2012 15th International IEEE Conference on Intelligent Transportation Systems
Anchorage, Alaska, USA, September 16-19, 2012

Relocation Strategies and Algorithms for free-floating Car Sharing Systems

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Abstract*—During the last two years so-called free-floating Car Sharing Systems became very popular. These systems in comparison to the conventional Car Sharing Systems allow short one-way trips. Today, the spatial distribution of vehicles within free-floating Car Sharing Systems is either self-organized, which means it is only dependent on the customer's demand or in a few cases the positioning is manually controlled by system operators. None of the known free-floating Car Sharing Systems has a clear defined relocation strategy or is online optimized based on the current demand. Within this paper several relocation strategies are introduced and categorized. For each category a relocation algorithm is described and evaluated. Also a new integrated two-step algorithm for optimal positioning and strategy selection is described in detail. This new approach consists of an offline demand clustering that allows for strategy pre-selection. The online module of the approach measures the differences between optimal vehicle positioning and current positioning and selects the best relocation strategy for implementation.

I. INTRODUCTION

During the last decades, Car Sharing emerged as a new type of mobility services. The idea of *sharing a car* was first realized by *Carpooling*, which was used as a rationing tactic in the US during World War II and later on organized professionally by the first carpooling organization SEFAGE in Zurich in 1948. A second wave followed due to the oil and energy crisis in the 1970s, when the first employee vanpools were established and the sharing of vehicles was organized in car clubs and neighborhood groups. Today, the whole process is simplified by the internet and mobile technology and hence, new forms of sharing cars emerge. For instance, now Carpooling is organized on internet platforms operating as bulletin boards for (one-way-)trips offered by car owners/drivers. Internet platforms are also used by car owners for providing their private cars to others. This form of sharing vehicles allows round-trips only. Most of the developments can be observed in the area of professionally organized Car Sharing by so called mobility providers, who offer different vehicles at different places assuring a high variety and a good maintenance. At first, only station based systems were implemented with vehicles available at fixed stations, e.g. at rented parking lots or garages. The booking of the vehicles had to be carried out before usage and the mandatory return of the vehicles to the initial station didn't allow one-way-trips. A disadvantage compared to rental cars, with which also one-way-trips are possible, remained. Therefore, later more flexibility was provided by *one-way* Car Sharing Systems, which also accepted returns at other stations in a specific parking zone or in a given region. During the last years, new *free-floating* systems came up. The provider usually defines a certain business district, mostly the city center and therein buys on-street parking licenses for each vehicle of his fleet. Thus, the return of the vehicles is possible on any parking spot within the district and the customer is not bound to stations anymore allowing for short one-way-trips. Mostly, the pricing model includes a starting fee and a time-dependent price function. Some providers have established additional charges, if the journey is finished outside of the district and reduced prices for parking periods. Those new systems, which don't require a booking in advance, make the usage of Car Sharing more flexible and spontaneous. Nevertheless, they still have their weaknesses. The principle of having a *car to go* and providing mobility on demand is not yet guaranteed due to bottlenecks in supply, which are currently not eliminated. Vehicles sometimes get stuck in areas of lower individual mobility demand (*cold spots*) while needed in zones of higher demand (*hot spots*). To make the system even more efficient and more profitable, this imbalance of supply and demand could be adjusted by applying different intervention strategies. A similar problem also emerges in the field of bike sharing where relocation methods were developed in the past (cp. e.g. [1],[4],[5]). However, the relocation of bicycles is easier than the one of cars. Up to 60 bicycles can be transported altogether to hot spots on a bicycle carrier, which saves costs and is relatively uncomplicated. In contrast, Car Sharing vehicles have to be reallocated separately or on a car transporter by high costs. This makes effective strategies even more important.

During the last years, a vision among a group of scientists of completely substituting car ownership by other efficient mobility concepts developed. This idea emerged above all due to the exploding number of vehicles on the streets, the resulting shortages in parking space, congestion and environmental problems. In this context, the term *cloud commuting* (cp. [6]) was found according to other goods like vinyl's or CD's, which have been replaced by real-time and on-demand access in the past. As providing vehicles is much more complex than e.g. providing music via the internet, efficient and cost-effective ways have to be invented.

This paper at first describes different relocation strategies for free-floating Car Sharing Systems and compares them. They are grouped into two different approaches: user-based and operator-based approaches. Later on, specific relocation algorithms for Car Sharing Systems are introduced. Finally, a

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new two-step algorithm for free-floating Car Sharing Systems is introduced.

II. Relocation strategies for free-floating Car Sharing Systems

In the following, different relocation strategies for free-floating Car Sharing Systems are described and compared. On the one hand, the so-called user-based approaches are based on users' (re)actions and the relocation process is carried out by themselves. On the other hand, operator-based approaches are based on the interventions made by an operator or system manager. A relocation strategy should be taken into account, if several constraints are fulfilled. Those are explained in the first section of this chapter as well as the whole decision process for or against a relocation strategy.

A. Constraints

The intervention in a Car Sharing System is always accompanied by costs. As the whole system has to be profitable for the provider, costs and additional benefits have to be compared. If the relocation costs compensate the additional earnings, a relocation strategy should be applied. Exceptions could be made shortly after implementation of the system, when the main objective is getting visible to the users and outperforming the competitors by a better supply.

Controlling the system can lead to higher total earnings and an optimized operation of the system. On the other hand, relocation strategies might neglect areas of very low demand, where in the worst case not a single Car Sharing vehicle would be available.

Leaving the system on its own without intervention saves costs and working time, but has serious disadvantages. In a self-organized system, the few frequent users might adapt the system to their behavior, so that it is difficult to gain new customers. Furthermore, the vehicles might get stuck in areas of low demand causing a loss of money. Finally, if no intervention is carried out to improve the system, no knowledge of the system optimum both for the users and the system owner is available.

The relocation focus should especially be on spots of high demand caused by a poor public transport connection, because Car Sharing Systems should not substitute existing efficient public transport systems. A good possibility for relocation is by night, when the demand is lower. If the current utilization of the Car Sharing vehicles is high, no intervention is needed.

B. User-based relocation strategies

User-based relocation strategies make use of different incentives or bonus models for the customers. One way of compensating the imbalance of supply and demand is the adjustment of the prize model. Trips to specific undersupplied areas could be offered at a lower rate or even for free when needed. Suggestions for alternative destinations basically only make sense prior to or shortly after departure. As longer the trip the harder to influence the users destination choice and the lower the willingness to change. The special-prized Car Sharing rides could be offered for instance via social communities or email and are particularly appropriate for trips to recreational facilities, which are usually less sensitive concerning the destination choice. Another incentive for users to drive to undersupplied hot spots is free parking in parking garages. If the number of vehicles leaving a hot spot is too high and there is a risk of future insufficient supply, trips of several Car Sharing customers could be combined and executed with one vehicle. The system informs the customers prior to departure, that a joint trip at a lower rate is possible. The informed customers with similar destinations then depart in one vehicle altogether. It is also possible, that an already driving user is asked to pick up another customer in a hot spot area, who has a similar destination. The prize for the Car Sharing is then divided among the users. This approach of combining Carpooling and Car Sharing does not or only to a small extent increase the earnings of the provider, but at least prevents an under-supply in a hot spot and assures customer's satisfaction. Theoretically, also the contrary is possible. Joint trips departing from cold spots could be splitted in order to regulate the over-supply in those areas.

User-based relocation strategies are especially advantageous from a financial point of view. Letting customers relocate the vehicles is free of costs except for free rides. Furthermore, those methods are environmentally sustainable. Vehicles are only driven by customers and no additional vehicle trips without customers are conducted.

Nevertheless, there are also some disadvantages. The customer can only be influenced to a certain degree. The customer acceptance and decision is difficult to control and predict. Furthermore, the explanation to the customer is difficult, because he might not understand why the system is trying to influence his routes/destinations and might thus refuse. Additionally, the customer loses some privacy, because he has to specify his destination before usage. Moreover, it can be stated that the described strategies are rather suitable for long-term than for short-term adjustments to the system. Finally, a user-based relocation process can hardly be combined with vehicle maintenance. This task can only be shifted to the users by stipulations and enforcement. However, this is not beneficial to customer satisfaction. Maintenance and cleaning thus mostly have to be carried out separately by the system operator by high costs.

C. Operator-based relocation strategies

Operator-based relocation strategies are based on interventions initiated by the system manager and executed by the Car Sharing provider itself. There are basically two different possibilities of relocation for the system provider.

On the one hand, the maintenance personnel or additional staff can relocate the vehicles. This can happen either separately for each car or for up to three cars by a car transporter. An advantage of this kind of intervention is its clear definition. Vehicles are in any case brought to the specific desired positions. Additionally, maintenance and gas filling can be combined with the relocation rides and thus cost can be reduced. However, one negative effect is the occurrence of additional rides without customers, which originally weren't necessary. This aspect is ecologically questionable. Moreover, high costs are generated by additional staff, additional gas consumption and the employment of car transporters.

On the other hand, buffer depots with a specific number of vehicles could be arranged at known hot spots, which could be released for utilization when the demand is high. This method has several advantages. First of all, no additional costly rides are necessary. Secondly, the depots can be filled a priori according to the expected demand while during the period of high demand nothing has to be done. Finally, those depots could be helpful for the integration of electric vehicles into Car Sharing Systems, because they could easily be equipped with charging stations. Vehicles that have to be loaded or maintained could be collected in the depot. If the charge of battery falls below a certain threshold, customers should be instructed to bring the vehicle to the nearest depot and eventually exchange it with another already loaded vehicle. Nevertheless, for filling the depot vehicles have to be taken from the existing fleet or additional vehicles are necessary, which have to be removed again in normal operation. Furthermore, the depot causes additional costs which have to be taken into account.

D. Comparison

In general, there are two main relocation strategies (see table 1). The first user-based category shifts the relocation process to the user. Incentives are created for the customer to deviate from the actual destination or vehicle occupancy in favor of a better balance of supply and demand. As mentioned before, the explanation of those strategies to the user and the prediction of the acceptance rate is rather difficult. Therefore, they should be primarily used in case of long-term events with a high destination traffic like fair trades or festivals.

The operator-based strategies consist of decisions made by the system manager, which can be immediately executed by the Car Sharing staff. Those methods are more reliable and thus more suitable for spontaneous or short-term events with a one-time punctual high demand like football matches. Especially the buffer depots are suitable for those events with clear beginning and end, because they can be filled in advance and released whenever needed.

TABLE I. COMPARISON OF USER-BASED AND OPERATOR-BASED RELOCATION STRATEGIES

Relocation strategy	Advantages	Disadvantages	Major application area
User-based	Low costs due to staff savings; no additional vehicle movements (environmentally sustainable)	Customers difficult to influence; user acceptance difficult to predict; loss of customer's privacy	Long-term events with high destination traffic
Operator-based	Reliability due to clear definition; combination with maintenance; a priori intervention in case of depots; easy integration of electric vehicles in case of depots	Costs for staff, rides, car transporters and depots; additional vehicle movements in case of relocation by staff; vehicles have to be taken from existing fleet in case of depots	Short-term events with defined beginning and end and one-time high demand

III. RELOCATION ALGORITHMS FOR CAR SHARING SYSTEMS

In the following, two different relocation algorithms for Car Sharing vehicles are described. One user-based and one operator-based algorithm are chosen from literature exemplarily.

A. User-based relocation algorithm

This rolling horizon method by Febbraro et al. (cp. [2]) for free-floating Car Sharing uses Discrete Event Systems (DESs), because those are suitable for representing the complexity and the macro-dynamics of a Car Sharing System. The relocation is carried out by those users, whose destinations are close to an area/station with an insufficient supply of vehicles. The algorithm is based on the minimization of the rejection ratio of reservations for Car Sharing cars and on a linear integer programming problem. It is assumed by the authors that the allowed delay is limited and the vehicle is either returned in a zone defined by the user or in a zone proposed by the system. A set of events can occur for each vehicle, e.g. an increase/decrease in the number of reservations, a change in position or in motion state (on trip or parked), etc. The areas of the customers' approximate destinations (*covered areas*) have to be known in advance for the forecasting of the vehicles' positions and the optimization of the vehicle distribution in those *covered areas*.

Consider a Car Sharing fleet with nv vehicles and the origin-destination matrix of the Car Sharing area (consisting of nv zones): $OD = [m_{i,j}]_{i,j=1,\dots,nz}$, where each entry is the number of users per period wanting to realize a trip from i to j. The mean number of reservations made in zone i during one period is then $T(i) = \sum_{j=1}^{nz} m_{i,j}, \forall\, i = 1, \dots, nz$. The reservations are assumed to be Poisson distributed and thus, the time between two bookings is assumed to be exponentially distributed with rate $\lambda = T(i)$. The probability of trips with origin i to end in destination j is $p_i(j) = \frac{m_{i,j}}{T(i)}\ \forall\ i = 1, \dots, nz, \quad j = 1, \dots, nz$. Finally, another event has to be considered: the relocation event, which computes the best (favored by the system manager) drop off position for each user. This alternative position is either accepted or not, depending on an incentive for the user, e.g. the ones mentioned in section II.C. The relocation algorithm has two phases: In the first one, optimal drop off locations have to be found satisfying the future demand and in the second one, the discount has to be assessed depending on the resulting detour for the user. The authors only considered phase 1, which is the above mentioned minimization of the reservation rejection ratio by supplying sufficient vehicles in each zone, especially in current hot spots. The optimum would be $T(i)$ vehicles, $i = 1, \dots, nv$ in each zone during the time period. Let $x_{i,v}\ \forall i, \forall v$ be the variable indicating the position of each vehicle, i.e. $x_{i,v} = 1$, for a vehicle located in zone i. The optimization problem is then formulated as

$$min \sum_{i=1}^{nz} \left| T(i) - \sum_{v=1}^{nv} x_{i,v} \right|$$

subject to

$$\sum_{i=1}^{nv} x_{i,v} = 1\ \forall v$$

$$x_{i,v} = 1\ \forall v \in V_\sim$$

$$x_{i,v} \in \{0,1\}\ \forall i, \forall v$$

The absolute value in the objective function represents the deviation of the number of vehicles in zone i from the desired number $T(i)$. The first constraint ensures the affiliation of each vehicle to only one zone. The second constraint considers the set of vehicles $V_\sim$ that cannot be reallocated and fixes those in specific zones i^{-}. The authors suggest a reformulation of this non-linear problem to a linear integer program and solve it by a branch and bound method.

The users decision of whether the suggested drop off location is accepted or not is modeled as discrete choice. The relevant probabilities are then computed by means of a binomial logit model with utility

$$U_k = V_k + \epsilon_k, \quad k = \{accept, not\ accept\},$$

where ϵ_k is a Gumbel stochastic variable with zero mean and variance $\frac{\theta \pi^2}{6}$ and

$$V_{not\ accept} = \beta_{not\ accept}$$

$$V_{accept} = \beta_d d + \beta_s s$$

are the utilities. Thereby, d is the resulting detour in case of acceptance and s is the applied discount. Thus, the probabilities are

$$p[accept] = \frac{e^{V_{accept}}}{e^{V_{accept}} + e^{V_{not\ accept}}}$$

$$p[not\ accept] = 1 - p[accept]$$

The availability of specific data could help with estimating the parameters θ and β_i . In the second phase of the relocation algorithm, the discount s should be optimized.

B. Operator-based relocation algorithm

Kek et al. (cp. [3]) propose a three-phase decision support system (cp. Fig. 1) to find operator-based relocation strategies for station-based Car Sharing Systems, that enable one-way-rides.

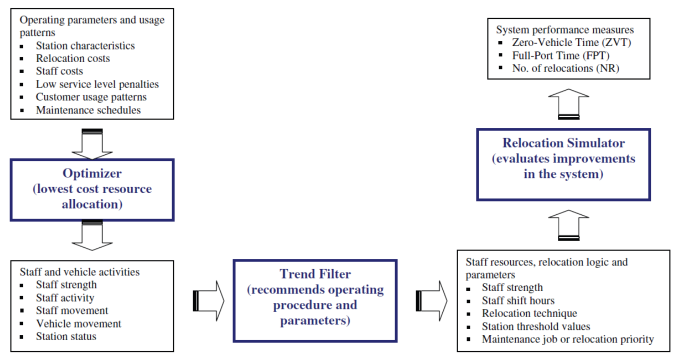

Figure 1. *Three-phase decision support system for operator-based relocation strategies (cp. [3])*

At first, the vehicle relocation problem is formulated as a mixed integer linear problem similar to the typical pickup and delivery problem.

Different types of staff activities are considered for the definition of the problem: waiting at a station for the next activity, maintenance (clean vehicle at a station, drive to a gas station), movement (travel between stations without driving a vehicle) and relocation. Moreover, at every time step the number of available and unavailable (already reserved or waiting for maintenance) vehicles as well as the number of empty parking spots should be monitored. Based on this and given a set of stations with a specific capacity and the maintenance schedule for the vehicle fleet, an Optimizer minimizes the generalized cost of the relocation. Thereby, movement and relocation costs, staff costs and penalty costs of rejecting requests for or the return of vehicles at a station are considered. The lowest cost resource allocation is thus found. It consists of optimized staff strength, staff activities, relocations and the resulting number of vehicles at the stations at each time step.

Afterwards, heuristics are introduced for translating the optimization outputs into near-optimal manpower and operating parameters. This so-called Trend Filter phase recommends an operating procedure for the Car Sharing System. The extracted key parameters are staff strength and shift hours, relocation techniques, station threshold values and the priority order of maintenance jobs and relocation trips when both are needed. Concerning the relocation techniques, two different ones are proposed by the authors: shortest time and inventory balancing. The first one is the most time-efficient movement of vehicles to or from a neighboring station. The second one is the filling of an undersupplied station with a vehicle from an oversupplied station. As mentioned before, several thresholds are extracted. Upper and lower critical thresholds initiate a relocation request if they are exceeded or fallen below, respectively. Upper and lower buffer thresholds allow a relocation to or from the station only if the number of vehicles is below or above, respectively. Choosing a larger range between upper and lower critical thresholds and a smaller range between upper and lower buffer thresholds would reduce the number of relocation requests as well as the number of relocation executions. The relocation cost would thus be reduced, but the level of service would change for the worse. Doing the contrary would have reverse effects. It is recommendable to change the upper and lower thresholds depending on the time of the day.

Finally, a Relocation Simulator is applied that evaluates the improvements in the system.

IV. Model for Relocation of Vehicles within Free-Floating Car Sharing Systems

This new integrated two-step algorithm for optimal positioning and strategy selection consists of an offline demand clustering and strategy pre-selection (Step 1). The online module (Step 2) measures the differences between optimal vehicle positioning and current positioning (ordinal number/index) and selects the best relocation strategy.

The idea of this new approach is a continuous monitoring of a Car Sharing System. The system is however not fully controlled in a closed-loop. In case of a certain deviation of the actual spatial vehicle distribution from the current optimal state, a case-sensitive relocation strategy is determined and could be implemented manually. Fig. 2 shows the whole two-step controlling process.

The first step is an *Offline Planning Module* which is carried out periodically, e.g. once a year. The idea of this offline analysis is the identification of certain periodically repeating demand patterns. This could be daily (time of the day, peak hours), weekly (weekend or weekday) or even longer (seasons) or based on specific events (football matches, fare trades etc). During this offline step, real vehicle positioning and booking data of the running Car Sharing System are at first collected and analyzed. The users' individual mobility structures and demand-patterns are identified via a cluster analysis and an according demand model is generated. So-called spatio-temporal “hot spots” and “cold spots” are identified (see Fig. 3). The main indicator for a “hot spot” is a very high frequency of booking in a given spatial area. Based on the results of the historical cluster analysis, the optimum, ideal state of spatially available vehicles can be identified for each demand scenario/cluster. Usually there is a mismatch between a current, given vehicle distribution and an optimal distribution. Thus, a cost-efficient relocation should be applied. To limit the searching space for the later

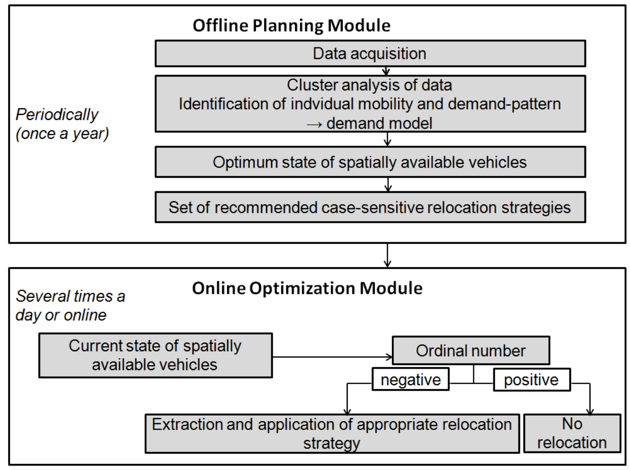

Figure 2. *Two-step decisision support tool for relocation strategies*

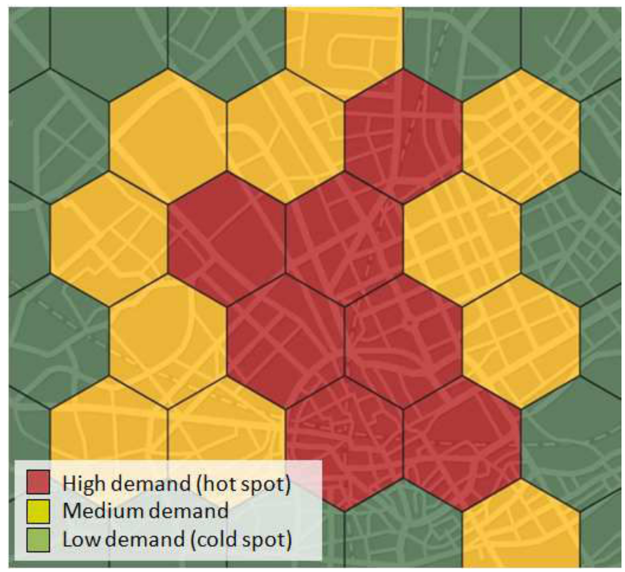

Figure 3. *Forecasted Car Sharing vehicle demand for a specific cluster*

online optimization process, relocation strategies are pre-selected and already pre-defined for a demand-cluster. For example for a huge event, like a soccer match at a given time at a given place, not all strategies (e.g. the user-based strategies) might be appropriate. For such an event, a buffer or a manual relocation seems to be much more promising.

For each cluster an appropriate relocation strategy is proposed. The objective of the relocation actions is to reach the afore estimated optimum state for the current cluster. Thus, the result of the *Offline Planning Module* is a set of recommended case-sensitive relocation policies. Contrary to the before described two relocation strategies and algorithms, there is no preliminary commitment on whether the applied actions are user-based or operator-based. Depending on the current situation, either one or a combination of both is chosen. This flexible approach allows the offline identification of the optimal vehicle distribution and the according optimal relocation strategies and is not only limited to the application of only one relocation strategy.

A second *Online Optimization Module* is carried out online, at least several times a day. The current state of the spatial vehicle distribution is continuously measured (see Fig. 4). Depending on the current point in time or expected events, the corresponding optimum spatial distribution of vehicles computed in step 1 is chosen. The comparison of optimum and current state produces an ordinal number, based on which the relocation decision is made. If the ordinal number/index is negative, the system operator intervenes in order to increase the ordinal number. Otherwise, supply and demand are relatively balanced and no relocation is taken into account. In case of a relocation decision, the recommended pre-elected strategies provided by the *Planning Module* are tested and numerically evaluated with a cost function. The strategy with the lowest cost for implementation leading to the optimal vehicle distribution is selected and suggested for implementation.

Let us consider as an example an event with clear beginning and end. As already mentioned in section II.C, operator-based relocation strategies are preferred in this case due to their real-time realization. If vehicles are missing in areas of high demand but there is an oversupply of vehicles in areas of lower demand, there are two different possibilities of adjusting the imbalance. Firstly, additional depots could be opened in the undersupplied areas. Secondly, vehicles could be relocated from oversupplied areas to undersupplied ones.

The introduced two-step model has several advantages. First of all, the partition into two independent phases, one offline and the other online, simplifies the relocation problem to a certain degree. The periodically executed data collection and analysis guarantees that the conducted relocation strategies remain up-to-date and adjust to changing user behavior and demand. Since the Planning Module is carried out offline, a sufficient amount of time can be invested in analyzing the data and thus generating a reliable and realistic demand model for each cluster.

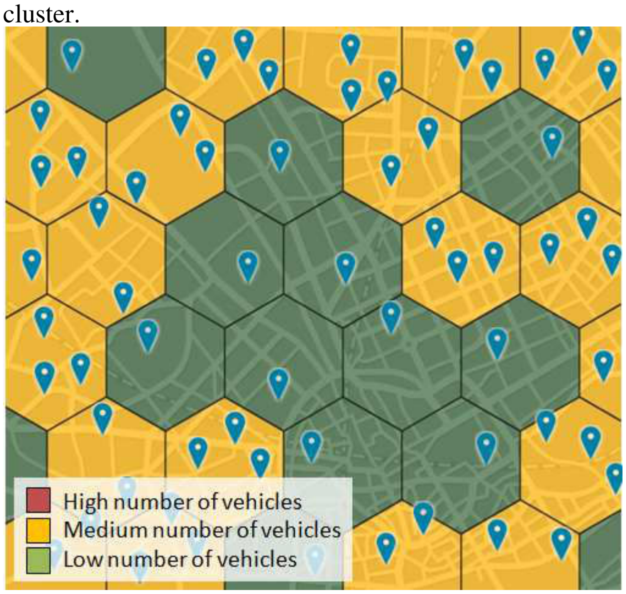

Figure 4. *Current spatial vehicle distribution*

Furthermore, the case-specific relocation strategies can be evaluated and tested using comprehensive simulation prior to the pre-selection. A higher quality of the strategies could thus be reached. The *Online Optimization Module* is easy to conduct, because a set of recommended relocation actions already exist for different scenarios. In case of a decision in favor of a relocation, the appropriate strategy simply has to be extracted and applied. Additionally, the relocation policies recommended by the *Planning Module* are easy to understand and straightforward.

V. CONCLUSION AND OUTLOOK

Different relocation strategies for one-way Car Sharing Systems have been described in detail, categorized and evaluated. Several user-based and operator-based strategies are introduced. Two algorithms have been described in order to illustrate the differences between the two procedures.

The new two-step algorithm for the relocation of vehicles within free-floating Car Sharing Systems tries to combine the two strategies by choosing the relocation methods depending on the given situation out of a set of predefined case-sensitive strategies. The separation of the process into an *Offline Planning Module* and an *Online Optimization Module* shows several advantages. The focus should be especially on the *Offline Planning Module*. The identification of individual mobility and demand patterns based on vehicle positioning data has to be concretized and automated. Furthermore, the optimum spatial vehicle distributions and the ordinal index have to be mathematically determined. Specific evaluation and testing processes have to be found for simplifying the pre-selection of the strategies.

Finally, there has to be mentioned that - in the past - few research was done on finding relocation algorithms for totally free-floating Car Sharing System. The focus has been mostly on station-based systems. However, the new systems have different dynamics that should be taken into account.

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