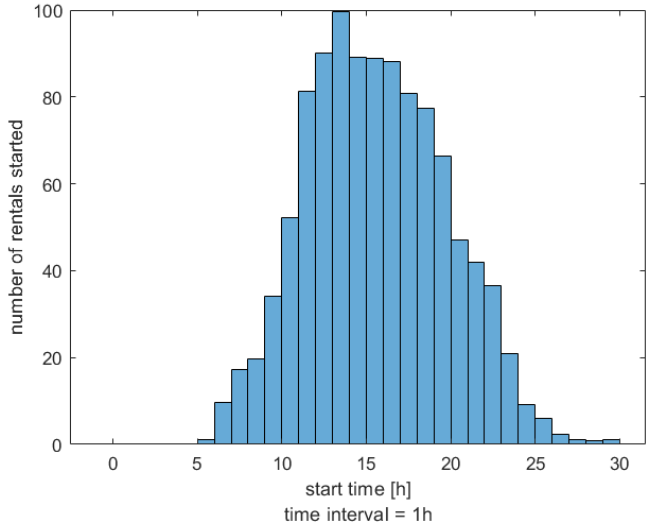
Table 5 summarises the main results for the scenario, where all vehicles are initially placed at Zurich main station. The number of rentals decreased by 24.2% and remains at a value of 1063.2 rentals on average. The revenue decreases similarly by 23.1%. Nevertheless, the mean trip duration increases slightly and values now 8.8 min. In contrast, the time until each vehicle is at least used once more than doubled compared to the reference scenario. It now takes 12 h 20 min until each car is rented once, which corresponds nearly to half of the simulated period. The high decrease in the revenue, as well as the long time until the vehicles are picked up for the first time, show that it is not profitable to locate all vehicles at one station because the demand is not as high as the supply and it takes longer than in other scenarios until the vehicles get distributed among the operating area. A map which represents the pick-up locations is added to appendix A 2, as there is no main difference to the other scenarios except for the fact that there are rentals started at Zurich main station, where the vehicles are placed initially.

Table 5: Main results for all vehicles initially placed at Zurich main station

Attribute	mean	standard deviation	Deviation from reference scenario
Number of rentals	1063.20	38.71	-24.20%
Total distance travelled [km]	2864.98	84.11	-27.78%
Mean distance travelled [m]	2697.08	115.55	-4.60%
Total trip duration [s]	564015.40	42291.12	-23.05%
Mean trip duration [s]	530.60	36.28	1.54%
Mean access time [s]	221.77	3.15	2.31%
Mean time until each vehicle is at least used once [h]	12.30	0.59	59.10%
Revenue [CHF]	3760.10	281.94	-23.05%

The temporal distribution of this scenario differs from the others (Figure 21). Interestingly, there are no carsharing trips starting before 5 am. From then on, the number of rentals during one hour starts to increase up to a maximum between 1 pm and 2 pm. The time and size of this maximum peak correspond to the ones of the other scenarios with 100 rentals. Nevertheless, the 10% quantile lays at 10.32 am and the 90% quantile is reached at 9.15 pm. Half of the rentals are conducted before 3.26 pm, which results in a delay of roughly 2 hours compared to the previous scenarios. It is visible that in comparison to the other scenarios, the number of rentals is relatively low up to 11 am. This shows that the agents do not use the shared vehicles in the morning and the demand just starts increasing around noon.

Figure 21: Histogram of rental start times for all vehicles initially placed at Zurich main station



4.1.6 Vehicles at the most frequented railway stations in Zurich

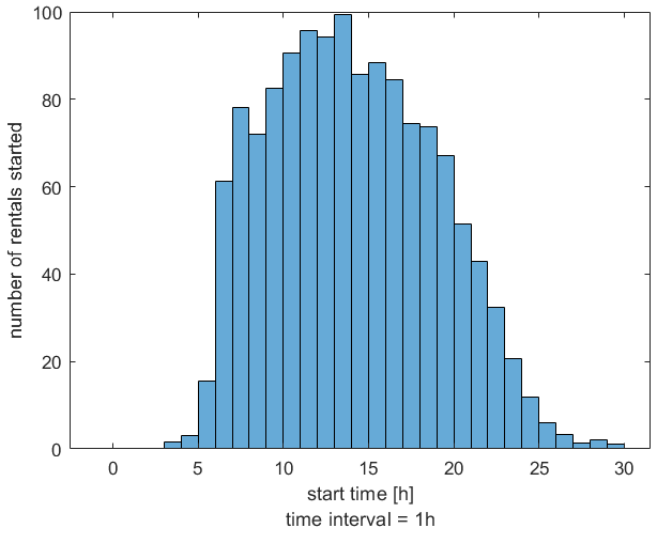
In this scenario, not only the number of rentals decreases but the revenue as well (Table 6). Nevertheless, the mean duration of a carsharing trip increases by 2.2% to a duration of 8.9 min on average. Furthermore, the time until each vehicle is used once, raises to 8 h 42 min, corresponding to an increase of 12.6% compared to the reference scenario. The efficiency and the profitability of this scenario are worse than in other scenarios, as the revenue as well as the mean time until each vehicle is at least used once, do not reach as good values as they do in other scenarios. Again, it is detected that the placement of 10 vehicles at one location is not favourable, as it takes long until each of the vehicles is used for the first time. If a vehicle remains unused for a long time at its initial location, the users in other parts of the operating areas cannot benefit from the carsharing service which results in fewer carsharing trips. This leads then to a smaller revenue for the operator and makes this initial vehicle placement unattractive.

Table 6: Main results for initial vehicle placement at the most frequented railway stations in Zurich

Attribute	mean	standard deviation	Deviation from reference scenario
Number of rentals	1341.00	31.06	-4.39%
Total distance travelled [km]	3809.73	136.58	-3.97%
Mean distance travelled [m]	2841.30	90.20	0.50%
Total trip duration [s]	715463.20	30081.91	-2.38%
Mean trip duration [s]	533.81	27.16	2.15%
Mean access time [s]	220.06	1.96	1.52%
Mean time until each vehicle is at least used once [h]	8.71	0.56	12.63%
Revenue [CHF]	4769.75	200.55	-2.38%

The temporal distribution of the rental start times is visible in Figure 22. The course of the histogram is similar to the one of the reference scenario. Nevertheless, there are no carsharing trips conducted before 3 am. More than 80% of the carsharing trips are carried out between 7.40 am and 8.45 pm, whereas half of the trips are started before 1.45 pm.

Figure 22: Histogram of rental start times for placement at the most frequented railway stations in Zurich



4.1.7 Regular grid

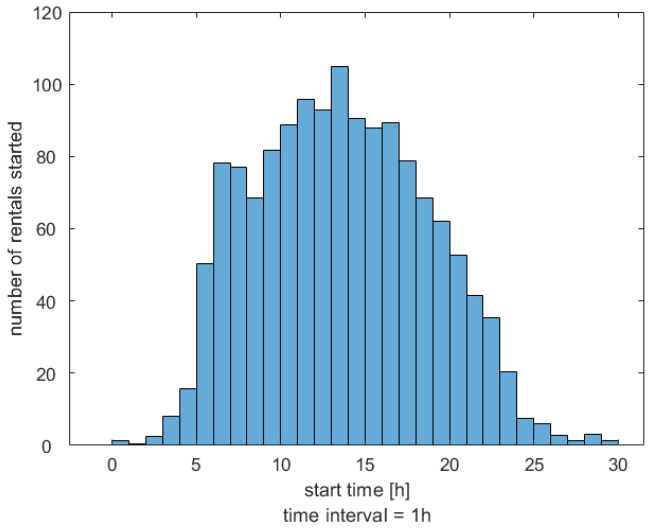
In the scenario, where the vehicles are initially placed according to a regular grid, an average of 1415.4 rentals results. Besides, the revenue increases by 4.7% with respect to the reference scenario. Nevertheless, the initial placement according to a regular grid might not be the best solution as the time until each vehicle is rented at least once is more than doubled compared to the reference scenario. On average, it lasts 17 h 50 min until each vehicle is used for the first time. In addition, during one simulation, one vehicle even remained unused for the whole simulation period of 30 hours. This fact shows that even if this scenario performs fairly good for the number of rentals and the revenue, the optimal initial vehicle distribution is not found. The efficiency of the system can still be increased and the vehicles should be placed at a location where they are picked up earlier during the simulation day. To give an overview of the performance of this scenario, the main results are listed in Table 7.

Table 7: Main results for initial vehicle placement according to a regular grid

Attribute	mean	standard deviation	Deviation from reference scenario
Number of rentals	1415.40	54.88	0.91%
Total distance travelled [km]	4049.55	147.06	2.08%
Mean distance travelled [m]	2862.76	105.23	1.26%
Total trip duration [s]	767154.20	15704.26	4.67%
Mean trip duration [s]	542.68	24.12	3.85%
Mean access time [s]	218.72	2.00	0.90%
Mean time until each vehicle is at least used once [h]	17.84	9.32	130.68%
Revenue [CHF]	5114.36	104.70	4.67%

The temporal distribution of the rental start times does not differ remarkably from the other scenarios (Figure 23). The number of rentals conducted starts increasing significantly after 5 am and reaches a peak between 1 pm and 2 pm. 10% of the rentals are started before 6.50 am and 10% are conducted after 8.35 pm. Besides, half of the free-floating carsharing trips are carried out before 1.25 pm.

Figure 23: Histogram of rental start times for placement according to a regular grid



4.1.8 Summary

Table 8 provides an overview of the results for all scenarios. To simplify reading out the main results, a bar chart is added for the three most important factors, namely the number of rentals, the revenue and the time until each vehicle is at least used once (Figure 24 to Figure 26).

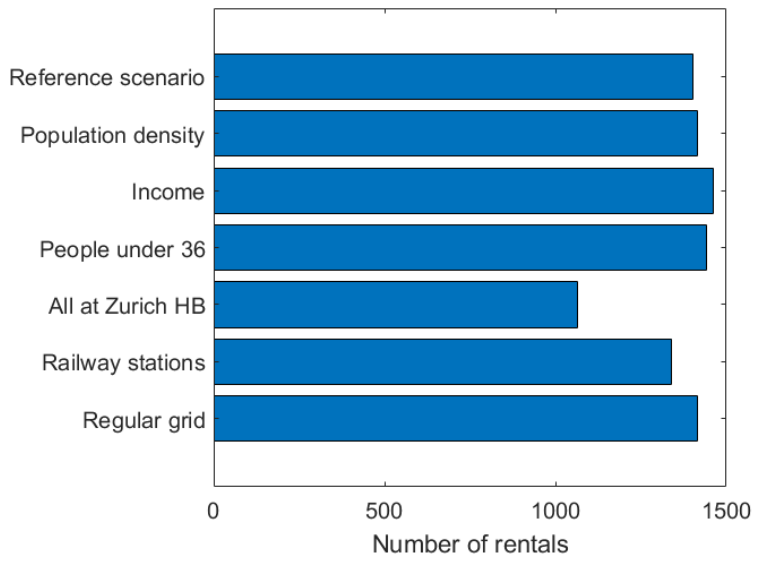
Table 8: Overview of the main results for all scenarios

	Scenario	Number of rentals	Total trip distance [km]	Total trip duration [s]	Mean trip duration [s]	Mean access time [s]	Time to all used once [h]	Revenue [CHF]
1)	Reference scenario	1402.60	3967.06	732927.80	522.55	216.77	7.73	4886.19
2)	Population density	1415.80	4099.75	775019.20	547.40	214.81	6.34	5166.79
3)	Income	1463.20	4118.21	782593.00	535.01	215.73	6.73	5217.29
4)	People younger than 36	1442.20	4105.53	790716.20	548.73	215.02	6.38	5271.44
5)	All at Zurich HB	1063.20	2864.98	564015.40	530.60	221.77	12.30	3760.10
6)	Railway stations	1341.00	3809.73	715463.20	533.81	220.06	8.71	4769.75
7)	Regular grid	1415.40	4049.55	767154.20	542.68	218.72	17.84	5114.36

The highest number of rentals is reached for the scenario, where the vehicles are initially distributed according to the income (Figure 24). In these simulations, on average a total of 1463 rentals are conducted. As mentioned previously, the income of a person does not have an influence on the transport mode choice of a person. Therefore, the scenario where the vehicles are placed according to the income needs to be considered with caution. Apart from the income scenario, the scenario of persons younger than 36 years and the population density reach the next highest rental numbers with 1442 and 1416 rentals respectively. Nevertheless, the variance between these three scenarios is not large and only amounts to 3.2%. On the contrary, it is detected that for the scenario, where all cars are initially placed at Zurich main station, the number of rentals is significantly lower than for the other scenarios. Furthermore, it is

remarkable that the regular grid scenario reaches nearly the same number of conducted carsharing trips like the one with initial vehicle placement according to the population density.

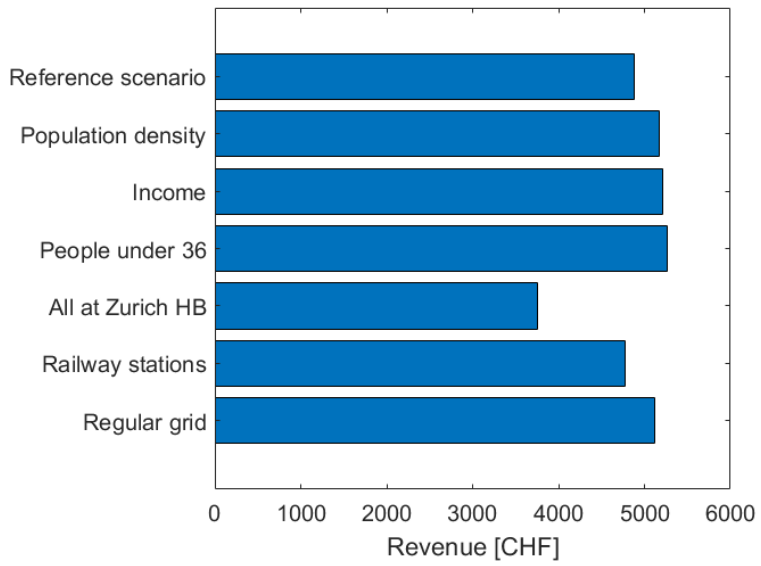
Figure 24: Number of rentals for each scenario



To determine the profitability of the carsharing service, the revenue can be compared between the different scenarios (Figure 25). This value is highest for the initial vehicle placement according to the population younger than 36 years followed by the income and the population density scenario. The values of these three scenarios lay within a very small range and their deviation is less than 2%. Besides, the regular grid again shows fairly good performance. The difference between the revenue of the regular grid and the one for the scenario of the people younger than 36 years only amounts to 157 CHF what corresponds to a difference of approximately 3%. Even if this deviation can be significant for a carsharing operator, larger differences would be expected. Besides, it has to be taken into account that a revenue increase of 3% does not mean that the operator's benefit increases by the same number as the operator's costs might increase as well. One reason for higher costs could be that the trip distance increases as well and therefore the costs for the fuel and the abrasion of the vehicle increase. For example, the regular grid scenario reaches on average a total trip distance of about 4050 km, while for the initial vehicle placement according to the income a total trip distance of 4118 km is covered. The deviation between these two scenarios also values about 2% and it should be investigated if the difference in the revenue or the operator's costs are higher to determine which initial vehicle placement is more profitable. Furthermore, additional costs occur to place the vehicles in the morning to specific locations as probably relocations need to be performed. It is further detected that the scenario with the highest number of trip rentals does not reach the highest

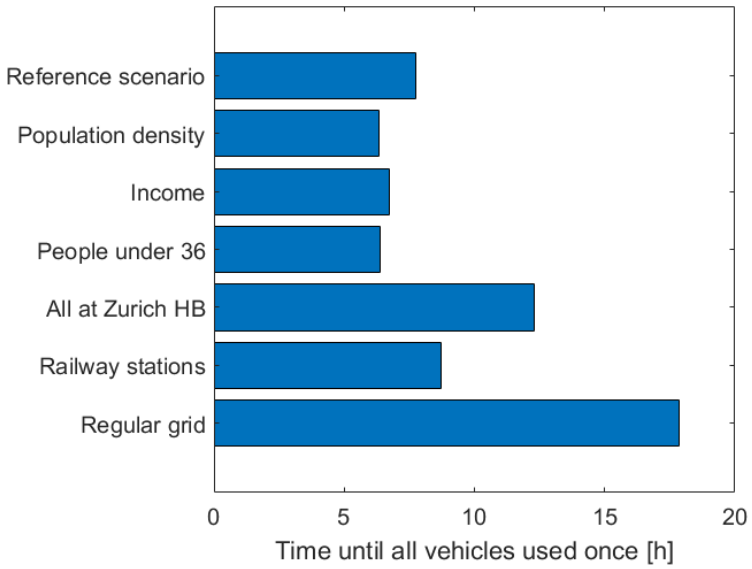
revenue. This shows, that not only the demand should be investigated but that the mean trip duration influences the revenue as well.

Figure 25: Revenue for each scenario



Moreover, the mean access time remains more or less constant and there are no large deviations within the scenarios. On the one hand, the mean time needed to access a vehicle values in all scenarios between 3min 34s and 3min 41s, which corresponds to a difference of less than 10s for the different initial vehicle locations. On the other hand, the time until each shared vehicle is at least used once, varies significantly between the different scenarios (Figure 26). The lowest time needed is 6 h 20 min and corresponds to the scenario with initial vehicle placement according to the population density. A similar value is reached for the placement according to the population below 36 years, where it only takes 3 min longer until each vehicle is at least rented once. With the initial vehicle placement according to the income a good value is reached as well. As in these three scenarios all vehicles are picked up at least once even before the end of the morning peak hours, which is generally described to be at 9 am, the applied initial vehicle locations are well-chosen in these scenarios. Nevertheless, in the scenario, where the vehicles are distributed according to a regular grid, it takes more than 17 h until each vehicle is used once. Therefore, the utilisation of the vehicles is not optimal in this scenario and a more reasonable initial vehicle placement should be chosen in order to maximise the efficiency of the carsharing service. Considering the revenue as an indicator for the profitability of the carsharing service, the scenario with the vehicle distribution according to the people younger than 36 years performs best. In addition, this scenario performs best together with the placement based on the population density if the time until each vehicle is used once is considered.

Figure 26: Time until all vehicles are at least used once for each scenario



For all scenarios, the mean trip time lies between 8.5 and 9.5 min. Furthermore, in all simulations the mean distance travelled is lower than 3 km. These findings show that the free-floating carsharing service is mostly used for short trips, which corresponds to previous investigations of the use of free-floating carsharing as a transport mode.

Another interesting insight of the simulations is that the maximal number of rentals is not reached during the peak hours which are mostly defined to be between 6 am and 9 am and in the evening between 4 pm and 7 pm. Even if an increase in the number of rentals is present during this time period for all scenarios except the one where all vehicles are placed at Zurich main station, the peak of the rentals is mostly reached between 11 am and noon or between 1 pm and 2 pm.

As in most scenarios, the number of rentals performed reaches a value higher than 1400, on average each vehicle is used more than 28 times. This number is rather large and it shows that the vehicles are used fairly often independent of their initial location. This might be a reason why the deviations between the scenarios are not that high as a balance of the number of vehicle rentals occurs throughout the simulation day. Nevertheless, it can be determined that the initial vehicle placement influences the demand and the operator's revenue, as the scenario where all vehicles are placed at Zurich main station or where they are placed at different railway stations within Zurich do not perform as good as the others do. An explanation for this is, that in these two scenarios, several vehicles are placed at the same station and therefore it takes longer until each vehicle gets used once and is then available at another location within the carsharing

operating area. This fact is also reflected in the time until each vehicle is at least used once. The respective time is higher for the two scenarios with vehicles at the railway stations than for the first four scenarios. In summary, it can be said that the initial vehicle placement does have an influence on the profitability and the efficiency of a free-floating carsharing service. Nevertheless, the observed deviations of the different scenarios are smaller than they were expected and especially the good performance of the initial vehicle placement according to a regular grid is surprising.

4.2 Initial vehicle placement with 500 vehicles

To test how a larger fleet size influences the effects of the initial vehicle placement, simulations are conducted with 500 shared vehicles. The results for the simulations, where 500 free-floating carsharing vehicles are initially distributed according to a regular grid, can be seen in Table 9. On average, 9943.8 carsharing trips are conducted and a revenue of 37’665.29 CHF results. Furthermore, it needs to be mentioned that for the first scenario, where the vehicles are placed according to a regular grid, two vehicles remain unused during the whole simulation day. If the mean number of pick-ups per vehicle is then calculated for the other 498 vehicles, a value of about 20 rentals per vehicles is reached. The time until each vehicle is at least picked up once is determined for the vehicles which get picked up during the simulation day and the two unused vehicles are neglected.

Table 9: Main results for initial vehicle placement according to a regular grid with 500 vehicles

Attribute	mean	standard deviation
Number of rentals	9943.80	146.40
Total distance travelled [km]	29176.76	569.96
Mean distance travelled [m]	2934.19	40.01
Total trip duration [s]	5649793.40	198676.62
Mean trip duration [s]	568.17	24.57
Mean access time [s]	145.26	1.77
Mean time until each vehicle is at least used once [h]	13.66	1.15
Revenue [CHF]	37665.29	1324.51

In contrast, Table 10 shows the results for the simulations where 500 vehicles are initially placed according to the population density. Apart from the mean and the standard deviation, the percentual change to the regular grid scenario is determined. Interestingly, even if the number of rentals is slightly higher in the second scenario, the revenue decreased by 2.11% compared to the regular grid scenario. This is explained by the fact that the average trip time is 2.66% lower for the second scenario than for the first one. Even if the absolute difference for the average trip time only values around 15s, the difference in the total trip time amounts to 33 h because nearly 10’000 trips are conducted. Thus, as no basis fee is paid for the use of a free-floating carsharing vehicle, but the fees are only determined according to the trip time, the revenue decreases even if the demand for carsharing trips increases. Moreover, again a value of 20 pick-ups per vehicle results. Furthermore, it is visible that in this scenario the time until each vehicle is at least picked up once decreased by 2 h compared to the regular grid scenario.

Table 10: Main results of initial vehicle placement according to the population density with 500 vehicles

Attribute	mean	standard deviation	Deviation from regular grid scenario
Number of rentals	9999.60	54.88	0.56%
Total distance travelled [km]	29178.74	360.37	0.01%
Mean distance travelled [m]	2918.01	28.99	-0.55%
Total trip duration [s]	5530458.80	146672.93	-2.11%
Mean trip duration [s]	553.06	13.37	-2.66%
Mean access time [s]	143.62	0.88	-1.13%
Mean time until each vehicle is at least used once [h]	11.73	0.61	-14.14%
Revenue [CHF]	36869.73	977.82	-2.11%

In summary, it is detected that the profitability of a carsharing service does not necessarily correlate with the number of rentals conducted. As the examination of the two different scenarios shows, the revenue can decrease even if the number of conducted rentals increases. It demonstrates that not only the demand needs to be investigated but the planned trip duration as

well in order to increase the profitability of a carsharing service. Nevertheless, the two scenarios show that the influence of the initial vehicle placement does not get bigger for a larger vehicle fleet, as the deviations between the scenarios still stay the same. Furthermore, the vehicles continue to be picked up a significant amount of times during a day with an average of 20 rentals per vehicle. This shows that the demand within the carsharing operating area is relatively high and that the vehicles might get picked up even if they are located in an area with less potential users.

4.3 Initial vehicle placement with less attractive free-floating carsharing service

As in the previous simulations, relatively many rentals are conducted per vehicle, the parameters of the discrete mode-choice model are adjusted and a less attractive free-floating carsharing service is created for the following simulations. In these simulations, again a vehicle fleet size of 50 cars is applied.

In Table 11, the main results for the first scenario are depicted, where the vehicles are placed according to a regular grid. On average, a total of 240.4 rentals are conducted and a revenue of 1727.49 CHF results. The mean number of rentals per vehicle measures 4.8. But the distribution of the number of rentals over the vehicles is not constant and some vehicles get used up to 13 times while other vehicles remain unused for some simulations. In total, four vehicles remain unused in one simulation and one vehicle in two of the performed simulations. Nevertheless, these vehicles get picked up in the other simulations of the same scenario with another random seed. Furthermore, it is observed that for the five different simulations with various random seeds, a different distribution in the number of rentals per vehicle results, meaning that not always the same vehicles stay unused and that also the most used vehicle differs among the different simulations. This shows that not only the initial vehicle placement has an effect on the total number of rentals, but the trips end location as well because this determines how fast the vehicle gets used again. To calculate the mean time until each vehicle is at least used once, the vehicles which remain unused for the whole simulation period are neglected. On average, it takes about 26 h until each of the remaining vehicles is at least used once. This means that some vehicles stay unused up to midnight of the first day and just get used for trips which start after midnight of the simulation day. Obviously, the cars which are picked up that late in the simulation day, do not perform many carsharing trips. In summary, the results of the used simulation framework for these simulations nonetheless seem more appropriate than the once explained in chapter 4.1 as the number of conducted carsharing trips seems more realistic for a vehicle fleet of 50 cars.

Table 11: Main results for initial vehicle placement according to a regular grid for the less attractive carsharing service

Attribute	mean	standard deviation
Number of rentals	240.40	12.26
Total distance travelled [km]	929.90	68.92
Mean distance travelled [m]	3868.48	215.81
Total trip duration [s]	172749.20	13553.09
Mean trip duration [s]	718.59	52.95
Mean access time [s]	213.84	5.75
Mean time until each vehicle is at least used once [h]	26.08	4.13
Revenue [CHF]	1727.49	135.53

The results for the simulations with initial vehicle placement according to the population density are listed in Table 12. In comparison to the regular grid, the number of rentals increases by 5.57% and now reaches a value of 253.8. Additionally, the revenue grows by 8.73% and a total of 1878.32 CHF results. For this scenario, on average 5.1 trips are conducted per vehicle which is slightly higher than for the first scenario. Furthermore, the variation of the number of conducted trips between the different vehicles is again relatively high with the highest value of 13 pick-ups of a vehicle. One vehicle remains unused in one of the conducted simulations but gets picked up in the other simulations with different random seeds. As in the previous scenario, the differences in the number of rentals per specific vehicle are high between the simulations with different random seeds and no vehicle can be determined which performs best or worst overall simulations of this scenario. Besides, on average it takes 13 h 28 min until each vehicle is at least used once what is around 12 h less than in the previous scenario. In summary, it is thus observed that the scenario with initial vehicle placement according to the population density performs better than the first scenario, as the revenue, as well as the number of rentals increases, while the mean time until each vehicle is used once decreases. Furthermore, the difference in the number of rentals of the first two scenarios increased compared to the previous simulations with 50 or 500 vehicles. Similarly, the difference in the revenue increases, as for this scenario, the mean trip duration deviates from the previous scenario as well.

Table 12: Main results for initial vehicle placement according to the population density for less attractive carsharing service

Attribute	mean	standard deviation	Deviation from regular grid scenario
Number of rentals	253.80	9.78	5.57%
Total distance travelled [km]	982.83	51.11	5.69%
Mean distance travelled [m]	3871.62	95.30	0.08%
Total trip duration [s]	187832.40	11767.90	8.73%
Mean trip duration [s]	740.78	52.40	3.09%
Mean access time [s]	207.01	7.07	-3.19%
Mean time until each vehicle is at least used once [h]	13.46	2.36	-48.39%
Revenue [CHF]	1878.32	117.68	8.73%

For the simulations, where the vehicles are initially placed according to the population density of people under 36 years, the results are depicted in Table 13. It is visible that the average number of rentals reaches its maximum for the three tested scenarios with a total of 259.4 free-floating carsharing trips which corresponds to an increase of 7.9% compared to the regular grid scenario. As not only the number of conducted trips increased but the mean trip duration as well, an even larger growth can be seen for the revenue. On average, the operator collects fees for 1965.07 CHF, which corresponds to an increase of 13.75% from the first scenario. Furthermore, the time until all vehicles are at least picked up once decreases to only 13 h 6 min. Moreover, only one vehicle remained unused for two out of the five simulations with a different random seed.

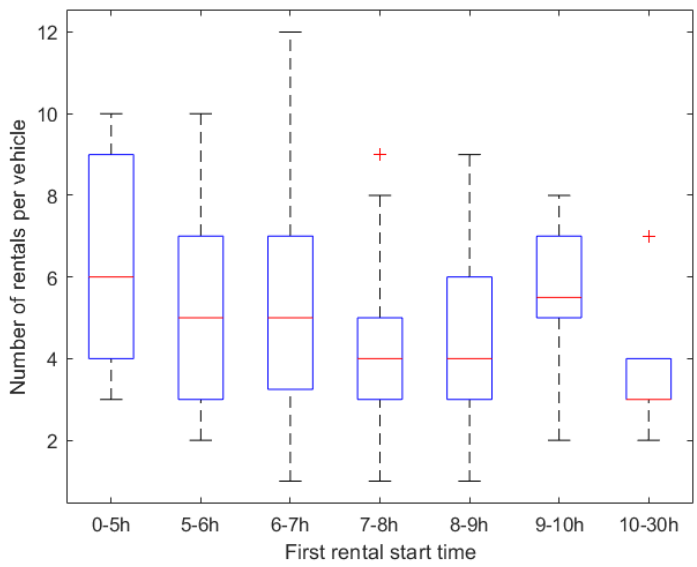
Table 13: Main results for initial vehicle placement according to population density of people under 36 years for less attractive carsharing service

Attribute	mean	standard deviation	Deviation from regular grid scenario
Number of rentals	259.40	16.23	7.90%
Total distance travelled [km]	1005.12	86.38	8.09%
Mean distance travelled [m]	3871.75	167.52	0.08%
Total trip duration [s]	196506.60	25977.70	13.75%
Mean trip duration [s]	758.79	96..6	5.59%
Mean access time [s]	208.17	3.91	-2.65%
Mean time until each vehicle is at least used once [h]	13.11	2.01	-49.73%
Revenue [CHF]	1965.07	259.78	13.75%

For the third scenario, on average, a vehicle gets used for 5.2 trips, while the most used vehicle is picked up 12 times within a simulation day. The analysis of the number of rentals per vehicles shows, that it does not strictly correlate with the time of the first pick up. For example, the vehicle, which is used first in the simulation day, does not show the highest number of rentals as it remained unused for more than 5 hours after the first rental. There again, a vehicle which is picked up later for the first time only remained unused for a few minutes within the rentals and is therefore more often used. In Figure 27, for each vehicle, the number of rentals conducted with this vehicle is depicted against the first rental start time of the specific vehicle. It would be expected, that for early first pick-up times the number of rentals per vehicle is higher than for later ones. Nevertheless, the observed data does not allow to detect a strict correlation between the number of rentals and the first pick-up time as even for vehicles with similar first rental start times, a large deviation between the number of rentals exist. For example, two vehicles get picked up for the first time nearly at the same time point, at about 6.40 am, but one vehicle performs 12 carsharing trips during the whole simulation day while with the other one only one trip is performed. This shows that the number of conducted carsharing trips not only depends on the initial vehicle locations but on the trip destinations as well as this location determines how long a vehicle remains unused after a rental. Nevertheless, it is further visible

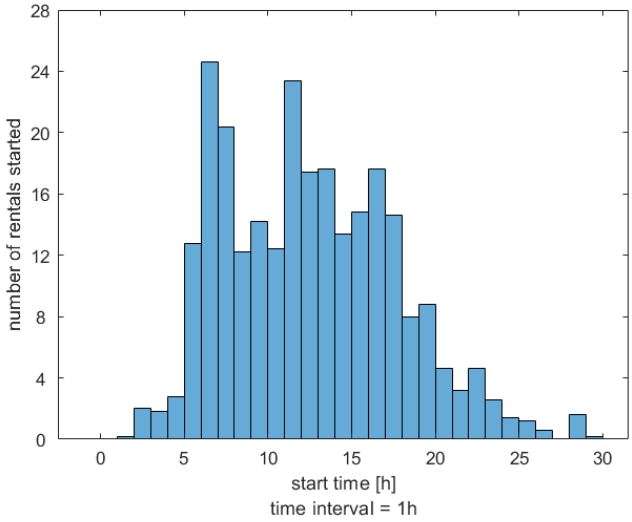
that if the first rental of a vehicle is for example conducted after 10 am, the number of rentals does not reach as high values as the ones which get picked up the first time before 10 am. This observation occurs for all three scenarios and the data of the third scenario is just chosen to represent all of them. The diagrams of the other two scenarios are added to appendix A 3 (Figure 36 and Figure 37). Nonetheless, the time until all vehicles are at least used once can be taken as an indicator on how well the initial locations are chosen, even if the number of rentals and the revenue not necessarily correlate with it.

Figure 27: Number of rentals against first rental start time for placement according to the population density of people under 36 years for less attractive carsharing service



Additionally, Figure 28 shows the temporal distribution of the carsharing rental starts for the scenario with initial vehicle placement according to the population density of people under 36 years. It is visible, that a first peak occurs between 6 am and 7 am, at the beginning of the morning peak hours. Then the number of rentals slightly decreases until a second peak is reached between 11 am and 12 pm. Furthermore, more than 80% of the rentals are started between 6.30 am and 7.30 pm and more than half of the carsharing trips are conducted before 12.10 pm. As the main pattern of the rental start times is the same for all three scenarios, the histogram of the rental start times for the first and the second scenario is not discussed in detail and they are added to the appendix A 3 (Figure 38 and Figure 39).

Figure 28: Histogram of rental start times for placement according to the population density of people under 36 years for less attractive carsharing service



Another insight of the conducted simulations is that the mean trip duration increased for all three scenarios compared to the previously conducted simulations. On average, a carsharing trip takes now 12 to 13 min which corresponds to an increase of about 50%. The highest value of the mean trip duration is reached by the third scenario with initial vehicle placement according to a regular grid. A reason for this growth in the trip duration might be that the carsharing service is now less attractive for short way trips and therefore another transport mode is chosen to perform these trips.

In summary, it is observed that the initial vehicle placement according to the population density of people under 36 years performs best. This conclusion is not only made because the number of rentals reaches its maximum for this scenario, but the highest revenue is achieved as well. Furthermore, the time needed until each vehicle gets picked up for the first time is minimal for this scenario which means that the initial vehicle locations are favourable for the users.

4.4 Simulations over one week

4.4.1 Regular grid

To test, if relocations over the night can increase the efficiency and profitability of a carsharing service, simulations are conducted over five days. Therefore, a vehicle fleet of 50 cars is used and the adjusted parameters of chapter 3.4 are implemented. Table 14 presents the results of the simulations over one week with initial vehicle placement according to a regular grid for the first day. Again, all simulations are conducted with five different random seeds, where for each random seed one series over 5 days is simulated. Apart from the mean and the standard deviation (sd), the deviation from the values of day 1 (dev.) are determined. As the number of unused vehicles is rather low, the deviation from day 1 is not listed for this attribute as the results would not be very helpful.

The results show that the number of conducted free-floating carsharing trips is highest for the first day. Furthermore, the number of rentals oscillates during the five simulation days and no clear trend can be determined. Nevertheless, on day 5 the number of carsharing trips is lowest of all simulation days. It is further visible that the change in the revenue compared to the first day does not always correlate with the change in the number of rentals. This can again be explained by the fact that the mean trip duration varies for the different simulation days and the revenue is calculated per conducted trip minute. The revenue performs an oscillation, since it decreases for day 2 but then increases again for day 3 and 4 where even higher revenues than for day 1 result. On day 5, the revenue sinks drastically with a decrease of -8.47% compared to day 1 and the lowest revenue of all simulation days is reached. Thus, the initial vehicle placement according to a regular grid for day 1 is not an optimal initial vehicle placement as the revenue could still be increased on day 2 and day 3.

In addition to the number of rentals and the revenue, the number of unused vehicles is determined for each simulation day. This value increases between day 1 and day 3, followed by a slight decrease for day 4 and an increase again for day 5. Nonetheless, the large standard deviation of this value should be taken into account. It shows that for the simulation with different random seeds the number of unused vehicles varies remarkably. For example, on day 5 for one simulation six vehicles stayed unused while for another simulation only one vehicle is not picked up for the whole simulation day. Furthermore, not always the same vehicles remain unused and a vehicle might not get picked up for one day but for the next day rentals of this vehicle are performed. Nevertheless, no strong connection can be determined between the number of unused vehicles and the earned revenue as for some days the revenue grows even if the number of unused vehicles increases.

Table 14: Main results of simulations over one week for initial vehicle placement according to a regular grid

	Number of rentals			Revenue [CHF]			Unused vehicles	
	Mean	Sd	Dev.	Mean	Sd	Dev.	Mean	Sd
Day 1	240.40	12.26		1727.49	135.53		1.20	1.1
Day 2	226.60	18.78	-5.74%	1652.92	108.03	-4.32%	2.00	0.71
Day 3	232.60	21.17	-3.24%	1740.42	244.59	0.75%	2.60	1.52
Day 4	227.60	16.26	-5.32%	1751.06	163.62	1.36%	2.40	1.52
Day 5	220.60	24.46	-8.24%	1581.18	216.49	-8.47%	2.80	2.12

To see whether relocations to the initial vehicle placement according to a regular grid would be profitable for the operator, the explained algorithm of chapter 3.5 is applied. As the revenue reaches its lowest value for day 5, it is suggested to perform relocations at the end of day 4 and the cars are relocated to the initial locations of day 1. Table 15 summarises the results for the relocation performance. On average, 29.40 vehicles are relocated and a total relocation distance of 62.13 km is covered while the total access distance between the relocations values 70.58 km. Thus, the distance between a relocation destination and the next relocation start point measures 2.44km on average and the mean relocation distance values 2.11km. On average, the performance of one relocation only takes about 3 min and the time to access the next vehicle to relocate is nearly 10min. Concerning the costs, average expenses of 135.11 CHF occur. In comparison, the additionally gained revenue equals 146.31 CHF which is only slightly higher than the relocation costs. In this scenario, relocations thus might not be profitable for the operator as not all occurring costs are considered, as for example depreciation, maintenance and tire costs are not taken into account. Moreover, the distances between the relocation start points and destinations are calculated as air distance. Hence, the real distances and times to perform the relocations are higher and the costs will increase as well, making the relocations even less attractive. This shows that relocations might be unattractive and not profitable for the operator even if the number of rentals increases by 8.24% through the performed relocations. Furthermore, the revenue oscillates during the five simulation days and a further volatility could be expected, meaning that the revenue could increase again for the following days. Therefore, relocations are not be recommended for this scenario.

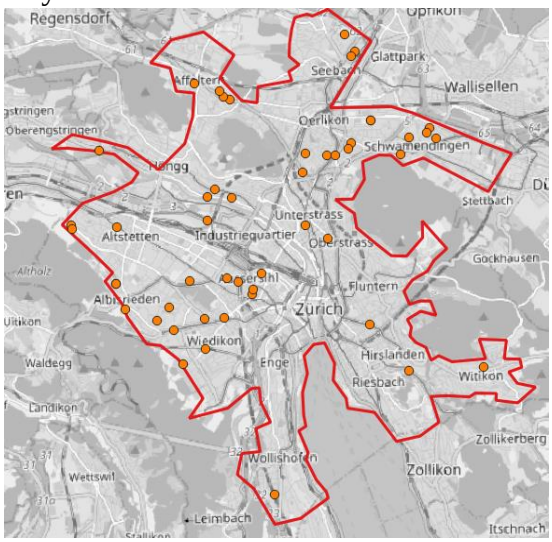
Table 15: Main results for relocations at the end of day 4 of the regular grid scenario

Attribute	Mean	Standard deviation
Number of relocations	29.40	2.51
Relocation distance [km]	62.13	16.48
Access distance [km]	70.58	12.85
Total time [h]	6.26	1.22
Total costs [CHF]	135.11	26.92

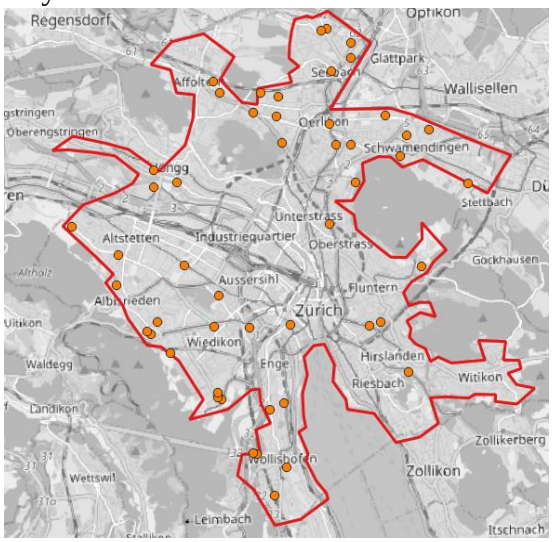
Moreover, the initial vehicle locations for day 2 to day 5 are presented in Figure 29 for one of the conducted simulation series. It is visible, that the distances between the vehicles are lower than on the first day, where the vehicles are placed according to a regular grid. Furthermore, it is analysed that for day 2 to 5 it takes longer until 90% of the vehicles are picked up than on the first day. A possible reason for this might be, that several vehicles are placed next to each other and therefore the vehicle supply might be higher than the demand.

Figure 29: Initial locations of the vehicles on day 2 to day 5 for the regular grid scenario

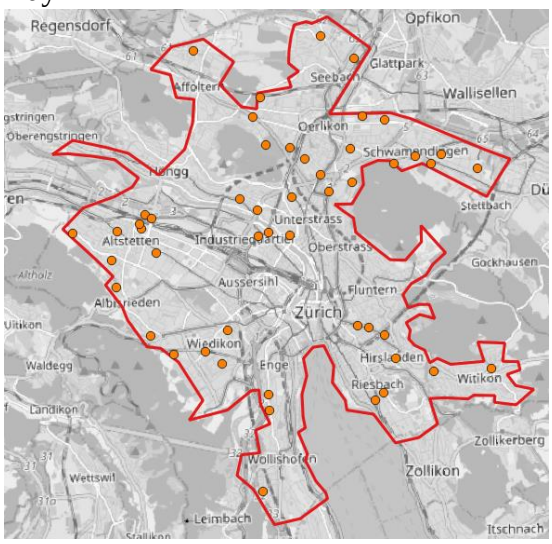
Day 2



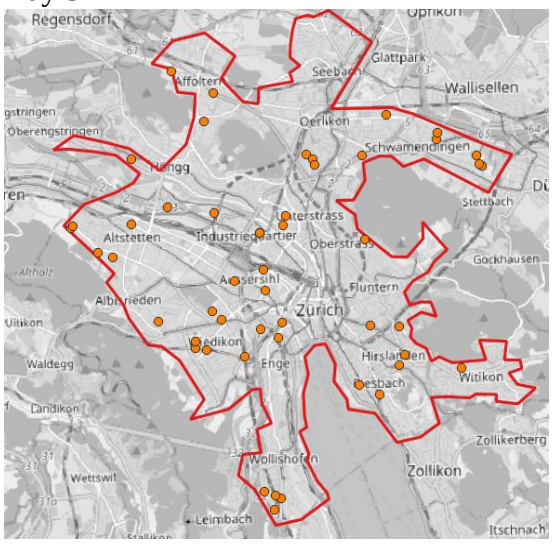
Day 3



Day 4



Day 5



Source: Background map: OpenStreetMap (2020)

4.4.2 Population density of people under 36 years

In a second series, the simulations over five days are conducted for an initial vehicle placement according to the population density of people under 36 years. This scenario is chosen because it showed the best performance of all conducted simulations considering the revenue and the number of rentals. Table 16 presents the results for the five simulation days. It can be seen that the number of rentals as well as the revenue is maximal for the first day and that for all following days the mentioned values decreased. After the large decrease in the revenue of -15.66% for day 2, a slight increase is present for day 3 and day 4, even if the initial revenue of day 1 is not reached again. For day 5, the revenue reaches then the lowest value. Another interesting insight

is, that similar to the regular grid scenario, no connection between the number of unused vehicles and the revenue can directly be seen. Again, a possible explanation for this is, that the standard deviation of the number of unused vehicles is relatively high and thus no dependency of the two attributes is visible. Moreover, the number of vehicles which remain unused for the whole simulation day is increasing from day 1 with 0.40 unused vehicles to day 3 with a value of 2.80 before decreasing again towards day 5, where an average value of 0.80 unused vehicles is reached. To summarise, it is observed that the best initial vehicle placement for this scenario is found for day 1, where the vehicles are initially located according to the population density of possible clients under 36 years. Furthermore, the differences in the revenue are higher for this scenario than for the previous one with initial vehicle placement according to a regular grid. This shows again that the chosen vehicle locations for day 1 seem to be appropriate for the efficiency and the profitability of the carsharing service as no better performance occurred during the simulations over five days.

Table 16: Main results of simulations over one week for initial vehicle placement according to population density of people under 36 years

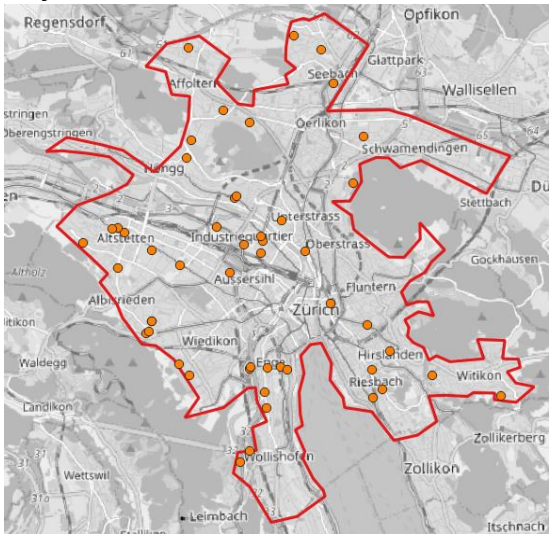
	Number of rentals			Revenue [CHF]			Unused vehicles	
	Mean	Sd	Dev.	Mean	Sd	Dev.	Mean	Sd
Day 1	259.40	16.23		1965.07	259.78		0.40	0.55
Day 2	229.20	18.10	-11.64%	1657.42	182.08	-15.66%	1.20	0.84
Day 3	223.00	14.71	-14.03%	1732.87	245.00	-11.82%	2.80	2.49
Day 4	241.00	14.83	-7.09%	1837.68	144.14	-6.48%	1.60	1.67
Day 5	225.00	21.37	-13.26%	1642.80	257.20	-16.40%	0.80	1.10

It is further observed, that the time until all vehicles are at least picked up once is lowest for day 1 and increases for all following days. This can be explained by the fact that the vehicles might be located in areas with lower user demand after the first day. Additionally, two or more vehicles are sometimes located next to each other and it takes therefore longer until all of them are used for carsharing trips. It is thus shown that the initial vehicle placements of day 2 to 5 are not efficient for the carsharing operator. Figure 30 therefore presents the initial vehicle locations of day 2 to 5, which correspond to the end locations of the previous day, for one series of simulations over five days. It is visible, that more cars are located in the outer parts of the

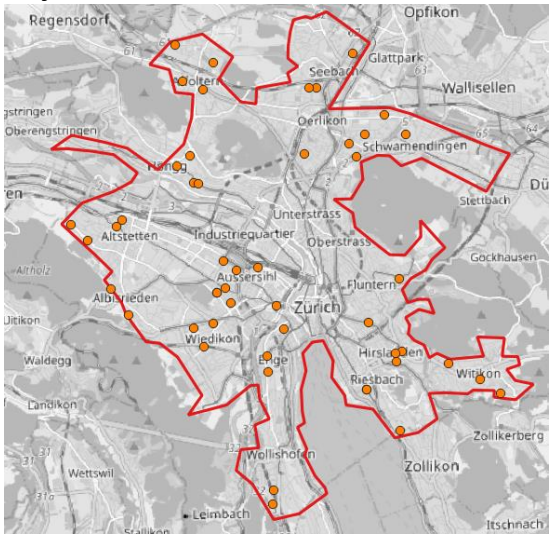
operating area and fewer vehicles are present in the areas, where the population density is high. Moreover, in most cases, several vehicles are located next to each other. These two factors might be reasons why the number of rentals is lower for the following days than it is on the first day.

Figure 30: Initial locations of the vehicles on day 2 to day 5 for the population density of people under 36 years scenario

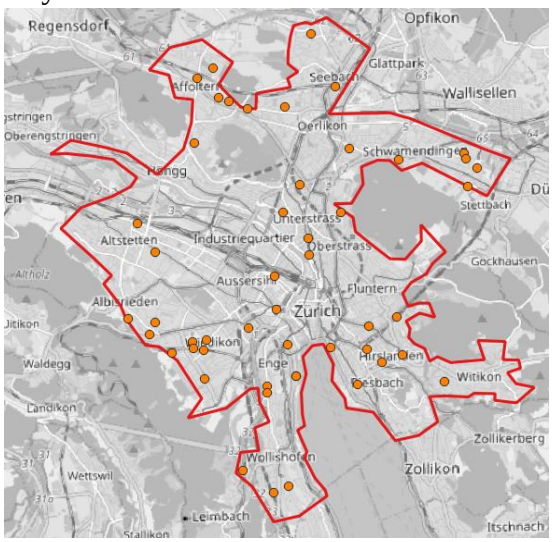
Day 2



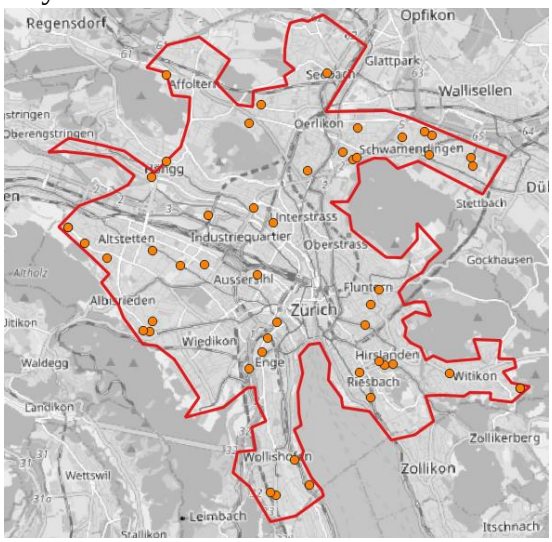
Day 3



Day 4



Day 5



Source: Background map: OpenStreetMap (2020)

As for this scenario, no increase in the revenue compared to day 1 is visible, a possible strategy would be to relocate the vehicles at the end of day 1 to their initial positions. An overview of the results of such a relocation performance can be seen in Table 17. On average, 29.20 vehicles would be relocated and a total distance of 63.55 km is needed to perform all vehicle relocations.

This results in a mean distance of 2.17 km per relocation. Furthermore, the access distance between two vehicles values on average 2.24 km and lasts about 9 min. For this scenario, half of the relocation distances lays beneath 1.7 km and only 25% of the relocations are conducted over a distance larger than 3 km. It is visible that on average the costs for the relocations amount to 129.05 CHF, which is lower than the additionally gained revenue of 307.65 CHF. This shows that relocations might be profitable for the operator as a net benefit of 178.60 CHF results what corresponds to approximately 11% of the revenue which would be gained on day 2 if no relocations are performed. Nevertheless, it needs to be kept in mind that the used algorithm includes several simplifications and especially only the air distances are taken into account. Thus, the real relocation distances, as well as the corresponding time and costs, are underestimated and relocations at the end of each day finally may not be profitable for the operator. Since the revenue of the following days never reaches again the level of day one, it is nevertheless recommended to perform relocations at some day during the week in order to reach a higher revenue level again. The operator could, due to reasons of profitability, decide not to perform relocations at the end of each day but for example always after two days in order to keep the costs lower.

Table 17: Main results for relocations at the end of day 1 of the scenario for initial vehicle placement according to population density of people under 36 years

Attribute	Mean	Standard deviation
Number of relocations	29.20	1.10
Relocation distance [km]	63.55	8.59
Access distance [km]	65.32	7.20
Total time [h]	5.94	0.67
Total costs [CHF]	129.05	14.59

5 Discussion and Outlook

5.1 Discussion of the results

In the past years, more and more carsharing providers decided to offer free-floating carsharing and this service type has become present in the whole world. Nevertheless, it is still unknown how the initial vehicle placement of a free-floating carsharing fleet influences the demand and the profitability of a carsharing service. Therefore, this thesis tries to analyse the impact of different vehicle locations at the start of a simulation day on the demand and the operator's revenue.

In this thesis, simulations are conducted using the transport simulation tool MATSim. The framework is applied to investigate the profitability of a free-floating carsharing service in the area of Zurich with an initial fleet size of 50 vehicles. To determine the impact of different initial vehicle placements, various scenarios are generated in which the vehicles are placed at different locations at the beginning of a simulation day. For the first simulations, the parameters in the discrete mode-choice model are set so that the free-floating carsharing service was quite attractive. In these simulations, the vehicles get used 28 times a day on average and the demand seemed to be relatively high. Nevertheless, differences could be observed for the different scenarios. It is shown that it is not favourable to initially place several vehicles at the same locations, as it takes longer until each of these vehicles is picked up once and is therefore available at other locations within the carsharing operating area. Furthermore, it is shown that initial vehicle placements according to the population density of a specific group are more attractive than a vehicle placement according to a regular grid since the revenue, as well as the number of rentals, are higher for these scenarios. In addition, the time until each vehicle is at least used once is lowest for these scenarios, meaning that the vehicles get picked up faster and the initial vehicles locations seem more attractive.

Nonetheless, the differences between the conducted scenarios are lower than they would have been expected. For example, the difference in revenue for the regular grid scenario and the scenario with initial vehicle placement according to the population density of people under 36 years only amounts to 3%. It is surprising how well the scenario with an initial vehicle placement according to a regular grid performed. As the number of rentals per vehicle with an average value of about 28 is relatively high, it is assumed that the demand within the operating area is high and that the vehicles get picked up almost independent of their location. One reason for this might be that a fleet size of 50 vehicles is too small for the number of potential users within the operating area as for example no membership is required and thus everybody

possessing a driver's licence can use the shared vehicles. Therefore, the vehicle fleet is enlarged to 500 vehicles to test how the influence of the initial vehicle placement behaves with a larger fleet size. The simulations are conducted with the regular grid and the population density scenario. Interestingly, for these simulations, the number of rentals is higher for the population density scenario, but the revenue reaches a higher value for the regular grid scenario. This shows, that apart from the potential demand, also the trip duration should be analysed in order to maximise the profit of a carsharing operator. The trip duration namely has a high influence on the profitability, since the fees are paid per carsharing trip minute. For the simulations with 500 free-floating carsharing vehicles, the demand is still relatively high and an average utilisation of 20 rentals per vehicle results. Compared to the scenarios with 50 vehicles, the number of rentals per vehicle decreases by approximately 30%. Nevertheless, the differences between the two scenarios are still low and the change in the revenue only equals to 2%. Moreover, the initial vehicle placement based on the population density again seems more attractive, as the vehicles are picked up faster for this scenario than for the initial vehicle placement according to a regular grid.

To create a more realistic free-floating carsharing demand, the parameters of the discrete mode-choice model are adjusted and the simulations are repeated with a less attractive carsharing service. The results of these simulations seem more appropriate as on average, each vehicle gets picked up about 5 times per simulation day. Furthermore, with the adjusted framework, larger deviations within the various initial vehicle placements occur, as for example, a difference in the revenue of 13.75% between the regular grid scenario and the scenario with initial vehicle placement according to the population density of people under 36 years. As the number of rentals peaks for this scenario as well and the mean time until each vehicle is at least used once reaches a minimum, this initial vehicle placement seems to perform the best of all suggested scenarios. Nevertheless, it should be mentioned that the number of rentals actually only increased by 7.9% compared to the previously discussed scenario and that the high increase of the revenue is also connected to the increase of the mean trip duration of 5.6%. A possible explanation for the good performance of this scenario is that 85% of people under 36 years do not possess a public transport pass. Therefore, it might be more attractive for them to use a free-floating carsharing vehicle than public transport. Besides, the differences between the regular grid scenario and the population density scenario increased as well and it is now shown that it is more profitable to place the vehicles in areas with higher population density rather than placing them according to a regular grid.

In summary, it is observed that the operator should bring the shared vehicles to the people who are potential users. This is shown by the fact that the scenarios, where the vehicles are initially placed according to the population density of a specific group, perform better than the regular

grid scenario. It is especially observed, that all vehicles are picked up faster if the vehicles are located at locations with high number of potential users. Furthermore, the vehicles should not be stored in areas where the travel demand might be high during the day, but lower in the morning. This is seen in the scenario with vehicle placements at railway stations within the operating area. If in the morning the vehicles are stored in areas, where many people travel to, the individuals cannot use a shared vehicle to access these places. Moreover, it is not recommended to locate several vehicles at the same location, as it takes longer until all of them get used. This can also be seen by the fact, that the scenarios with initial vehicle placement at the most frequented railway stations in Zurich or of all vehicles at Zurich main station perform worst.

Nonetheless, it needs to be kept in mind that free-floating carsharing trips can be ended wherever the user wants and the customers are not forced to park the vehicle at another carsharing station. Therefore, the impact of the initial vehicle placement is only directly present for the first rental of each vehicle. The efficiency and profitability of a free-floating carsharing service thus not only depend on the initial vehicle placement but on the trip destinations of the users as well. If for example, the first customer in the morning ends his carsharing trip in an area, where nobody else wants to start a carsharing trip, the vehicle could remain unused for the rest of the day. Hence, the corresponding service would be unprofitable even if the initial vehicle location could be appropriately chosen. This insight is supported by the obtained distribution of the number of rentals per vehicle which cover a wide range. Furthermore, it is visible that for different random seeds, not the same vehicles are used the most or less, but the distribution is completely different even if the vehicles have the same initial location. Additionally, it is observed that even if a vehicle gets picked up first in the morning, it does not necessarily correspond with the most used vehicle over the simulation day. After a rental, some vehicles remain unused for 5 or 6 hours while others get picked up again within minutes. In comparison, in one-way station-based carsharing systems, the placement of the stations influences all rentals conducted during a day, because the user needs to park the vehicle at a provided station. Thus, the placement of the stations might influence the transport mode choice of the agents and the one-way station-based carsharing demand during the simulation day is directly influenced by the locations of the stations. In summary, the influence of the initial vehicle placement might be lower for free-floating carsharing services than for station-based systems. Besides, the carsharing operator should consider during the day relocations in order to increase the profitability of its service as vehicles could be stored in areas with low carsharing demand.

To see if over-night relocations should be performed, simulations over five days are conducted for two different scenarios. In the regular grid scenario, an oscillation of the revenue can be

observed during the five days and it is shown that the relocation costs nearly reach the value of the additionally gained revenue. If all costs caused by the relocations are taken into account, the additional revenue may even be exceeded. This shows that relocations can be unfavourable even if the number of rentals increases through them. For this first scenario, it thus might not be profitable to relocate the vehicles to a regular grid because this initial vehicle placement was not the best one that occurred over the five days. In contrast, for the scenario with initial vehicle placement according to the population density of people under 36 years, the revenue reaches its maximum for the first day and is lower for all following days. Thus, the used initial vehicle location for the first day seems to be the most profitable of the five days. In addition, the established relocation costs are lower than the additional revenue, meaning that in this case, it is profitable for the operator to perform relocations. It should still be mentioned that the algorithm used to determine the relocation costs, includes many simplifications and assumptions. The most important simplification is that the distances between the actual vehicle location and the relocation destination are measured as straight air distances. The real travelled distances during the vehicle relocations are therefore larger and more time might be needed to perform the relocations. This would result in higher relocation costs and it might not be profitable anymore to perform the relocations. Furthermore, the proposed algorithm does not include depreciation or maintenance in the cost calculation and the average speed during the relocations is considered to be 40 km/h. This speed might be too high for relocations in the inner part of the city of Zurich and further research should investigate the relocation speed more precisely. Besides, the salary level of 20 CHF/h is quite low for night-time work and the relocation costs increase with a higher salary.

Besides, the operator should not only consider over-night relocations, but test relocations during the day as well. As mentioned above, even if the initial vehicle locations are wisely chosen, an unprofitable service can be developed if the users end their trips in areas with low carsharing demand. Therefore, it should be investigated how the carsharing service can be improved with relocations during the day.

At last, it needs to be said that the results of the simulations are only valid for the chosen initial vehicle distributions. If for example the zone division within the operating area is chosen differently or the vehicles are even just slightly placed at another location within a given zone, the outcome of the simulations could change drastically. As mentioned before, this is explained by the fact that the performance of the carsharing service also depends on the users' trip destinations. If a vehicle is now placed at a slightly different location in the morning, another user might pick it up and the trip destination of this customer could be different. Therefore, the rentals over the whole day might differ from the ones of the conducted simulations and the

utilisation of the carsharing service could generate different results even if the initial vehicle locations are only changed slightly.

5.2 Suggested improvements

The performed simulations included some simplifications which do not represent the real world. These aspects nevertheless influence the free-floating carsharing demand and are therefore discussed as possible improvements for further studies.

In the conducted simulations, all persons with a driving licence are allowed to use the free-floating carsharing fleet. In reality, this is not the case and a membership of the corresponding carsharing operator is required to perform a carsharing trip. This membership requirement can influence the carsharing demand as the number of potential users decreases. Furthermore, specific parts of the population might be more openminded about a membership than others. This could influence the demand and the success of an initial vehicle placement could change if a membership is required for the carsharing service. Thus, further research should include a membership requirement for the free-floating carsharing service and investigate the occurring effects.

In the used framework, the agents who perform a carsharing trip can end their trip wherever they want and no parking restriction is applied. This means that the users do not need to park their vehicle on a public parking space but they can leave the car right next to their trip destination location. This is an advantage compared to the real world as no egress walk occurs which makes the total travel time shorter. If the vehicles need to be parked at public parking locations, the demand could change as the access walk distance and time might increase as well. Therefore, further investigations should include parking restrictions so that free-floating carsharing trip can only end in areas where public parking spaces are available. Nevertheless, also for trips with private cars no parking search time is considered and therefore, this impact is neglected for both, free-floating carsharing trips and trips with private cars.

Moreover, the used discrete mode-choice model does not consider the income of an agent in the decision for a specific transport mode. Nevertheless, previous research states that this factor plays an important role and the demand for the free-floating carsharing service might change if the income is considered. People with a higher income would probably more likely take a transport mode with a higher price than people with low income. Thus, further research should try to include the income in the transport mode decision process and analyse how the demand and the profitability of free-floating carsharing are influenced by this factor. Furthermore, it is shown that the parameters chosen for the discrete mode-choice model have a high influence on

the demand and the revenue of the free-floating carsharing service. It should therefore be investigated which parameters best represent reality and further investigations should be conducted with these parameters.

Additionally, in the simulations only one free-floating carsharing provider offers carsharing. In the real-world, most often more than one company operates within a city, or a carsharing provider offers different carsharing service types in addition to the free-floating carsharing as for example one-way station-based or round-trip carsharing. These offers can influence the demand for free-floating carsharing as they are probably cheaper than free-floating carsharing. However, they might have the same potential users. Nevertheless, they do not offer the same flexibility as the free-floating carsharing service. For further research, it would be interesting to see how multiple carsharing operators influence each other and especially how the presence of different carsharing service types impacts the demand of a free-floating carsharing service in Zurich. The impact of two competing free-floating carsharing providers is already investigated in Balac et al. (2019).

Furthermore, the used initial vehicle locations are only generated according to social-demographic patterns or according to the geographical locations of railway stations. It should be further investigated how the demand is distributed among the operating area. Previous research, for example, uses the data of taxi customers to detect where the demand for a carsharing service might be high. Another approach would be to analyse the data of already existing carsharing operators to investigate the areas with higher demand.

To see if relocations overnight are profitable for the operator, further research should be conducted to develop an algorithm which considers all arising relocation costs as the simplified code used in this thesis only takes the salary of the relocation agents and the fuel costs into account. The algorithm should be expanded so that the real distances and times needed to perform a relocation can be determined. Up to now the code only included the air distances within two locations. Furthermore, it should be defined at which time point in the night the relocations are performed. In the used framework, a simulation day lasts 30h, which means that it ends at 6 am of the following day. This implementation is applied because there are agents whose daily activities end after midnight. Nevertheless, if simulations over several days are conducted, it could happen that for the following day, an agent already picks up a vehicle in the morning even before the car is parked at the given locations in the previous day. Nonetheless, it is checked that in the conducted simulations this actually only happened five times for one vehicle and that the effect is therefore not taken into account since it is low compared to the total number of rentals.

A further suggestion is to combine user-based and operator-based relocations in order to reduce the relocation costs. User-based relocations could be pursued, which offer incentives to the carsharing customers. Additionally, operator-based relocations could be performed in areas, where the user-based strategy does not show the desired effects. Furthermore, vehicle relocations should not only be considered during the night but during the day as well, as the simulations show, that the trip destination plays an important role on how fast a vehicle gets picked up again.

Besides, the used framework only includes one simulation day. This means that even if simulations are conducted in a series over five days, the agents do always have the same daily plan for each simulation. This does not represent reality as especially the leisure time is not filled with the same activities for each day. In addition, the simulation framework does not include weekends on which the daily plans of the agents are largely different from the ones during the working days. As previous research detected that the most deviations between vehicle supply and user demand occur within the vehicles' location on Sunday evening and the carsharing demand on Monday morning, it is suggested that further research should try to include daily activities for the weekend as well.

6 Conclusion

First of all, this thesis describes the main differences between the various existing carsharing service types. In the following sections, the focus lies on the free-floating carsharing service, where an imbalance between the user demand and the vehicle supply is likely to occur. In a literature review, different approaches to the solution of the relocation problem are analysed. Furthermore, the literature investigation showed that no study focused yet on the fact of the initial vehicle placement of free-floating carsharing services. Hence, previous work on this topic is discussed for one-way station-based carsharing.

In the following parts, simulations are conducted with the transport simulation tool MATSim in order to investigate the impact of the initial vehicle placement of a free-floating carsharing service in the operating area of Zurich. It concludes, that it is not wise to locate too many vehicles at the same initial location but to find locations where the vehicles can get picked up early. Besides, it results, that the scenarios, where the vehicles are distributed according to the population density of a specific group perform best. This shows that the vehicles should initially be placed at locations with high potential users. Furthermore, the cars should be placed at locations where individuals start trips in the morning and not at places, where the travel demand just increases during the day. A further insight is that the profitability of a free-floating carsharing service not only depends on the number of rentals but on the travel time as well, as the fees are only charged per trip minute. Further research should investigate the potential demand of a free-floating carsharing service in Zurich and the behaviour of the users should be analysed to determine the optimal initial vehicle locations.

Nevertheless, it should be kept in mind that the initial vehicle placement in the morning only directly affects the first rental of each vehicle, as afterwards, the vehicle is located at the trip destination of the first customer. Therefore, the influence of the initial vehicle placement for free-floating carsharing services might be lower than the stations' locations in one-way station-based carsharing services.

The development of five simulation days in a series shows that over-night relocations might be favourable for the operator, as in one scenario, the revenue decreased after the first day and never reached the same profitability level again. Nevertheless, the provider needs to consider the costs of relocations and estimate if the performance of relocations is profitable. Relocations might thus not be profitable, even if the number of rentals can be increased. Since only a simple algorithm is developed to roughly estimate the relocation costs, it is suggested to develop a more accurate method to see if over-night relocations are profitable for the operator.

7 Reference list

Awatshi, A., D. Breuil, S. Chauhan, M. Parent and T. Reveillere (2007) A multicriteria decision making approach for carsharing stations selection, *Journal of Decision Systems*, **16(1)**, 57-78.

Balac, M, H. Becker, F. Ciari and K. Axhausen (2019) Modelling competing free-floating carsharing operators – A case study for Zurich, Switzerland, *Transportation Research Part C*, **98**, 101-117.

Balac, M., F. Ciari and K. Axhausen (2017) Modeling the impact of parking price policy on free-floating carsharing: Case study for Zurich, Switzerland, *Transportation Research Part C*, **77**, 207-225.

Becker, H., F. Ciari and K. Axhausen (2017) Comparing car-sharing schemes in Switzerland: User groups and usage patterns, *Transportation Research Part A*, **97**, 17-29.

Car2go (2017) car2go insights: Do you know: What a "relocation" is and which car2gos are relocated?, https://blog.car2go.com/2017/06/26/know-relocation-car2gos-relocated/, March 2020.

Car2go (2020) car2go Tarife: Alles inklusive, https://www.car2go.com/DE/de/berlin/costs/, March 2020.

Carsharing.at (2019) ShareNow – die Zukunft hat begonnen, https://carsharing.at/share-now-die-zukunft-hat-schon-begonnen/, March 2020.

Changaival, B., G. Danoy, D. Kliazovich, F. Guinand, M. Brust, J. Musial, K. Lavangnananda and P. Bouvry (2019) Toward Real-World Vehicle Placement Optimization in Round-Trip Carsharing, *Proceedings of the Genetic and Evolutionary Computation Conference*, Prague, 2019.

Ciari, F., C. Weis and M. Balac (2015) Evaluating the influence of carsharing stations' location on potential membership: a Swiss case study, *EURO Journal on Transportation and Logistics*, **5(3)**, 345-369.

Correia, G. and A. Antunes (2012) Optimization approach to depot location and trip selection in one-way carsharing systems, *Transportation Research Part E: Logistics and Transportation Review*, **48(1)**, 233-247.

Daimler (2018) Flexible Preise für eine höhere Verfügbarkeit: car2go führt neues Preisschema ein, https://media.daimler.com/marsMediaSite/de/instance/ko/Flexible-Preise-fuer-eine-hoehere-Verfuegbarkeit-car2go-fuehrt-neues-Preisschema-ein.xhtml?oid=41934089, March 2020.

Efthymiou, D., C. Antoniou, Y. Tyrinopoylos and E. Mitsakis (2011) Spatial Exploration of Effective electric vehicle infrastructure location, *Transport Research Arena – Europe 2012*, 1–10.

Febbraro, A., N. Sacco and M. Saeednia (2012) One-way carsharing: solving the relocation problem, *Transportation Research Record: Journal of the Transportation Research Board*, **2319**, 113–120.

Getaround (2019) Getaround becomes global carsharing leader with $300 million acquisition of European platform Drivy, https://www.getaround.com/press/library/2019/4/24-Getaround-Announces-300M-Acquisition-of-European-Platform-Drivy, March 2020.

Hampshire, R. and C. Gaites (2011) Peer-to-peer carsharing: Market analysis and potential growth, *Transportation Research Record: Journal of the Transportation Research Board*, **2217**, 119-126.

Heilig, M., N. Mallig, O. Schröder, M. Kagerbauer, P. Vortisch (2017) Implementation of free-floating and station-based carsharing in an agent-based travel demand model, *Travel Behaviour and Society*, **12**, 151-158.

Herbawi, W., M. Knoll, M. Kaiser and W. Gruel (2016) An Evolutionary Algorithm for the Vehicle Relocation Problem in Free Floating Carsharing, *2016 IEEE Congress on Evolutionary Computation (CEC)*, Vancouver, 2016, 2873-2879.

Hörl, S., M. Balac and K. Axhausen (2018) A first look at bridging discrete choice modelling and agent-based microsimulation in MATSim, *Procedia Computer Science*, **130**, 900-907.

Hörl, S., M. Balac and K. Axhausen (2019) Pairing discrete mode choice models and agent-based transport simulation with MATSim, *98th Annual Meeting of the Transportation Research Board*, Washington D. C., 2019.

Hörl, S., F. Becker, T. Dubernet and K. Axhausen (2019) Induzierter Verkehr durch autonome Fahrzeuge: Eine abschätzung, Forschungsprojekte SVI 2016/001, *Schriftenreihe*, **1650**, UVEK, Bern.

Horni, A., K. Nagel and K. Axhausen (eds.) (2016) *The Multi-Agent Transport Simulation MATSim*, Ubiquity Press, London.

Illgen, S. and M. Höck (2019) Literature review of the vehicle relocation problem in one-way car sharing networks, *Transportation Research Part B*, **120**, 193-204.

Jorge, D. and G. Correia (2013) Carsharing systems demand estimation and defined operations: a literature review, *EJTIR*, **13(3)**, 201–220.

Kumar, P. and M. Bierlaire (2012) Optimizing locations for a vehicle sharing system, Swiss Transport Research Conference.

Li, W., Y. Li, J. Fan and H. Deng (2017) Siting of Carsharing Stations Based on Spatial Multi-Criteria Evaluation: A Case Study of Shanghai EVCARD, *Sustainability*, **9(1)**, 152.

Martinez, L., G. Correia, F. Moura, M. Lopes (2017) Insights into carsharing demand dynamics: Outputs of an agent-based model application to Lisbon, Portugal, *International Journal of Sustainable Transportation*, **11**, 148-159.

Mobility Genossenschaft (2020a) Go: Mobility-Go kurz erklärt, https://www.mobility.ch/de/go/so-funktionierts/, March 2020.

Mobility Genossenschaft (2020b) One-way: Einwegfahrten zwischen fix definierten Standorten, https://www.mobility.ch/de/one-way/standorte/, March 2020.

Mobility Genossenschaft (2020c) Return: Von klein bis gross: 2'890 Autos in verschiedenen Kategorien, https://www.mobility.ch/de/return/fahrzeuge/, March 2020.

OpenStreetMap (2020), OpenStreetMap in QGis, https://www.openstreetmap.org/, March 2020.

Paschke, S., M. Balac and F. Ciari (2016) Implementation of vehicle relocation for carsharing services in the multi-agent transport simulation MATSim, *Arbeitsberichte Verkehrs- und Raumplanung*, **1188**, Institut für Verkehrsplanung und Transportsysteme (IVT), ETH Zürich, Zürich.

Santos, A., P. Cândido, A. Balardino and W. Herbawi (2017) Vehicle Relocation Problem in Free Floating Carsharing Using Multiple Shuttles, *2017 IEEE Congress on Evolutionary Computation (CEC)*, San Sebastian, 2017, 2544-2551.

Shaheen, S., N. Chan and H. Micheaux (2015) One-Way Carsharing's Evolution and Operator Perspectives form the Americas, *Transportation*, **42**, 519-536.

Shaheen, S. and P. Cohen (2007) Growth in worldwide carsharing: An International comparison, *Transportation Research Record: Journal of the Transportation Research Board*, **1992**, 81-89.

Shaheen, S. and P. Cohen (2012) Carsharing and Personal Vehicle Services: Worldwide Market Developments and Emerging Trends, *International Journal of Sustainable Transportation*, **7**, 5-34.

Shaheen, S., E. Martin and A. Bansal (2018) Peer-to-Peer (P2P) Carsharing Understanding Early Markets, Social Dynamics and Behavioral Impacts, University of California Transportation Center.

Share Now (2020) Länder: Wähle dein Land, https://www.share-now.com/de/de/country-list/, March 2020.

Sharoo (2020) sharoo Vermieter werden, https://www.sharoo.com/vermieter-werden/, March 2020.

Sai, Q., J. Bi and J. Chai (2020) Optimal Model for Carsharing Station Location Based on Multi-Factor Constraints, *Algorithms*, **13(2)**, 43.

Weikl, S. and K. Bogenberger (2013) Relocation strategies and algorithms for free-floating carsharing systems, *IEEE Intelligent Transportation System Magazine*, **5 (4)**, 100-111.

Weikl, S. and K. Bogenberger (2015) A practice-ready relocation model for free-floating carsharing systems with electric vehicles – Mesoscopic approach and field trial results, *Transportation Research Part C*, **57**, 206-223.

Yu, Y., J. Zhang and J. Li (2017) A new site location approach based on Filtering and Clustering for car sharing system, *Advances in Computer Science Research*, **71**, 1094-1099.

Zipcar (2020) Zipcar Locations, https://www.zipcar.com/cities, March 2020.

A Appendix

A 1 Results for the accessibility approach of the initial vehicle placement

Table 18: Main results for initial vehicle placement according to the population density with accessibility approach

Attribute	mean	standard deviation	Deviation from reference scenario
Number of rentals	1402.80	38.01	0.01%
Total distance travelled	4041.02	204.59	1.86%
Mean distance travelled [m]	2880.94	129.10	1.90%
Total trip duration [s]	776447.00	44809.63	5.94%
Mean trip duration [s]	553.32	23.80	5.89%
Mean access time [s]	218.56	2.55	0.83%
Mean time until each vehicle is at least used once [h]	7.53	1.85	-2.60%
Revenue [CHF]	5176.31	298.73	5.94%

Table 19: Main results for initial vehicle placement according to the income with accessibility approach

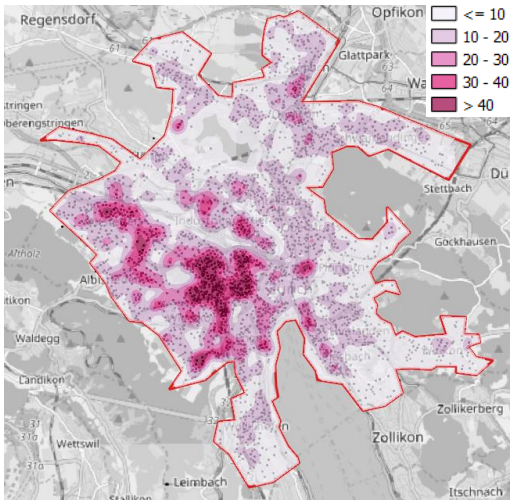
Attribute	mean	standard deviation	Deviation from reference scenario
Number of rentals	1408.80	40.55	0.44%
Total distance travelled [km]	4070.33	130.66	2.60%
Mean distance travelled [m]	2889.23	43.47	2.20%
Total trip duration [s]	795818.00	40643.18	8.58%
Mean trip duration [s]	565.20	32.16	8.16%
Mean access time [s]	218.01	2.50	0.57%
Mean time until each vehicle is at least used once [h]	6.42	0.36	-16.92%
Revenue [CHF]	5305.45	270.95	8.58%

Table 20: Main results for initial vehicle placement according to the population density of people under 36 years with accessibility approach

Attribute	mean	standard deviation	Deviation from reference scenario
Number of rentals	1415.40	34.82	0.91%
Total distance travelled [km]	3944.27	138.16	-0.57%
Mean distance travelled [m]	2786.77	73.24	-1.43%
Total trip duration [s]	758348.00	51101.82	3.47%
Mean trip duration [s]	535.57	28.97	2.49%
Mean access time [s]	216.70	0.73	-0.03%
Mean time until each vehicle is at least used once [h]	7.58	2.07	-1.93%
Revenue [CHF]	5055.65	340.68	3.47%

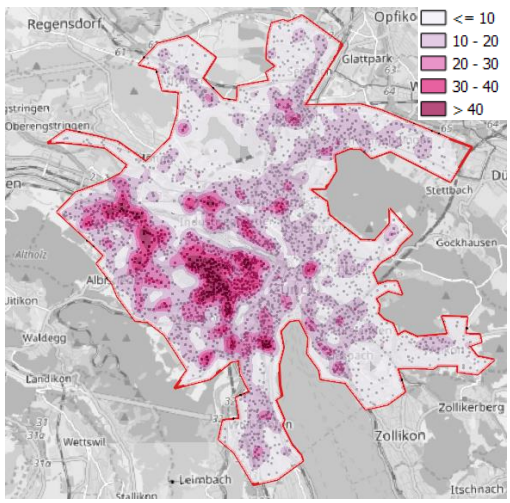
A 2 Pick-up locations for different scenarios

Figure 31: Spatial distribution of pick-up locations for vehicle placement according to the income



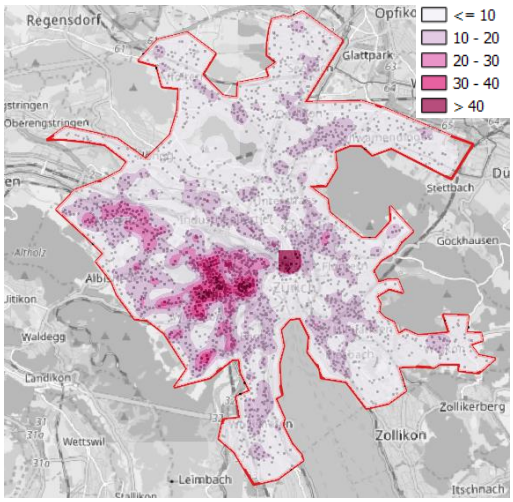
Source: Background map: OpenStreetMap (2020)

Figure 32: Spatial distribution of pick-up locations for vehicle placement according to the population density of people under 36 years



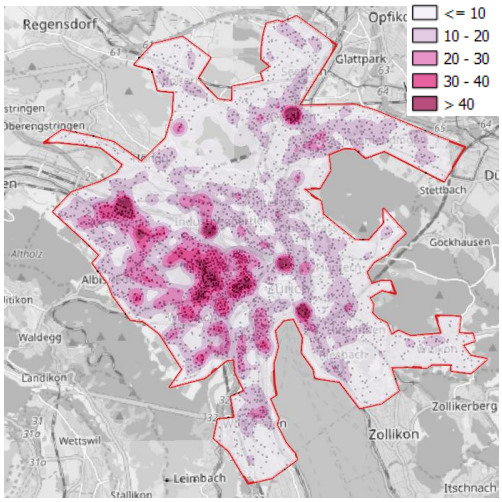
Source: Background map: OpenStreetMap (2020)

Figure 33: Spatial distribution of pick-up locations for all vehicles initially placed at Zurich main station



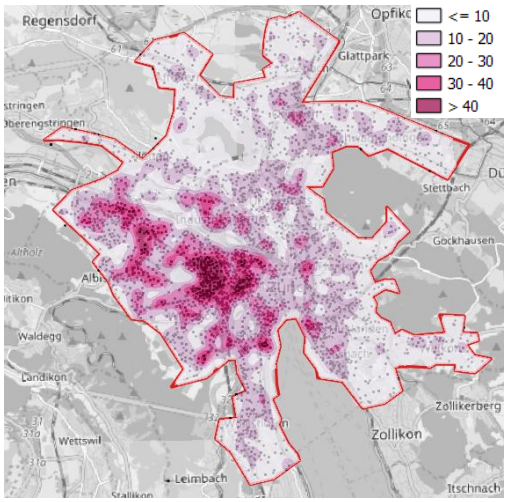
Source: Background map: OpenStreetMap (2020)

Figure 34: Spatial distribution of pick-up locations for vehicle placement at the most used railway stations in Zurich



Source: Background map: OpenStreetMap (2020)

Figure 35: Spatial distribution of pick-up locations for vehicle placement according to a regular grid



Source: Background map: OpenStreetMap (2020)

A 3 Diagram of number of rentals against first rental start time

Figure 36: Number of rentals against first rental start time for placement according to a regular grid

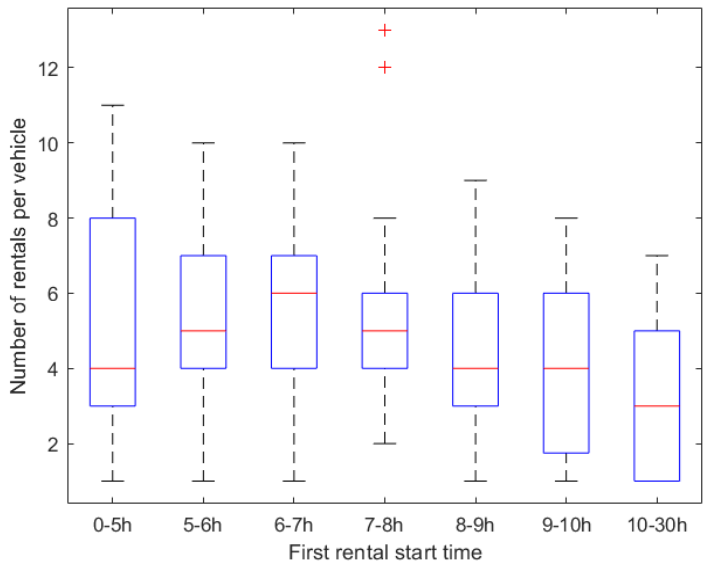
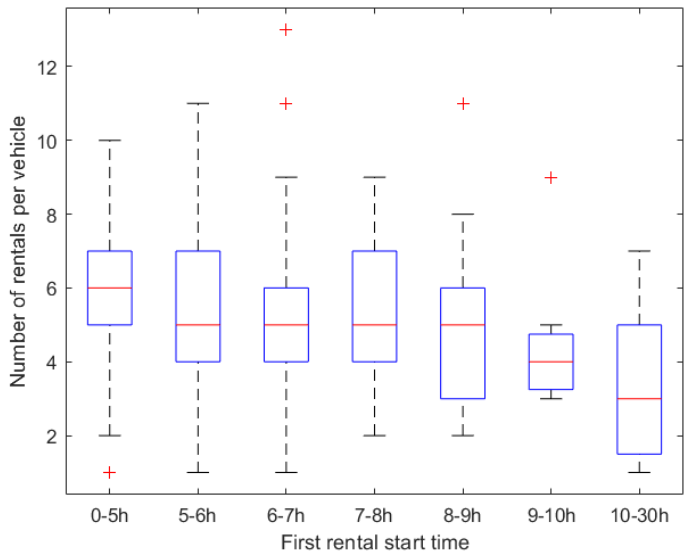


Figure 37: Number of rentals against first rental start time for placement according to the population density



A 4 Histogram of rental start times for less attractive carsharing service

Figure 38: Histogram of rental start times for placement according to a regular grid for less attractive carsharing service

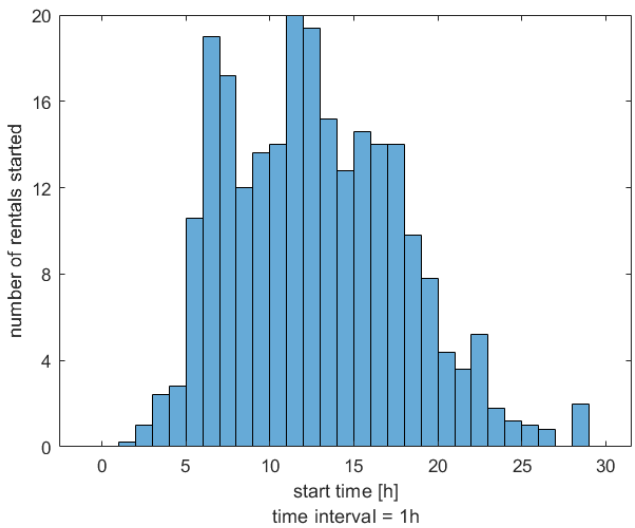
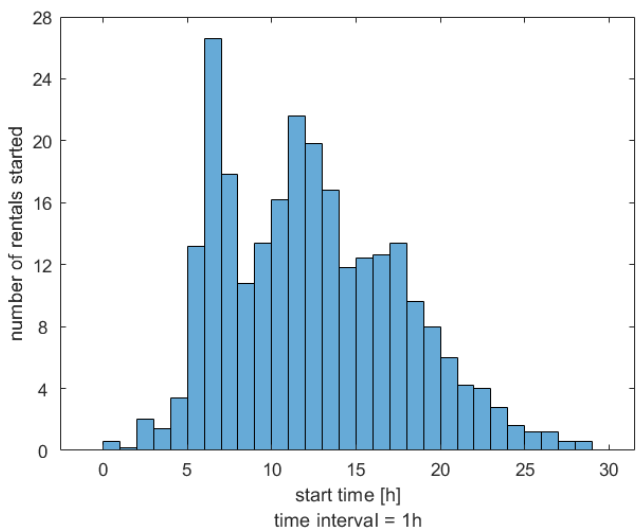


Figure 39: Histogram of rental start times for placement according to the population density for less attractive carsharing service



A 5 Matlab code for the relocation performance

```
clear all; clc;
%coordinates, of the vehicle locations at the start of the day = relocation destination
coord_loc = [
    x_loc1    y_loc1
    ...
    x_loc50   y_loc50
 ];

% coordinates where vehicles are located at the end of the day
coord_veh = [
    x_veh1    y_veh1
    ...
    x_veh50   y_veh50
];

% Matrix with distance between each vehicle at the end of the day to each
% possible relocation destination = location in the morning
% vehicle_ID of end coord vehicle = matrix line
% location ID of suggested relocation destination = matrix column
% initially all set to 0
distance=zeros (50,50);

% vector which defines if a vehicle is already relocated to this location:
% 0= still free, 1 = vehicle relocated to this location
loc_used=zeros(1,50);

% vector which defines if a vehicle has already been relocated:
%0 = not relocated yet, 1 = relocated
vehicle_used=zeros(1,50);

% vector which defines which vehicle is relocated to which station:
% vehilce_ID = row number, relocation destination = element in row,1
relocation_loc=zeros(50,1);

% vector which defines, whether a relocation has taken place or not
% vehicle ID = row_number; 0 = not conducted yet; 1 = relocation conducted
relocation_cond=zeros(50,1);

% calculate distance of each vehicle at the end of the day to all possible
% relocation destinations: i = vehicle_ID; k=location_ID
for i=1:50
    for k=1:50
        distance(i,k) = sqrt((coord_veh(i,1)-coord_loc(k,1))^2+(coord_veh(i,2)-coord_loc(k,2))^2);
        k=k+1;
    end
    i=i+1;
end


% check if relocation to a station is necessary: not necessary, if a
% vehicle is located closer than 500m to a possible location and no other
% vehicle is located closer to the given location
% i = initial location number (according to coord_loc); k = vehicle ID (according to coord_veh)
% copy_dis = copy of distance. The distance will be set to a high value,
% if the station location or the vehilce is used

copy_dis=distance;

% sort distances for all location to vehicles: shortest distance at top, longest distance at bottom
min_loc_dis=sort(distance);
```

```
% detects which vehicles do not need to be relocated --> sets the distance
% to a high value if no relocation needed, matches the relocation
% destination and the vehicle and sets the vehicle_used to 1 and the
% loc_used to 1
for j=1:50
    short=min_loc_dis(j,:);                % matrix with the ith-shortest distance for each location to an vehicle
        for m=1:50
            dis_short=min(short);                % finds the shortest distance available
            [i,k]=find(distance==dis_short);     % vehicle i and location k which have the shortest distance available
            pos=find(short==dis_short);          % finds the position of the shortest distance in the matrix A
            z=size(i); y=z(1,1);
            i1=i(1,1); k1=k(1,1);

            if y>1 && vehicle_used(1,i1)== 0
                i=i(1,1); k=k(1,1);
            else
                if y>1
                i=i(2,1); k=k(2,1);
                end
            end

            % matches vehicle and relocation destination and marks vehicle
            % and destination as used
            if dis_short<500 && vehicle_used(1,i)==0 && loc_used(1,k)==0
                vehicle_used(1,i)=1;
                loc_used(1,k)=1;
                relocation_loc(i,1)=k;
                relocation_cond(i,1)=1;

                % sets the distance from the vehicle k to all destinations to
                % a high value
                % sets the distance from the destination j to all vehicles
                % to a high value
                for h=1:50
                        copy_dis(i,h)=100000000000;
                        copy_dis(h,k)=100000000000;
                        h=h+1;
                end
            end
            % sets the distance in A to a high value so that it is not used
            % again as minimal distance
            short(1,pos)=1000000;
            m=m+1;
        end
        j=j+1;
end

%counts how many vehicles are already relocated
sum_rel=sum(vehicle_used);

% determines which vehicle is located to which location:
% always takes the vehicle-location pair with the minimal distance of all
% pairs and defines a relocation to them.
% If a pair is assigned, the distance of vehicle and the location
% to all other locations/vehicles are set to a high value to make sure
% that no other relocation takes place to this location / from the vehicle.
% continue with this approach until a destination location is assigned to
% all vehicles
```

```
while sum_rel < 50
    min_act=min(copy_dis(:));              % actual minimal distance
    [i,k]=find(copy_dis == min_act);       % actual vehicle i and location k
    z=size(i); y=z(1,1);
    i1=i(1,1);
    if y>1 && vehicle_used(1,i1)== 0
        i=i(1,1); k=k(1,1);
    else if y>1
            i=i(2,1); k=k(2,1);
        end
    end

   if vehicle_used(1,i)== 0 && loc_used(1,k) == 0
        vehicle_used(1,i)=1;
        loc_used(1,k)=1;
        relocation_loc(i,1)=k;
        for h=1:50
           copy_dis(i,h)=100000000000;
           copy_dis(h,k)=100000000000;
           h=h+1;
        end
   end
    sum_rel=sum(vehicle_used);

end


% calculate order of relocations and distance between all relocations


% determine start vehicle (chosen to be the vehicle with the highest
% x-coordinate)
start=0; x_start=0;
for i=1:50
    if coord_veh(i,1) > x_start && relocation_cond(i,1)==0;
        start = i;
        x_start=coord_veh(i,1);
    end
end

%determine order of relocations

con=sum(relocation_cond);    % number of relocations conducted
act=start;                 % actual relocation (vehicle_ID)
min_dis=1000000;           % set minimum distance between previous relocation destination and
                           % next relocation start location to a large number
order=zeros(1,50);         % order of relocations: vehicle_ID in order position
order(1,1)=start;
rel_numb=1;                % at which relocation are we?
relocation_cond(act,1)=1;    % first relocation conducted
```

```
% determine which vehicle should be relocated as next vehicle
% the minimum distance between the previous relocation destination and
% the next relocation start point is minimized
while con < 50
    rel_numb=rel_numb+1;
    loc = relocation_loc(act);
    for i=1:50
        if relocation_cond(i,1)==0
            dis = sqrt((coord_loc(loc,1)-coord_veh(i,1))^2+(coord_loc(loc,2)-coord_veh(i,2))^2);
            if dis < min_dis
                min_dis=dis;
                act_it=i;
            end
        end
        i=i+1;
    end
    act=act_it;
    relocation_cond(act,1)=1;
    order(1,rel_numb)=act;
    con=sum(relocation_cond);
    min_dis=1000000;
end

%calculate number of relocations conducted = n
n=0;
for i=1:50
    if order(1,i) > 0
        n=n+1;
    end
    i=i+1;
end

% calculate total relocation distance tot_d
% r = location where vehicle_act is located to
% distance for this relocation = d
tot_d=0;
rel_distance=zeros(1,n);        % matrix with all relocation distances

for i=1:n
    veh_act=order(1,i);
    r=relocation_loc(veh_act,1);
    d = sqrt((coord_veh(veh_act,1)-coord_loc(r,1))^2+(coord_veh(veh_act,2)-coord_loc(r,2))^2);
    tot_d=tot_d+d;
    rel_distance(1,i)=d;
end

% determine distance travelled between previous relocation destinations and
% next relocation start points
tot_dist_bet=0;

% vehicle which is relocated = veh_act_ord
% relocation destination = rel
% next vehicle to relocate = next

for i=1:n-1
    veh_act_ord=order(1,i);
    rel=relocation_loc(veh_act_ord,1);
    next=order(1,i+1);
    dist = sqrt((coord_loc(rel,1)-coord_veh(next,1))^2+(coord_loc(rel,2)-coord_veh(next,2))^2);
    tot_dist_bet=tot_dist_bet+dist;
    i=i+1;
end
```

```
% calculate time needed to cover the distance between the relocations for
% an agent travelling by bicycle with an average velocity of 15 km/h

time_bet=tot_dist_bet/1000/15;

%calculate time needed to conduct vehicle relocation with a average
%velocity of 40km/h

time_rel=tot_d/1000/40;

%calculate total time needed for relocations

time=time_bet+time_rel;

% calculate loan of relocation agent for the relocation time with a loan of
% 20CHF/h
loan=time*20;

%calculate costs for relocation (fuel price = 1.60/l ; 10 l fuel/100km needed)
% --> 0.16 CHF/km

fuel=0.16*tot_d/1000;


% calculate total costs
costs=loan+fuel;
```