CASE OF STUDY OF A MIXED CARSHARING SYSTEM DESIGN

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ABSTRACT

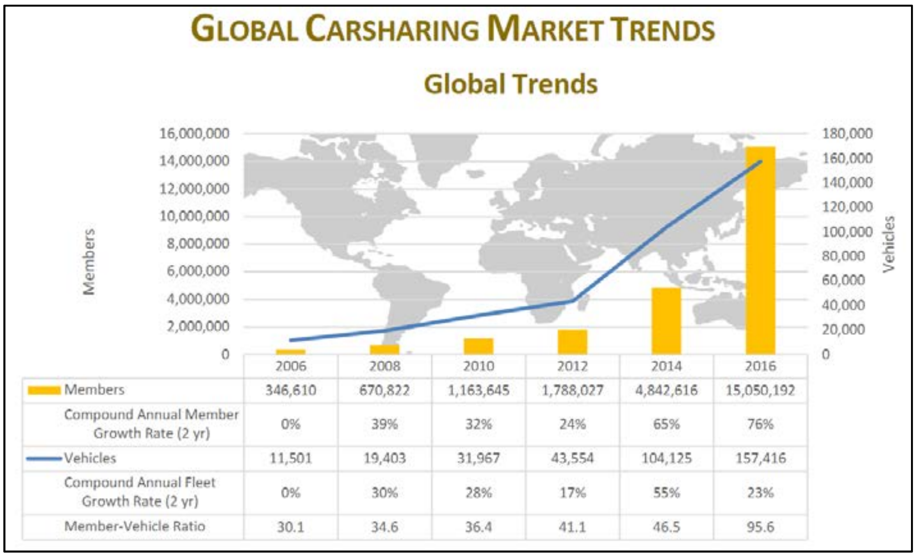
One of the most significant issues when designing a carsharing system is the decision of implementing a free-floating or stations-based system. The advantages and drawbacks of each system are well known. Free-floating systems provide more accessibility to users. But they are more sensible to demand imbalance and can be limited if public space availability is restricted by municipalities. Station-based don't need public space occupation, but the station infrastructure requires more investment. The authors have developed a macroscopic design model that considers the case of a mixed carsharing system, which includes both free-floating and station-based options working together. This model not only allows to compare which option will perform better on any given scenario, but also to provide solutions that combine the accessibility and cheapness of free-floating with the lack of public space limitations of station-based systems. This document describes that model and shows its application to a case of study.

1. INTRODUCTION

Carsharing is the evolution of car rentals. The idea behind them is the same: to provide a flexible on-demand transportation alternative with less costs than acquiring a private car or vehicles for hire (e.g. taxis). And from this idea, the system has been improved using new technologies in order to increase its flexibility. Membership systems, geolocations, and mobile apps have eased a lot the process of search, reservation, and payment for the use. Allowing users, for example, to spend less time in the renting process, making only one-way trips, or paying per minutes instead of an hourly or daily basis.

These new features have produced a positive effect on the market size. As of October 2016, carsharing was operating in 2095 cities in 46 countries with approximately 15 million members sharing over 157.000 vehicles. The second carsharing market is Europe with 19% of worldwide members and 37% of the fleet. (Shaheen and Cohen, 2020)

However, those features have also added a completely new dimension on the complexity of the design and management of these systems. One of the most significant issues is the decision of implementing a free-floating or station-based carsharing configuration.



	2006	2008	2010	2012	2014	2016
Members	346,610	670,822	1,163,645	1,788,027	4,842,616	15,050,192
Compound Annual Member Growth Rate (2 yr)	0%	39%	32%	24%	65%	76%
Vehicles	11,501	19,403	31,967	43,554	104,125	157,416
Compound Annual Fleet Growth Rate (2 yr)	0%	30%	28%	17%	55%	23%
Member-Vehicle Ratio	30.1	34.6	36.4	41.1	46.5	95.6

Fig. 1 – Global carsharing market (Source: Shaheen and Cohen, 2020)

On free-floating carsharing (FF), the fleet of cars is placed on the city streets. Users can check the location of nearby available cars through a mobile app and reserve the desired vehicle to make their trips. Once the ride has been complete, users can return the car by parking it on any available place inside a designed service region (typically the whole municipality area).

On station-based carsharing (SB), the fleet is distributed through certain specific parking lots or stations. Users can also check the availability of cars via mobile app, and make a reservation. But, at the end, they must return the car on any of those designated parking locations. So, in practice, all trips are station-to-station.

Each carsharing type has some advantages and drawbacks, Soriguera and Jiménez (2017), Tournier (2017) and Ciari et al. (2014) mentioned a few of them:

- Firstly, from the operator point of view, FF requires less infrastructure costs since there is no need to pay any fee to the local parking provider in order to reserve parking spots. The cars can be parked at any free parking slot in the street, so there is no cost of renting the parking.
- Following this line, it is also important to emphasize in the fact that a FF service is easier to implement than a SB since it is not dependent of the construction times of parking slots.
- However, note that municipalities and local administrations could be reluctant to concede the free usage of public space, and therefore, they could limit the number of FF cars in service.
- From a customer perspective, accessibility is key. In the case of SB carsharing, there might not be stations near the trip origin or destination point. Hence, customers will lose

more time by accessing to the system, or even discard the trip if the access or egress distance is too big.

- However, on SB systems it is easier to ensure a good distribution and availability of cars, since the stations distribution and capacity limits demand imbalance. FF services are usually perceived as less reliable. Users don't take for granted to find a car. Either for that current trip, or on the way back home after the activity on destination is finished. So, service usage is discouraged when there's no a viable alternative.

Since both the SB and FF systems have different pros and cons, during the design phase it's crucial to compare the expected performance of both configurations in order to decide which one would be better in our case. Or, moreover, it could be interesting to design mixed configurations that combine the advantages of both. For example, SB systems with a limited number of stations can improve their coverage by including a number of FF cars. Or otherwise, if the public space occupation is very limited by the municipalities, FF systems could operate with a bigger fleet by including cars on stations.

With that purpose, the authors developed a macroscopic design model defined for a mixed carsharing system, which includes a FF and a SB part working simultaneously (Jiménez-Meroño and Soriguera, 2021). The model is based on the continuous approximations methodology. The main advantage of those models is their simplicity. They can be run with easily obtainable parameters. And its insights are depicted more clearly than more complex models without losing much accuracy or robustness in their results. Therefore, this methodology is adequate to evaluate the performance and take strategic decisions in the design phase.

In the following section of the document, an overview of the model is provided. Section 2 corresponds to the state of art and the review of academic literature. On Section 3, the main characteristics of the model are presented. That includes the tradeoff and decision variables characterization, the demand modelling, the cost equations, and the possible restrictions to apply. On Section 4, the model is applied to a case study based on the city of Barcelona, in order to provide an example of how it works and how it can be used in practice. Finally, the document ends with the conclusions section, acknowledgments and reference list.

2. CARSHARING STATE OF ART

2.1 Current picture of carsharing

Carsharing companies can be classified into two groups. The first one are agencies that were founded as rent-a-car companies, but they have been gradually introducing new features that change their business model. That's the case of Communauto, Enterprise, Flinkster, or Zipcar. Since those companies do not implement the same features on all cities or regions at once, many of them still rely on round-trip rentals.

The second group are companies that were founded with the carsharing business model in mind. Most of them, later than 2010. ShareNow, Enjoy, or Yandex.Drive belong to this group. They all operate offering one-way trips, either on SB or FF mode.

The authors consider that this trend shows that one-way services will be the prevailing option on future implementations. And, under a design point of view, it would be more useful to focus on that option. It could be argued that round-trip services are a remainder of the former rent-a-car structure due to the difficulty to adapt an existing business model. So, for the purpose of this work, only the one-way case is studied.

Name	Location	Service Type	Fleet size	Members	Vehicle Type	Fare
Cambio Carsharing	Belgium, Germany	Station-based round-trip	+1.700	63.500	Car/e-car	From 0.23 €/min
Communauto	France, Canada	Free-floating one-way Station-based round-trip	+2.000	+40.000	Car/e-car	From 0.28 €/h
Delimobil	Russia	Free-floating one-way	+12.000	+1.000.000	Car	
Enjoy	Italy	Free-floating one-way	2.670		Car	From 0.25 €/min
Enterprise Car Club	UK	Station-based round-trip	+500	20.000	Car/e-car	From 3.53 €/h
Flinkster	Austria, Germany, Netherlands	Free-floating one-way & round-trip	+6.500	+300.000	Car/e-car	From 1.50 €/h
ShareNow	Many European cities (see Table 4) and USA*	Free-floating one-way	+20.000		Car/e-car	From 0.19 €/min
Stadtmobil	Germany	Station-based round-trip	+2.600	+40.000	Car	From 0.26 €/km
Ubeeqo	Belgium, France, Germany, Italy, Spain, UK	Station-based one-way			Car/e-car	From 3.50 €/h
Yandex Drive	Russia	Free-floating one-way	+21.000		Car	
Zipcar	UK, USA, Canada, Costa Rica, Iceland, Turkey, Taiwan	Station-based round-trip and one-way trip	12.000	+1.000.000	Car/e-car	From 4.05 €/h

*On February, 29th 2020, ShareNow stopped its activity in North America, London, Brussels and Florence.

Table 1 – Main car-sharing operators in operation in Europe.

City	GDP [€/capita]	Fleet size [vehicles]	Service area [km²]	Average price [€/min]	Average demand [trips/day]	Average trip
Berlin	41.967	2.975	165	0.25	-	
Madrid	35.041	2.400	80	0.27	-	31.9 min
Milan	49.500	3.021	120	0.26	3.500	
Moscow	19.696	30.000	850	0.079	150.000	13.34 km

Table 2 – Aggregated car-sharing services offered for different European cities.

2.2 Literature review

Many scientific papers have provided a good overview of the key factors for the success of carsharing programs. For instance, Alzahrani et al. (2019) and Münzel et al. (2018) analyze market studies and the factors that influence the selection of the best carsharing alternative of Portland and Germany, respectively. Schmöller et al. (2015), or Le Vine and Polak (2019) focused on different impacts that carsharing systems have had in different aspects of Munich and Berlin and London, respectively. From a more environmental point of view, Martin and Shaheen (2011) provide an overview on the green-house emission impacts of carsharing in North America. Another interesting work was carried out by Vosooghi et al. (2017) where different existing methods of demand estimation for one-way carsharing systems are analyzed. The main conclusion is that there are research gaps to be addressed regarding carsharing systems. For example, the integration of carsharing with the more traditional transportation modes or the general benefits of using autonomous vehicles in carsharing systems.

Regarding the carsharing system design, research can be classified into two different levels: strategical level, basically the planning of the system layout and the vehicle fleet; and operative level, mainly the optimization of the repositioning operations basically in one-way systems. Significant literature is reviewed next, following this classification.

Strategical planning addresses all the decisions that need to be taken when dealing with the implementation/expansion of a carsharing system. These decisions will be valid for the medium to long term. They include the study and optimization of the number and location of stations in the station-based system or the sub-zones in the free-floating system, the required number of parking spots, the dimensioning of the vehicle fleet and the definition of the repositioning period.

Kortum et al. (2016) provide an overall overview on free-floating carsharing. They evaluate empirical data on use of free-floating carsharing in different cities of Europe and North America. They make evident that carsharing is becoming a more integral part of the mobility of city, although different growth patterns can be observed for the different analysed cities. It is remarkable that the data included in this study is until 2015 and some cities appeared saturated at that time.

Recently, Ampudia-Renuncio et al. (2020) provide a spatial evaluation of the FFCS trip profile, obtaining the main flows throughout the whole service area. This spatial analysis is the first one carried out in Spain that uses real rental data collected from the different operators. Their results show that for short distance, users prefer carsharing system than the available public transport since carsharing is faster and public transport is highly correlated with parking availability at origin and destination.

The station-based one-way carsharing problem was assessed by Huang et al. (2018). They included to the problem relocations and non-linear demand. For relocations, they presented a Mixed-integer Non-linear Programming model to solve the carsharing station location and capacity problem. Then, for flexible demand, they construct a logit model to represent the non-linear demand rate by using the utility of carsharing and private cars. They draw the conclusion that pricing and parking space rental costs are key factors that influence the profitability of carsharing operators.

The operational level includes daily decisions. They mainly assess the rebalancing operations, which take place mainly in one-way carsharing systems. Different strategies are proposed to solve the system imbalance across the whole service area. Some of the most influential literature regarding this topic is herein presented.

An overall literature review of the vehicle relocation problem in one-way carsharing was carried out by Illgen and Höck (2019), who revised the relevant literature regarding one-way trips and relocations from 2012 to 2019 with several case studies in order to give a more thorough overview on different methodologies proposed by different authors.

Boyaci et al. (2017) carried out a simulation for a station-based carsharing system where, iteratively, optimize the decision variables related to vehicle and relocation personnel. In their work, the results show the importance of efficient algorithms when dealing with relocation operations. They proved the importance of forecasting the demand to optimize the initial locations of vehicles for an efficient use of the resources.

A relocation algorithm for free-floating carsharing with conventional and electric vehicles is proposed by Weikl and Bogenberger (2015). In their work, they carried out three real world field tests for different stages of development of the model. In the final result they achieve promising results in reducing the idle time of the vehicles and a high efficiency of relocations. It is interesting since the model was applied to the carsharing system in Munich (Germany). So, it provides a realistic scenario that can be easily applied to other free-floating carsharing systems.

3. MODEL DEFINITION

In this section, the main characteristics of the model are summarized. The complete formulation and details of the model are described in Jiménez-Meroño & Soriguera (2021).

3.1 Model overview and decision variables

Model is defined over a continuous service region, where the free-floating (FF) and station-based (SB) systems act simultaneously. Users will behave as it follows:

- The FF service is preferred on origin due to accessibility reasons. Users will check first for vehicles on street inside their virtual station. If there's any available vehicle, users will reserve and rent that vehicle.
- If the virtual station is empty, users will try to use the SB system. If users are inside the coverage of the SB system, they will opt for the SB system. Otherwise, the trip is lost.
- When opting for the SB system, users will check the nearest station. If there is any available vehicle, users will reserve and rent that vehicle. Otherwise, the trip is lost.

In order to control the tradeoff between demand losses and agency costs, operators have five options that correspond to the five degrees of freedom of the system. Each one is associated to a single decision variable:

- Change the on-street FF fleet size ($\boldsymbol{m_{FF}}$) or the SB fleet size ($\boldsymbol{m_{SB}}$).
- Change the number of employees carrying repositioning operations. The variable that characterizes repositioning operations is the repositioning period. It defines the average time until a station (or virtual station) is rebalanced. That variable can be different for FF and SB and their values are $\boldsymbol{h_{FF}}$, $\boldsymbol{h_{SB}}$.
- Change the number of stations in order to modify the coverage and accessibility of the SB system. This coverage is determined by the density of stations per km^2 is defined as $\boldsymbol{\Delta_{SB}}$. And, therefore, the total number of stations is $\Delta_{SB} \cdot R$.

Name	Description		Symbol	Units
Station density	Number of parking stations per area unit		$\boldsymbol{\Delta_{SB}}$	[stations/km2]
Available fleet size	Number of available vehicles in the system	Total	$\boldsymbol{m}$	[cars]
		Free-floating	$\boldsymbol{m_{FF}}$	
		Station-based	$\boldsymbol{m_{SB}}$	
Repositioning period	Avg. time between complete rebalancing	Free-floating	$\boldsymbol{h_{FF}}$	[hours]
		Station-based	$\boldsymbol{h_{SB}}$	

Table 3 – Decision variables summary.

There are two additional degrees of freedom not considered in this model: changing the available parking, and changing the battery recharging system.

The model considers that parking availability only affects demand on long term decisions. Not finding parking on the desired destination can discourage users from using the service more times in the future. But the current trip will be made eventually, either parking on street or on a station. For that reason, the number of parking places is considered an output here. And it is restricted to be at least as big as the fleet size.

Finally, battery recharging is a complex process by itself with several decision variables. The number of electric cars, the number and type of chargers, or battery autonomy can be changed and result in more or less demand losses. Including all of them would overcomplicate the model and shadow the main design insights. Therefore, battery recharging is considered here a constraint.

3.2 Demand modelling

The amount of served trips (λ_{FF} and λ_{SB} in trips/km^2·h) depends on two factors. First, if there is enough demand of trips in the system (i.e. potential demand density, input of the model). And second, if there is enough fleet capacity to serve those trips. Served trips will be the minimum of both.

However, note that potential demand and fleet are variable in time and space. This phenomenon is accounted by the definition of three correction factors defined stochastically:

- Temporal fluctuations. On off-peak hours, potential demand will be lower than the average. So, there's a probability of having more available vehicles than potential demand. Therefore, demand served is reduced.
- Demand spatial imbalance. There are regions that are usually attraction poles. Cars tend to accumulate on those zones. If the accumulation of cars exceeds the potential demand, some of the cars will remain unused. Therefore, demand served is reduced.
- Demand spatial decentralization. This phenomenon is equivalent to the previous one but on a station level. In this case, one station can randomly exceed the potential demand at any moment, no matter if it's located near of an attraction pole or not.

According to those criteria and stochastic phenomena, demand served is estimated.

3.3 System cost equations

Once demand is estimated, it is possible to calculate all costs of the system. Costs are depicted in monetary units per time unit (€/h in our case). So, consequently, all results will be also divided per time units (i.e. trips per hour, penalties per hour, or even hours of repositioning work per hour).

Both agency and user costs are considered in order to define two possible objective functions: the total generalized cost and the agency revenue.

- Infrastructure costs ($\boldsymbol{Z_I}$). It accounts for all the investments made to acquire and renew the vehicle fleet and parkings.
- Operative costs excluding repositioning ($\boldsymbol{Z_O}$). This term includes all charges that can be imputed to vehicle usage, such as maintenance, cleaning, and fuel consumption.
- Repositioning cost ($\boldsymbol{Z_R}$). It's the cost that summarizes all relocation operations. Those operations are meant to compensate system demand imbalance or move electric vehicles to recharging points.
- User access cost ($\boldsymbol{Z_{AC}}$). It accounts the walking time of users at origin or destination.
- User no service penalties ($\boldsymbol{Z_{NSP}}$). This cost applies to all lost demand in order to account the losses and annoyance perceived by the users after a failed trip attempt.

With those costs, two objective functions are defined. The first one is the total generalized cost per time unit. It includes all user and agency costs. The second one is the agency profit per time unit. It consists in the revenue generated by the served demand minus the agency costs.

$$Z_{GCF} = Z_I + Z_O + Z_R + Z_A + Z_{NSP} \tag{1}$$

$$Z_{PRF} = fare \cdot (\lambda_{FF} + \lambda_{SB}) \cdot R - (Z_I + Z_O + Z_R) \tag{2}$$

Note that, in case of agency revenue maximization, the fare must be an input of the model.

3.4 Battery consumption and charging restrictions

The design model could be applied for any type of fleet, including partially or totally electric vehicles. In that case, the model includes solutions to ensure that the average recharging ratio is enough to compensate the battery consumption ratio. To do so, two different charging systems are defined: distributed and centralized charging.

Distributed charging uses the SB parking facilities to install domestic recharging points. Recharging with these devices is slow, but installation is cheaper and easier than other faster alternatives. If this option is considered, the solution must ensure that vehicles on stations and relocating operations are enough to reach the minimum recharging rate.

Alternatively, centralized charging considers a central hub, inaccessible to users, where all recharging operations take place. This infrastructure is equipped with superchargers, which allow to recharge vehicles quicker. However, they require a more expensive installation and additional repositioning operations in order to move the cars to the hub and redistribute them again once the battery is charged.

4. CASE OF STUDY: BARCELONA

4.1 Description of the scenarios

The base for this case study will be a mixed carsharing system placed in a region of 39.19 km^2 in central Barcelona. Six different optimization scenarios are compared. In three of them the sum of users' and agency costs will be minimized. And in the other three, the agency profit will be maximized. For each objective function, three different vehicle and recharging configurations will be addressed: 100% of electric vehicles with decentralized recharge on stations, 100% of electric vehicles with hub recharging, and 0% of electric vehicles (all ICE vehicles).

Scenario	**Objective function**	**% of electric vehicles**	**Battery charging configuration**
#1	Max. profit	100 %	Distributed
#2	Max. profit	100 %	Centralized
#3	Max. profit	0 %	-
#4	Min. GCF	100 %	Distributed
#5	Min. GCF	100 %	Centralized
#6	Min. GCF	0 %	-

Table 4 – Optimization scenarios summary.

Since the number of parking places and recharging parameters are not decision variables, and therefore, are not subject to optimization, further considerations must be taken into account:

- By default, the number of parking places is set to the minimum feasible.
- In case of decentralized recharging, if the fleet constraint is not fulfilled, the number of SB vehicles will be increased until reaching the minimum. Note that reducing the FF fleet size is another possible solution. But it is considered that, in general, that case would result in less demand served and a worse performance.
- The number of charging devices on parkings is also set to the minimum feasible.

Tables 5 and 6 summarize the parameter estimation for the city of Barcelona.

Parameter description		Units	Value	Source
Demand inputs	Area of the service region	[km^2]	39.19	The area selected was a region of central Barcelona. Demand data was provided by Inlab UPC as a O/D matrix of 228 zones. Only trips longer than 1.5km were considered, and a carsharing market penetration of 0.5%. (InLab, 2019)
	Request subregion	[-]	0.53	
	Return subregion	[-]	0.47	
	Average potential demand density	[trips/h·km^2]	9.77	
	Standard temporal deviation	[trips/h·km^2]	0.977	
	Request imbalance	[-]	0.215	
	Return imbalance	[-]	0.241	
	Fraction of station returns	[-]	0.43	Estimation from EMEF 2019 (Autoritat del Transport Metropolità, 2020).
User behavior inputs	Maximum access distance	[km]	0.4	Transportation Research Board (2013)
	Average walking speed	[km/h]	3	Generalitat de Catalunya (2017)
	Users' average value of time	[€/h]	11.4	Official value used for transport investment appraisal in Barcelona (Autoritat del Transport Metropolità, personal communication, July 2017).
	Users' no service penalty (FF)	[€/trip]	7.93	Considered as the average taxi fare in central Barcelona (Autoritat Catalana de la Competencia, 2018; Institut Metropolità del Taxi, 2020)
	Users' no service penalty (SB)	[€/trip]	2.50	Estimation according to the works of Herrmann et al. (2014) and Ampudia-Renuncio et al. (2018). 80% avg. public transportation fare (Transport Metropolità de Barcelona, 2020) + 20% Avg. taxi fare in Barcelona (see above).

Table 5 – Input estimation (Part 1).

Parameter description		Units	Value	Source
City inputs	Average circulating time	[min]	11.1	Result of dividing the average trip distance by the average car speed.
	Average parking time	[min]	6.6	Survey conducted in nineteen major European cities (Conduent, 2016)
	Average service time	[min]	27.7	Result of $\tau_c + \tau_p + \tau_r/2$.
	Average car speed in the city	[km/h]	15.3	This is 2/3 of the average measured speed in Barcelona. The 1/3 reduction considers delays at intersections. (Ajuntament de Barcelona, 2018)
	Average repositioning speed (in electric scooter)	[km/h]	8.8	Liu et al. (2019)
Agency costs and policies	Acquisition cost per vehicle	[€/car·h]	0.33 (electric car)	Seat Mii market cost (SEAT, 2020a), considering a useful life of 5 years, a residual value of 50%, an unavailability ratio of %5 due to maintenance and repairs (Bösch et al., 2018), and average insurance costs.
			0.23 (ICE car)	
	Average cost per parking (SB)	[€/parking·h]	0.25 (no charger)	Long-term renting cost of a parking slot in Barcelona (B:SM, 2020; SABA, 2020) plus the installation of charging infrastructure (Wallbox, 2020; Schroeder and Traber, 2012; Zhang et al., 2018).
			0.30 (Wallbox)	
			1.18 (fast charger)	
	Average cost per parking (FF)	[€/parking·h]	0	Subsidized on-street parking
	Average operative cost per trip	[€/trip]	1.37 (electric car)	Energy and fuel consumption is estimated according to trip distance, the SEAT Mii technical specifications (SEAT, 2020b), and the price index in Catalonia (IDESCAT, 2017). Cost of administrative control and manteinance are adapted from Bösch et al. (2018) to the currency and power purchase in Spain.
			1.45 (ICE car)	
	Average cost per repositioning worker	[€/worker·h]	21.54	Labor cost of 14.32 €/h according to IDESCAT (2017). 33% of the working time is considered lost or ineffective for repositioning. The prorated acquisition cost of scooters is included but it is residual (0.04 €/h).
	Average time spent on fixed repositioning operations	[min]	6	(SEAT, personal communication, March 2020)
	Average autonomy of electric vehicles	[h]	13.07	SEAT Mii technical specifications (SEAT 2020b).
	Average recharging time of electric vehicles	[h]	4	
			1	
	Hub location	[km]	0	The hub is considered near the city centre.
	Maximum reservation time	[min]	20	Similar to Car2Go policies in Madrid. (Car2Go, 2020).
	Average fare	[€/min]	0.27	

Table 6 – Input estimation (Part 2).

4.1.2 Limitation of the number of stations

Before examining other results, it should be noted that the optimum station density, Δ_{SB}, resulted in a huge value for all studied scenarios.

When the generalized cost is minimized, user access cost is much larger than all the other agency costs and user penalties. So, the model keeps adding stations in order to minimize access distance even after reaching the full SB coverage.

In case of maximizing profit, where user costs are not considered, the effect is attenuated, but still the optimal Δ_{SB} results unrealistically large. This is because sometimes the number of repositioning operations is determined by the battery recharging operations or the compensation between the FF and SB modes (i.e. returning cars to station). In those cases, the station density, Δ_{SB}, has no effect on increasing the number of operations. In fact, it decreases its cost because it reduces the average repositioning distance. That effect exceeds any other cost increase associated to the number of stations.

The conclusion is that in those cases, the number of parking stations to be used should be as large as possible, because this will reduce both, user and agency cost. This conclusion could change if the infrastructure cost includes some kind of penalty for being able to park on several different stations.

Taking the previous conclusion into account, for the purpose of this study, the number of parking stations has been set to a more realistic fixed number of 48 stations. This corresponds to Δ_{SB}= 1.22 stations/km2 and represents a SB coverage of roughly 20% of the service region ($c \cdot \Delta_{SB}$= 0.195).

4.2 Optimization results

Tables 7, 8 and 9 summarize the main optimization results for all scenarios. In the following subchapters, the main findings and comparisons are explained with more detail.

Parameter		**Units**	**Max. Agency Profit**			**Min. Generalized Cost**		
			Scn. 1	**Scn. 2**	**Scn. 3**	**Scn. 4**	**Scn. 5**	**Scn. 6**
Density of stations		[stations/km^2]	1,22	1,22	1,22	1,22	1,22	1,22
Fleet size	FF	[cars]	314	166	370	91	99	121
	SB	[cars]	31	27	26	47	8	9
	Total	[cars]	367	214	421	149	120	136
Parking slots in stations		[parking slots]	33	27	27	47	8	9
Repositioning period	**FF**	[hours]	113,0	351,1	115,7	82,1	38759,4	19308,1
	SB	[hours]	46,6	6,7	11,6	13,5	1066,9	244,5

Table 7 – Optimization results. Decision variables.

Parameter			Units	Max. Agency Profit			Min. Generalized Cost		
				Scn. 1	**Scn. 2**	**Scn. 3**	**Scn. 4**	**Scn. 5**	**Scn. 6**
Fleet size	**FF**	In use	[cars]	123	109	125	91	85	90
		Idle vehicles	[cars]	191	57	245	0	14	31
		Total	[cars]	314	166	370	91	99	121
	SB	In use	[cars]	8	13	10	17	8	9
		Idle vehicles	[cars]	23	14	16	30	0	0
		Total	[cars]	31	27	26	47	8	9
	Spare	Hub operations	[cars]	-	9	-	-	7	-
		Repositioning	[cars]	5	2	4	4	0	1
		Reparation	[cars]	17	10	20	7	6	6
		Total	[cars]	22	21	24	11	13	7
	Total system fleet		[trips/vehicle]	367	214	420	149	120	137
Daily trips per vehicle			[trips/vehicle]	10,75	17,96	9,62	22,01	24,61	21,62
Total number of stations			[stations]	48	48	48	48	48	48
Parking in stations			[parking slots]	33	27	27	47	8	9
Charging points at hub			[parking slots]	-	6	-	-	5	-
Repositioning rate	Free-floating		[operations/h]	10,21	8,41	13,26	16,59	0,23	0,55
	Station-based		[operations/h]	6,03	0,00	2,91	0,00	0,00	0,00
	Maintain FF restriction		[operations/h]	0,00	6,07	0,00	16,59	0,23	0,55
	Maintain EVs battery		[operations/h]	6,03	0,00	0,00	4,46	0,00	0,00
	Total		[operations/h]	16,25	8,41	16,16	16,59	0,23	0,55
Average repositioning time			[h/operation]	0,26	0,35	0,25	0,24	0,50	0,24
Total repositioning time			[hours/h]	4,15	5,09	4,01	4,01	2,39	0,13
Total time lost			[hours/h]	2,07	2,54	2,01	2,01	1,19	0,07
Number of repositioning teams			[workers]	6,2	7,6	6,0	6,0	3,6	0,2
Average team performance			[ops/worker·h]	2,61	1,89	2,69	2,76	1,34	2,76
Average access distance			[meters]	200,0	200,0	199,9	200,0	200,0	200,0
Total demand	Served		[trips/h·km^2]	7,28	6,79	7,49	5,97	5,18	5,49
			[%]	74,55	69,48	76,62	61,10	53,00	56,19
			[trips/day]	3711	3458	3814	3041,	2638	2797
	Lost		[%]	25,45	30,52	23,38	38,90	47,00	43,81
			[trips/day]	1267	1519	1164	1936	2340	2181
	SB fraction		[%]	93,69	89,29	92,56	84,48	91,46	91,32
	FF fraction		[%]	6,31	10,71	7,44	15,52	8,54	8,68

Table 8 – Optimization results. KPIs.

Parameter		**Units**	**Max. Agency Profit**			**Min. Generalized Cost**		
			Scn. 1	**Scn. 2**	**Scn. 3**	**Scn. 4**	**Scn. 5**	**Scn. 6**
Infrastructure costs	**Fleet**	[€/h]	115,32	67,19	92,15	46,92	37,68	29,78
	FF parking	[€/h]	0,00	0,00	0,00	0,00	0,00	0,00
	SB parking	[€/h]	9,48	6,71	6,77	12,83	1,99	2,16
	HUB parking	[€/h]	0,00	7,08	0,00	0,00	5,40	0,00
Operation costs (without repositioning)		[€/h]	391,08	364,45	425,40	320,49	278,00	311,93
Repositioning costs		[€/h]	89,29	109,63	86,41	86,38	51,40	2,84
Access costs		[€/h]	433,90	404,35	445,71	355,58	308,44	326,99
Demand lost	**FF penalties**	[€/h]	232,06	292,16	223,77	372,38	396,57	374,74
	SB penalties	[€/h]	36,51	0,00	0,00	0,00	169,20	141,64
Total agency costs		[€/h]	605,17	555,06	610,73	466,61	374,47	346,70
		[M€/year]	5,30	4,86	5,35	4,09	3,28	3,04
Total users' costs		[€/h]	702,47	696,51	669,48	727,96	874,21	843,38
Total costs		[€/h]	1307,63	1251,58	1280,20	1194,58	1248,68	1190,08
Gen. cost per trip		[€/trip]	4,58	4,70	4,36	5,11	6,15	5,53
Fare		[€/trip]	4,78	4,78	4,78	4,78	4,78	4,78
Revenue neutral fare		[€/trip]	2,12	2,09	2,08	1,99	1,85	1,61
Profit	per trip	[€/trip]	2,66	2,69	2,70	2,78	2,93	3,17
	per day	[€/day]	9865,56	9309,48	10285,20	8465,92	7737,42	8856,59

Table 9 – Optimization results. Costs.

4.2.1 Optimum demand served

In all scenarios, SB served demand is a small fraction of total served demand. This is due to three reasons. The FF preference and lesser coverage makes that only a fraction of users is a potential candidate to access the SB system. SB cars are more expensive than the FF cars because of the associated cost of renting the parking place on a station. And, since only a fraction of users returns the car to stations, serving more SB demand means additional repositioning costs to compensate that imbalance. For those reasons, the optimal system for all scenarios in this case is almost a pure FF system.

Also, in all scenarios only a fraction of the demand is served. This allows increasing the vehicle utilization rates and reducing artificial rebalancing needs, which is translated into reduced agency costs and higher profit.

Difference between both objective functions lays in which is that percentage of served demand (70-75% in case of agency profit maximization and 53-60% in case of minimizing users and agency costs). The reason for that is that no-service penalties are less expensive than the revenue lost when maximizing profit. Therefore, when profit is maximized, more vehicles are necessary. Because of this higher vehicle availability in the max. profit scenario, the average usage of each vehicle (trips/day) decays. This yields a lower profit per trip, but is compensated by the larger demand served.

4.2.2 Electric vehicles and recharging

With respect to the difference between the electric vehicles or ICE, in general, the system seems to perform a bit better when composed only of ICE vehicles (Scenarios 3 and 6). In any case, differences are slight, and different effects compensate each other. For instance, the additional vehicles due to battery recharging tend to be compensated by the lower cost of gasoline vehicles, pushing toward a higher fleet. Also, the operative costs of gasoline vehicles are higher, implying a somehow lower optimal demand to serve.

When comparing the recharging options for electric vehicles, overall, the difference is slightly in favor of decentralized charging. This is because the additional repositioning costs force the system to reduce the fleet of cars, resulting in less demand served than the decentralized recharging at stations.

However, that not diminish the positive effect of installing superchargers. The cost increase is compensated by the quicker recharge. It’s their distribution on a central hub what makes them costlier. In case of splitting the superchargers in different installations, their performance gets very close to the domestic recharging at stations.

Parameter		**Units**	**Decentralized (Scn. 1)**	**ONE HUB (Scn. 3)**	**SIX HUBS**
Fleet size	FF	[cars]	314	166	226,03
	SB	[cars]	31	27	36,31
	Total	[cars]	367	214	286,26
Charging points at hub		[parking slots]	-	6	6
Number of repositioning teams		[workers]	6,2	7,6	6,1
Profit	per trip	[€/trip]	2,66	2,69	2,70
	per day	[€/day]	9865,56	9309,48	9635,01

Table 10 – Optimization results. Costs.

4.2.3 Robustness of optimal results

Robustness is a desirable property in optimization frameworks. A robust optimal solution means that small deviations in the selection of the optimal decision variables imply equally small deviations in the result of the objective function. Errors in the analytical definition of the model, or in the estimated parameters, are unavoidable; but the objective should be that these errors do not affect significantly the final objectives (i.e. the design of the system and the results in costs).

This subsection shows that the optimal results obtained, are robust, in the sense that the effects in costs and profit of the system due to sub-optimal selection of decision variables are small, so that the system may be feasible even when its design is suboptimal. Figure 2 shows the variations on the profit and agency cost as a function of variation of decision variables. See, for instance, that variations of 50% with respect to the optimal FF fleet size, m_{FF}, imply variations in agency costs of 10% or less. Also, the effects on the profit of the system are even less, because larger fleets allow to serve more demand, while for smaller fleets the utilization rate of vehicles might increase.

For the other decision variables, especially for the repositioning period, the result is even more robust. The reason is that, after all, the repositioning period is a convenience variable related to the number of repositioning employees. Note that this latter variable results to be small (6-7 employees working simultaneously). Hiring an additional one would imply a small difference on the overall performance, but relatively a bigger increase on the variable.

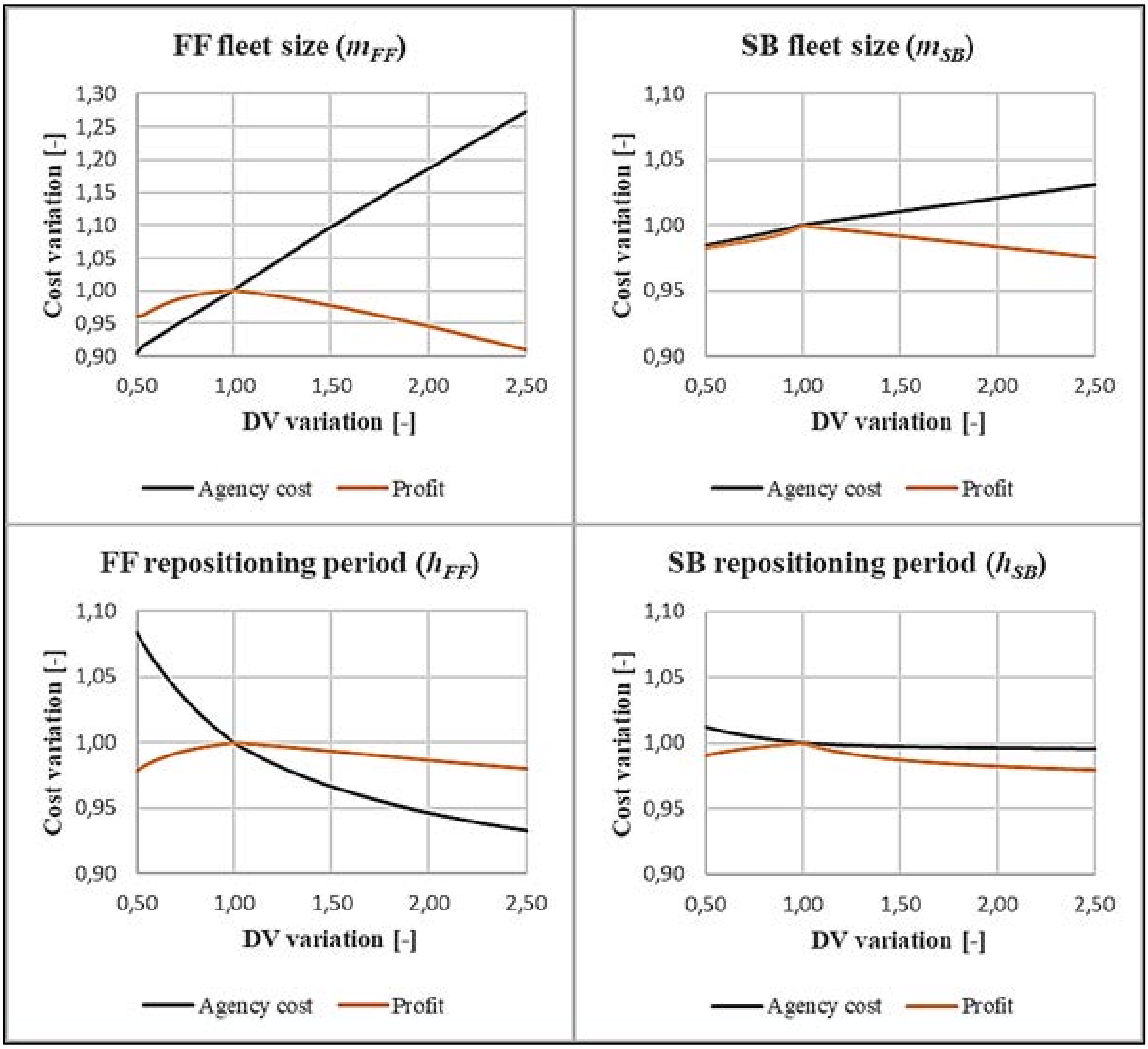


Fig. 2 – Robustness of DVs around the optimum value

5. CONCLUSIONS

An analytical planning model for a one-way mixed FF and SB car-sharing system has been developed. This is based on the modeling of the strategical variables of the system and their relevant trade-offs, using continuous approximations. This analytical approach requires a simplification of the reality (e.g. assumption of spatially uniform demand level) and to obviate some details of operation. However, results provide clear insights, valid in a wide range of contexts and which should be the foundations for further research.

This concluding section summarizes the main findings when the model was applied to a case of study for the city of Barcelona with different scenarios considered. Note that, despite input parameters have been estimated especifically for this case of study, many of them would be very similar for any city of similar size and socio-economical context. So, the insights and considerations to be taken into account would be still valid in many cases if the model is applied in the future in the context of planning a one-way carsharing system.

Take the following bullet points as general conclusions of this document:

- The model gives preference for the FF system. The SB system becomes auxiliary when the difference between SB and FF parking cost is big. A sensitivity analysis of the on-street parking cost would be an interesting point for future research.
- In all scenarios, model shows that it is advisable to leave part of the potential demand not-served (30-35% in case of agency profit maximization and 40-50% in case of minimizing users and agency costs). This allows increasing the vehicle utilization rates and reducing artificial rebalancing. However, the model assumes that potential demand is constant even if a fraction of users is experiencing no-service situations. Further research must be made in order to estimate which is the minimum level of service that must be achieved to maintain that potential demand.
- With respect to the recharging infrastructure, it seems a better option to decentralize the charging points. Superchargers can be as profitable as domestic chargers. Their higher cost gets compensated by their efficiency, which reduces the duration of repositioning tasks.
- The sensitivity of system costs and profit to suboptimal designs is small. This means that the proposed designs are robust, and deviations could be accepted without implying severe penalties. However, it should be noted that this sensitivity is larger when the deployed resources are below the optimal values. This means that special care should be devoted to avoid being excessively conservative in the fleet size deployment, knowing that over-sized fleets almost do not penalize profit.

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