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A Methodology for Designing One-Way Station-Based Carsharing Services in a GIS Environment: A Case Study in Palermo

Gabriele D'Orso * and Marco Migliore

Department of Engineering, University of Palermo, Viale delle Scienze Building 8, 90128 Palermo, Italy; marco.migliore@unipa.it
* Correspondence: gabriele.dorso@unipa.it

Abstract: One-way carsharing is recognized as one of the most popular transportation services in urban areas, being an alternative option to private cars. Over the last decades, a vast amount of literature on the design of specific aspects of this service (fleet size, stations' locations, fare, balancing operations) has formed. However, a holistic approach for designing carsharing services seems not to be developed. This paper proposes a new approach for designing one-way station-based carsharing services, presenting a five-step method, entirely developed in a GIS environment. The first three steps (suitability analysis, site selection analysis, and walkability analysis) allow finding the candidate locations for carsharing stations. After the assessment of the capacity of the potential stations, a location-allocation analysis allows for assessing the fleet size, the number of stations that maximize the coverage of carsharing demand, and their optimal locations. This paper presents a case study: a new one-way carsharing service was designed in Palermo (Italy) and compared to the existing carsharing service operating in the city. The results highlight that the current carsharing supply is undersized, having about 45% fewer stations and about half the cars compared to those resulting from the model, leaving some POIs unserved.

Keywords: one-way carsharing; GIS; decision support systems

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1. Introduction

In recent decades, carsharing has established itself as one of the most common sustainable mobility options and an important alternative to private cars in cities [1]. In October 2018, carsharing was operating in 47 countries and 6 continents, with approximately 32 million carsharing users and 198,000 vehicles worldwide [2].

Today, numerous private and municipal companies in cities around the world offer a wide and diverse range of carsharing services. Among this wide range of services, one-way station-based carsharing is one of the most adopted by carsharing operators, offering users more flexibility than traditional round-trip carsharing. One-way carsharing allows users to drop off a rented car to any designated station, which could be different from the pick-up station [3].

Carsharing became popular for bringing many benefits to cities, communities, and individual users. First, reducing private car dependency in urban areas, it may help solve the growing problems of traffic congestion, air pollution, and lack of public space that plague our cities [4–7]. Many carsharing users change their travel habits, allowing the reduction in private car ownership [8–11], which is today too high in comparison with the mobility needs of citizens, especially in Italian cities [12]. Thus, carsharing users gain the flexibility of private vehicles and reduce personal transportation costs by paying only user fees and avoiding maintenance costs [13]. Moreover, private cars are often oversized for most of their trip purposes [14]: people drive alone for most of their trips although they buy large family cars. Providing a set of different car models, such as low-emission vehicles, carsharing operators make it possible to adapt the vehicle to the actual travel needs, avoiding oversized vehicles and providing greater usage flexibility, for example allowing users to bypass the traffic restrictions imposed by local authorities.

Despite the demonstrated benefits of carsharing services and their global diffusion, the utilization of carsharing remains relatively low [15]. Indeed, carsharing is not a reasonable option for every traveler. Carsharing is an efficient mode of transport especially for occasional trips and trips with medium or low frequency. Those who do not own a car or do not have regular access to it are more likely to enroll in a carsharing scheme or to use carsharing regularly, complementing lifestyles oriented towards public transport in urban and nonurban areas [4].

In recent years, strong competition with new shared mobility services such as dockless bikesharing, e-scooter sharing, and ride-hailing services like Uber has eroded the carsharing market. For instance, Autolib in France experienced a usage rate of less than 20% per day [15] and shut down in July 2018 due to economic difficulties and in spite of high public subventions [16]. In 2019, carsharing and peer-to-peer carsharing accounted for less than 10 percent of the shared mobility global market [17]. Considering the total number of rides made by shared mobility services in Italy, the share of carsharing rides decreased from 44 to 13% from 2019 to 2022, while the share of e-scooter sharing rides reached 50% of the total [18].

In this perspective, a crucial factor for the success of carsharing services is the proper design of the elements that make up the system: location and capacity of stations for station-based services, size of the rental area for free-floating carsharing, fleet size, fare, and integration with public transportation services [19]. Depending on the characteristics of the city, especially its extension and topography, but also on the type of user and the type of trips that the carsharing operator wants to target, it is necessary to choose the business model that is more adaptable to the mobility habits of citizens and attractive [20]. Therefore, the service must be city- and customer-oriented, adapting to the city and its inhabitants through unique and customized solutions.

This paper proposes a new approach for designing station-based one-way carsharing in medium-sized and large cities, using GIS software to optimize the location of carsharing stations and the fleet size to create a service that targets a large and diverse user base. The contribution to research of the proposed method lies in several factors: (1) as part of a holistic approach, different analyses such as suitability and location-allocation analyses were integrated into a single procedure developed entirely in a GIS environment, using functions and algorithms typically implemented in these tools; (2) the suitability of the areas for accommodating the carsharing stations was evaluated not only taking into account the characteristics of demand, i.e., based on the presence or absence of an adequate number of residents belonging to the typical user base, but also taking into account the supply side, based on the accessibility of points of interest (POIs) and traffic attractor poles, as well as taking into account multimodality and integration with public transport; (3) the relationship between carsharing and walkability of the areas where carsharing stations are located was explored, since users typically walk from their origin to the pick-up station and from the drop-off station to their destination. Although many studies on walkability [21] have been developed in recent years and spatial access is one of the barriers for carsharing that has been studied by many different researchers [22], introducing a walkability assessment during the identification process of possible locations for carsharing stations represents, as far as we know, a novelty in the scientific literature on carsharing. Although the method is generalizable, the resulting carsharing supply is customized for each city where it is applied, since the characteristics of the carsharing demand, the peculiar distribution of POIs, and the specific pedestrian network of that city are considered. The remainder of the paper is organized as follows. Section 2 gives a brief overview of the methodologies used to design carsharing services. The new methodology is described in Section 3. In Section 4, a case study is presented: the city of Palermo, Italy, was chosen as the study area. In Section 5, some conclusions are drawn.

2. Literature Review

This paper aims to fill a gap in the literature on carsharing: to the best of our knowledge, no one has developed a unitary method for designing one-way station-based carsharing services using a single software. In the literature, there are many examples of methodologies that make it possible to design one or another aspect of this service.

Some authors developed new methodologies for finding the optimal fleet size. For example, Monteiro et al. [23] developed a methodology for assessing the fleet size, maximizing the number of potential customers for a station-based carsharing. Hu and Liu [24], on the other hand, set the maximization of the company's profits as the main objective of a model to size the fleet and determine the optimal capacity of the stations, considering road congestion.

Other authors developed methodologies to find the optimal location and the capacity of the stations. For example, Changaival et al. [25] proposed a novel optimization model for the round-trip carsharing fleet placement problem. Huang et al. [26] developed a mixed-integer nonlinear programming model to solve the carsharing station location and capacity problem with vehicle relocations. The optimization of the number, locations of the stations, and fleet size of a one-way carsharing service is, on the other hand, the goal of the method proposed by Correia and Altunes [27], which also tends to maximize profits.

In order to estimate the demand, over the last few years, agent-based simulation models have emerged, such as the one proposed by Ciari et al. [28].

Finally, fare definition is another crucial aspect investigated by several scholars. Perboli et al. [29] dealt with the design of carsharing prices, comparing the fare structure applied by four different operators in Turin through a Monte Carlo simulation. Jorge et al. [30], instead, developed a model in which prices vary by zone and time of day to minimize vehicles relocations and maximize profits. Pantuso [31] proposed two formulations for a pricing-based carsharing relocation problem, allowing a carsharing operator to set the price of carsharing rides between different zones of the city and decide the relocations to better serve demand.

All these design techniques consider the elements that characterize the service as separate, or, at most, investigate, with a multiobjective approach, only some of the relations that exist between them, neglecting others; indeed, all the aspects mentioned above are intertwined with each other and the effects of the design of one of these elements affect all the others. For example, a method to determine the optimal location of carsharing stations results in a number and distribution of the stations having direct consequences on the fleet size. Likewise, the capacity and location of the stations are influenced by the design of the pricing strategies. Fares should be set considering not only the balance between the carsharing company's revenues and expenses, and therefore the potential demand (on which revenues depend) and the fleet size (on which costs depend), but also the distribution of demand on the territory, the type of user to be served, and the location and type of stations (i.e., if they are stations mainly used as pick-up points or drop-off points), thus being intimately linked to the design mechanisms of these additional aspects. Finally, the estimate of carsharing demand cannot overlook the impact that fleet size, the pricing, and the location of stations have: an undersized fleet, prices perceived as too high, or a location of the stations in areas that are not very accessible necessarily contribute to decreasing the demand that the service may be able to attract. For example, the case of Autolib showed that as an increasing number of registered users competed for a relatively stable number of cars, it became more difficult for users to easily find an available car [32]. Considering existing services, a TRB report also listed nonaffordable ride prices among the top barriers for joining a carsharing service [33]. Therefore, a unitary design approach, which considers how the different elements that characterize the carsharing service are intimately linked to each other, is needed.

3. Method

The method is divided into five steps (Figure 1): after carrying out stated preferences/revealed preferences surveys to find the target user profile, (1) a suitability analysis model allows the identification of urban areas that are best suited to accommodate a carsharing station from the point of view of potential demand; (2) a site selection model identifies the candidate locations for carsharing stations at a more detailed level, taking into account spatial constraints, pedestrian accessibility, visibility, and proximity to POIs; (3) a walkability analysis aims to verify the actual suitability of the candidate locations considering pedestrian accessibility to them and the quality of the pedestrian environment; (4) a preliminary assessment of the capacity of candidate stations allows the assignment to each station of a number of parking spaces and vehicles necessary to satisfy the potential demand it can attract; (5) a location-allocation analysis makes it possible to assess the number and spatial distribution of stations that optimize the coverage of demand, taking into account the assigned number of parking spaces and vehicles. At the end of the methodology, the capacity of each station is verified, considering the demand assigned to it assessed by the location-allocation algorithm. The objective of the methodology is to design a carsharing service that is appropriately sized in terms of the number of stations and vehicles in relation to the potential demand in the area. This leads to finding not only the number but also the optimal location of carsharing stations.

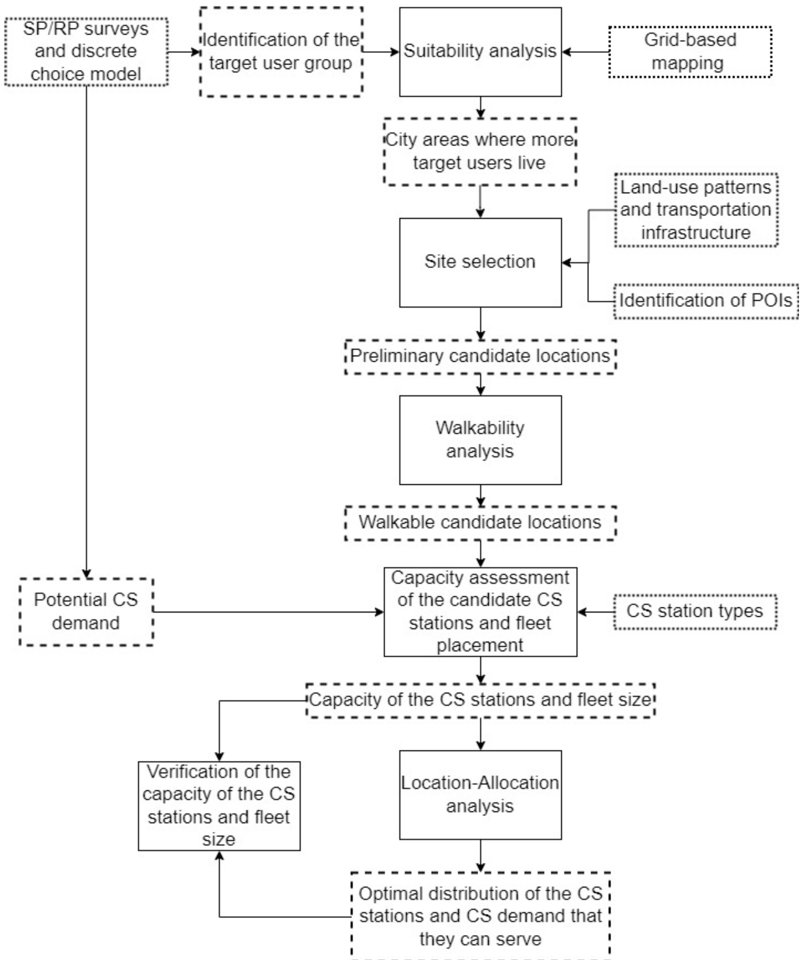

Figure 1. Methodology framework: steps of the method (solid line), inputs (dotted lines), and outputs that become inputs for the next step (dashed lines).

3.1. Suitability Analysis

The first phase of the process is a suitability analysis to identify the urban areas that can generate the largest share of carsharing users considering the affinity of the residents to the carsharing typical user profile (Figure 2).

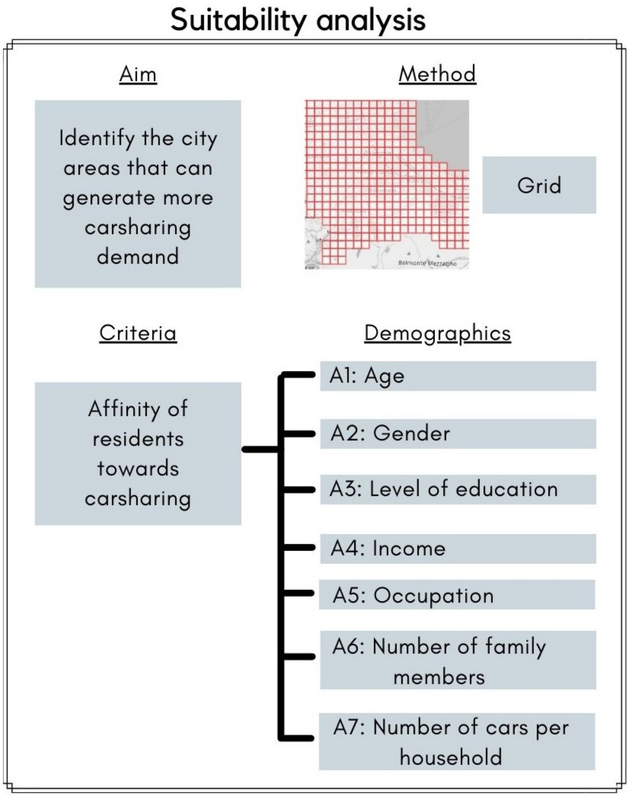

Figure 2. Suitability analysis.

Carsharing neighborhoods are more likely to have higher shares of one-person households and residents with bachelor's degrees, more workers commuting by transit and nonmotorized modes, lower vehicle ownership levels, higher population density, and more walkable environments than non-carsharing neighborhoods [34]. Therefore, the methodology provides for the exclusion of areas whose contribution to carsharing demand cannot be significant due to their characteristics and the demographic profile of their inhabitants.

The approach is to discretize the space by an orthogonal grid, dividing the urban area into n square cells whose side length is the average maximum distance that carsharing users accept to walk to reach the nearest carsharing station. The acceptable walking distance may vary from city to city depending on whether citizens are more likely to walk or not [35–37].

In this preliminary analysis, the suitability of the n grid cells for siting one or more carsharing stations is based on a single criterion, namely, the ability of these cells to generate carsharing demand that can justify the presence of a station. Therefore, it is necessary to accurately assess the demographic profile of the target customers, since carsharing demand will consist mainly of these users. The profile of the target customers can vary from city to city. Thus, prior to the suitability analysis, stated preferences/revealed preferences surveys should be conducted to identify the target group.

First, it is necessary to select the demographic and socioeconomic variables to be evaluated within each grid cell and useful for identifying the carsharing target user:

- Population by age, gender, level of education, and occupational status.
- Average income of resident households.
- Average number of family members.
- Average number of cars per household.

As a result of the suitability analysis, a suitability score, ranging from 0 to 1, is assigned to each grid cell; this score depends on the extent to which the inhabitants of the grid cell match the target user profile. This score also depends on the values that each variable has for each cell. A weight can also be assigned to these variables if some of them have a greater impact on characterizing the typical user of the service. These weights should be determined by a panel of experts (such as the managers of the carsharing company). A useful method to assign these weights could be the Analytic Hierarchy Process.

Suitability analysis can be performed through GIS software, directly using the features already available in some of these software: ArcGIS, for example, allows this type of analysis to be performed through the "Suitability Analysis" tool in the "Business Analyst" toolbox.

Each variable X_i (i = 1, . . ., m) that is considered as a suitability criterion, such as the number of inhabitants aged between 30 and 59 years, takes a certain value $X_{i,j}$ in cell j. Therefore, for each grid cell j (j = 1, . . ., n) and for each variable X_i, a weighted score $weighted\_score_{X_{i,j}}$ is calculated according to the following rules:

- If the correlation between the variable X_i and the affinity for carsharing is positive, the weighted score is equal to the product between the weight "$weight_{X_i}$" attributed to the variable and the percentage difference of the value assumed by the variable compared to a target value:

$$weighted\_score_{X_{i,j}} = weight_{X_i} \times \left[\frac{(X_{i,j} - minX_i)}{(maxX_i - minX_i)} \right] \quad (1)$$

where $maxX_i$ and $minX_i$ are the maximum and minimum values assumed by the variable considering the n cells.

- If the correlation between the variable X_i and the affinity for carsharing is negative, the weighted score is equal to

$$weighted\_score_{X_{i,j}} = weight_{X_i} \times \left[\frac{(maxX_i - X_{i,j})}{(maxX_i - minX_i)} \right] \quad (2)$$

The suitability score reached by cell j is given by the sum of the weighted scores obtained with reference to the variables taken into consideration:

$$suitability\_score_j = \sum_{i=1}^{m} weighted\_scoreX_{i,j} \quad (3)$$

The suitability assessment distinguishes between the cells into which the territory is divided: only those areas that exceed a pre-established threshold of the suitability score will be considered as potential areas for carsharing stations. This threshold is set by the carsharing company depending on the financial resources and the objectives for covering the potential demand that it seeks.

3.2. Site Selection

The suitability analysis allows for the identification of those areas that may generate demand for carsharing; however, it does not allow the identification of the areas where there are major attractions and potential destinations as potential locations for carsharing stations. Another limitation of the suitability analysis is that candidate locations are not yet precisely located within the identified cells. Therefore, to overcome these limitations, a model for site selection was developed (Figure 3). This model first allows the identification of the possible POIs, i.e., those locations representing the possible destinations of the trips made by the carsharing users, in a background map of a GIS software. The primary purpose is to identify additional locations that could not be included in the cells selected by the suitability analysis. Indeed, many POIs could be outside the cells resulting from the suitability analysis, which only considers the socioeconomic characteristics of resident citizens and, thus, the most frequent starting points of carsharing trips.

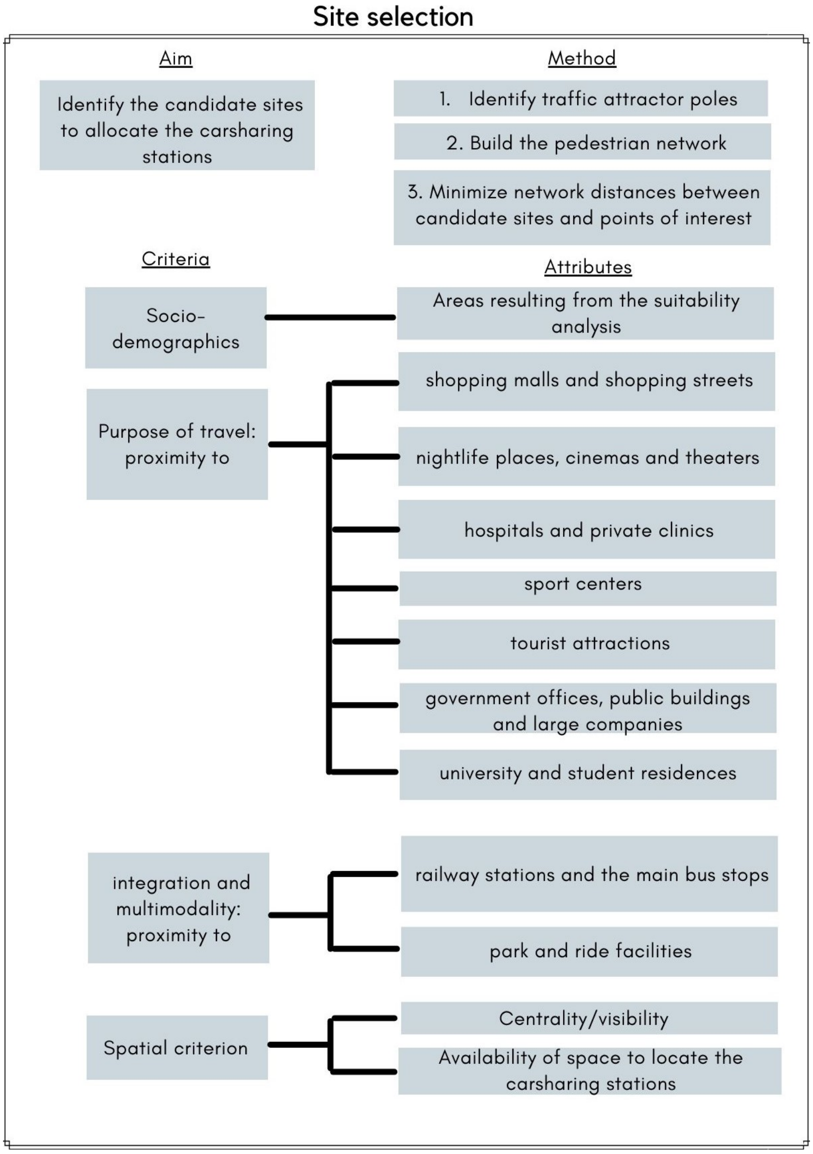

Figure 3. Site selection analysis.

At the same time, this model allows the identification of one or more candidate locations in the grid cells that achieve a suitability score above the threshold. In this case, if there are POIs within the cells, the identification of these points allows a better choice of the candidate locations of carsharing stations within the cells. The site selection model described here proposes that candidate sites are selected such that all POIs within the cells can be reached by walking, traveling at most the average maximum distance accepted by carsharing users. In fact, carsharing users typically walk to the nearest carsharing station and, at the end of their trip, from a carsharing station to their destination; thus, only areas that can be reached by walking from the carsharing stations can be served by carsharing.

To better identify the areas where candidate sites should be placed, it may be useful to assess the pedestrian catchment areas of the POIs in a GIS software: these are the areas that include all segments of the pedestrian network that are accessible within the maximum distance that most users are willing to walk. Identifying the pedestrian catchment areas makes it possible to exclude the locations of candidate sites that do not allow pedestrian access to POIs. Therefore, it is important to have the urban pedestrian network in a format that can be uploaded to GIS software to perform the site selection analysis. These data are generally not acquired by city governments or available to the public. In most cases, the pedestrian network, consisting of sidewalks and crosswalks, must be created from the beginning in a GIS environment.

In addition to proximity to POIs, the site selection analysis also considers the visibility and centrality of the location: carsharing stations must be located on well-known streets and be easily recognizable to users. Another criterion is considering spatial constraints: the candidate sites must be placed in roads that have space for reserved parking slots. Therefore, considering spatial constraints and visibility, the following criteria will be considered when selecting candidate sites within the cells resulting from the suitability analysis:

- In cells with no POIs, the candidate site will be located as centrally as possible, to ensure greater coverage of the demand generated by the cell.
- In cells with one POI, the candidate site will be in close proximity to that point. However, supposing that the POI is located in the peripheral areas of the cell, it is preferable to place the candidate site in a more central location that ensures greater coverage of the potential users generated by the cell, but always at a walkable distance to it.
- In the cells with multiple POIs, as mentioned earlier, the candidate site will be located at a point where all POIs can be reached within the maximum distance the user can walk.

As mentioned earlier, some POIs can be outside the cells resulting from the suitability analysis. In this case, always considering spatial constraints and visibility, candidate sites will be selected based on the following rules:

- If the POI is near one of the cells, a check will be made to see if the station's location determined for that cell can serve the POI within the maximum walkable distance.
- If the POI is outside and far from the cells that resulted from the suitability analysis, a possible location that could serve it will be identified in the immediate vicinity.
- If there are several POIs close to each other and far from the cells, only one candidate site is located so that these POIs can all be reached within the maximum allowable walking distance.

In defining the POIs, reference was made primarily to the most common reasons for carsharing trips. Carsharing is often used to reach destinations related to leisure and recreational activities such as shopping. For example, in Italy, leisure and shopping activities are the purposes of travel for 58% of carsharing trips [38]. There are also many carsharing trips to visit relatives and friends (10%) or to give rides to relatives and friends who do not have the opportunity to drive a car (8%). A total of 5% of carsharing trips are made for occasional commissions related to their employment, such as, for example, meeting a colleague at a professional studio or going to a government office.

Considering these trends, the following POIs can be considered as potential attractions for carsharing users:

- Shopping malls and shopping streets.
- Nightlife places.
- Cinemas and theaters.
- Sports centers.
- Hospitals and private clinics.
- Government offices open to public access and public buildings.

To extend the service catchment area to specific user groups, the following services may be further included:

- University centers and student residences, which can intercept the demand of non-resident students and visiting professors who generally do not have their own car in the city.
- Tourist attractions and places of interest for tourists (museums, monuments, and large hotels), which can make the service attractive to tourists.
- Large companies, which offer the carsharing service to employees as an alternative to the company car.

Considering that carsharing can be used as part of a multimodal behavior, especially by commuters not owning a car, train stations and the main bus stops were also included as POIs.

3.3. Walkability Analysis

The user experience of carsharing is partly comparable to the travel experience of a pedestrian, as the trips between carsharing stations and users' origins and destinations are generally made by walking. Poor walkability of the areas where the stations are located could affect the use of carsharing services. Therefore, the walkability of these areas must be evaluated to determine where best to locate the service stations. In this perspective, a methodology developed in [39] was integrated as a step (Figure 4) to measure the walkability of pedestrian routes around carsharing stations: it helps to identify the areas to be avoided for the locations of stations, as they are not walkable. Based on the scientific literature on the walkability factors affecting the user's route and mode choice, the micro-scale walkability indicators and the weights presented in Table 1 were considered.

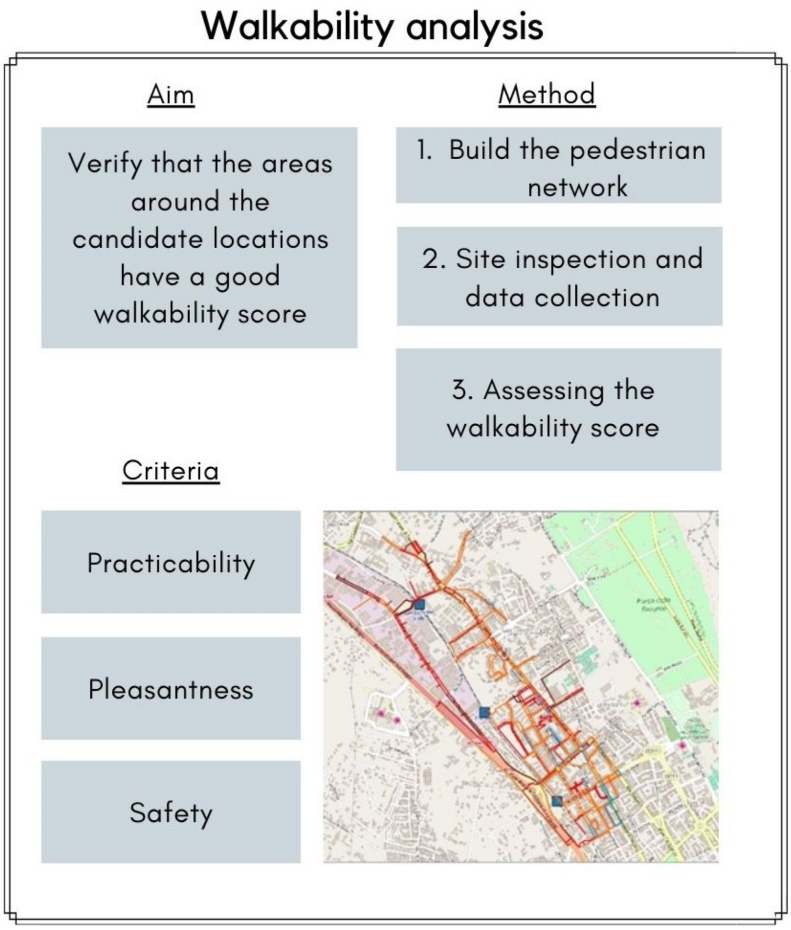

Figure 4. Walkability analysis.

The walkability assessment follows the following steps:

- Building the pedestrian network in a GIS environment.
- On-site inspections.
- Evaluating indicators and assigning scores for each pedestrian arc.
- Attribution of weights and calculation of the walkability score.
- Identification of arcs with poor walkability.

- Changing the location of candidate sites from poorly walkable streets to nearby streets with a better walkability score, always considering the limitations imposed by the site selection model (proximity to POIs, visibility, centrality, and space constraints).

For further information on the walkability assessment, see [39].

Table 1. Indicators for the walkability assessment by [39].

Factors	Weight	Indicators	Description
Practicability	0.3	Sidewalk slope	0: Steep slope for elderly people and wheelchair users (>5%) 1: Manageable slope (<5%)
		Pedestrian LOS	0: High pedestrian flows, small pavement width, obstacles (LOS D, E, F) 1: Low pedestrian flows, adequate sidewalk width or absence of obstacles (LOS A, B, C)
		Surface degradation	0: Presence of holes or dips, degraded sidewalk 1: Absence of holes or dips, pavement in a good state
Pleasantness	0.3	Street furniture	0: Absence of baskets, benches, and other elements of street furniture 1: Presence of baskets, benches, and other elements of street furniture
		Shelter for rain and sun	0: No shelter from sun or rain 1: Presence of shelters from sun or rain
		Green spaces	0: Absence of flower beds or green areas 1: Presence of flower beds or green areas
		Shops	0: Absence of shops 1: Presence of shop windows
		Building context, land use mix, and urban design	0: Degraded urban landscape (presence of damage to urban furniture, lack of cleanliness, presence of graffiti and abusive posters in buildings, presence of buildings with a degraded facade, presence of industrial buildings) 1: Nice urban landscape (perfect functionality of urban furniture, adequate cleaning, presence of well-maintained buildings)
Safety	0.4	Streetlights	0: Poor lighting according to the Uni standard (UNI 11248 [40]) or lack of streetlights 1: Proper and efficient streetlights according to the Uni standard (UNI 11248 [40])
		Traffic volume and vehicle speed	0: High traffic volumes (>1000 vph) or high speed (>50 km/h) 1: In other cases 2: Free flow (<300 vph) and low speed (<30 km/h)
		Barriers for pedestrian protection from vehicles	0: Absence of protection elements 1: Presence of barriers for pedestrian protection from vehicles
		Traffic control signal at intersections	0: Absence of traffic control signal at the intersection 1: Traffic control signal at the intersection but presence of conflicts between different traffic components 2: Traffic control signal that eliminates conflict points between vehicles and pedestrians
		Driveways	0: Presence of driveways along the way 1: Absence of one or more driveways

3.4. Capacity of the Candidate Stations and Fleet Placement

Once the candidate locations of the CS stations have been determined with the site selection analysis and verified with the walkability analysis, it is necessary to assign the capacity to each station, i.e., the number of parking slots (Figure 5). A different criterion was used depending on the type of station the candidate location could accommodate. We classified a carsharing station based on the number of trips attracted and generated as follows:

- "Origin-oriented" station: the ratio of attracted trips to total trips is less than 40%. The station is not located near POIs but is used primarily by users living nearby as a starting point for trips. The candidate stations are those identified in the grid cells having a suitability score over the threshold but not including POIs. In this case, these stations must have more occupied than free parking slots in the morning so that users can easily find a vehicle and start a trip during the day.
- "Mixed" station: the ratio between attracted trips and total trips is between 40% and 60%. The station is used as both a starting point and a destination for carsharing users. The locations considered for these stations are in grid cells that have achieved a suitability score beyond the threshold and also have POIs; it must be ensured that a sufficient number of cars and free parking slots are available throughout the day.
- "Destination-oriented" station: the ratio of attracted trips to total trips is between 60% and 80%. The station is primarily used as a destination by carsharing users. Locations

that serve POIs outside of the grid cells identified with the suitability analysis can be considered for this kind of station. These stations must have more free than occupied parking slots in the morning so that users can find a reserved slot during the day. Most parking slots must also be largely free at the end of the day so that too many vehicles are not assigned to underutilized stations as a starting point for rentals.

- Stations serving large attractor poles: the ratio of attracted trips to total trips is over 80%. In this case, the station serves a major attraction located in a sparsely populated area, such as a shopping center. At the beginning and at the end of the day, the parking slots for carsharing may be free since no one will use the station as a starting point for carsharing trips.

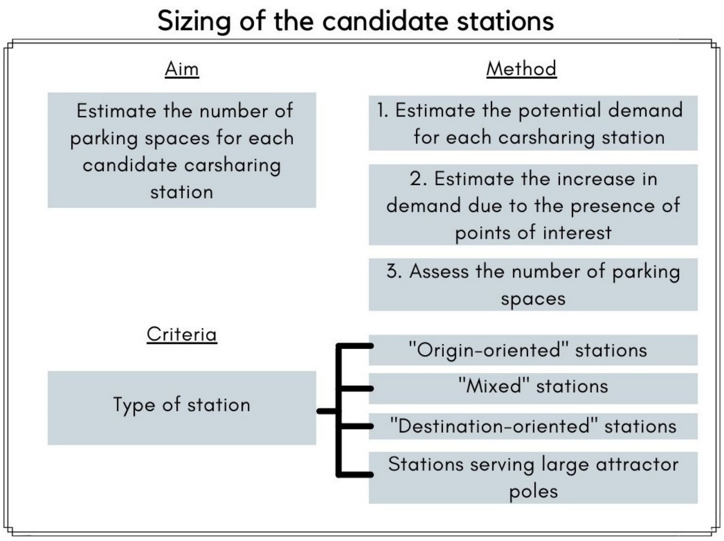

Figure 5. Sizing of the carsharing stations.

For the "origin-oriented" stations and the "mixed" stations, the criterion provides for estimating the number of rentals that each grid cell can generate. This number, of course, depends on the demand for carsharing in the city. To estimate the potential demand, we calculated the number of residents in each grid cell that can belong to the target user group according to age, education level, income, occupation, and family composition. Of these, only a certain percentage will find it useful to subscribe to carsharing and will do so. This percentage can be estimated by means of stated preferences/revealed preferences surveys and a discrete choice model based on the random utility theory.

Every day, only some of the subscribers living in a cell will use carsharing. Subscribers living in a grid cell will use the service with an average frequency that typically ranging from one to four times per month [38]. To determine the number of vehicles needed, and, thus, the number of parking slots needed for each location, it is necessary to assess the number of users who are likely to request the availability of a service vehicle at the site at the same time or at a time when the fleet could not yet be rebalanced. Carsharing trips are sporadic and usually made for trip purposes other than education and work; thus, rentals do not occur at the same time and cars can hopefully be used by several people sequentially during the day.

Based on these considerations, for each grid cell, the number of inhabitants that have the typical characteristics of carsharing users can be used to estimate the number of users that request to carshare, and, thus, the minimum number of carsharing cars that must be available to users. This number of cars is assigned to the candidate location in this cell. Each station usually consists of a number of two to four parking slots, also in order not to reduce the parking spaces available for private vehicles on the street by too much. Thus, knowing the number of cars needed in each cell of the grid, one can derive the number of parking slots for each station under consideration. For "origin-oriented" and "mixed" stations, the total number of parking slots assigned to each station is equal to the number of cars needed to serve users plus one: at least one parking slot must be free to accommodate users using the station as a destination. At this point, it is also possible to evaluate, for each cell of the grid, whether a single station is sufficient to respond to the requests of potential resident users: if the required number of vehicles relative to the number of users is greater than three, a single station is not sufficient and additional stations must be placed. The additional locations will be selected according to the criteria of the site selection model.

For candidate sites classified as "destination-oriented" stations or stations with major attractions, near one or more POIs, the number of parking slots is calculated based on the number of users the POIs can attract. The number of daily visitors at POIs can be used as a reference value to understand which poles can attract the most visitors. However, since these locations are mainly used as destinations for carsharing trips, the following values can be used:

- Only one car at the "destination-oriented" stations.
- Zero cars at the stations serving the major attractor poles.

Depending on the ability of the POIs to attract users, we considered that:

- For "destination-oriented" stations, the number of parking slots is equal to the number of free parking slots, which will vary between one and three, plus one (the parking slot occupied by the carsharing vehicle).
- For stations serving large attractor poles, the number of parking slots will vary between three and four, and all parking slots will be free.

3.5. Location-Allocation Analysis

After the potential locations have been identified in the previous phases of the methodology, the location-allocation analysis aims to identify among them those that allow demand to be met in order to achieve an optimal distribution of carsharing stations (Figure 6).

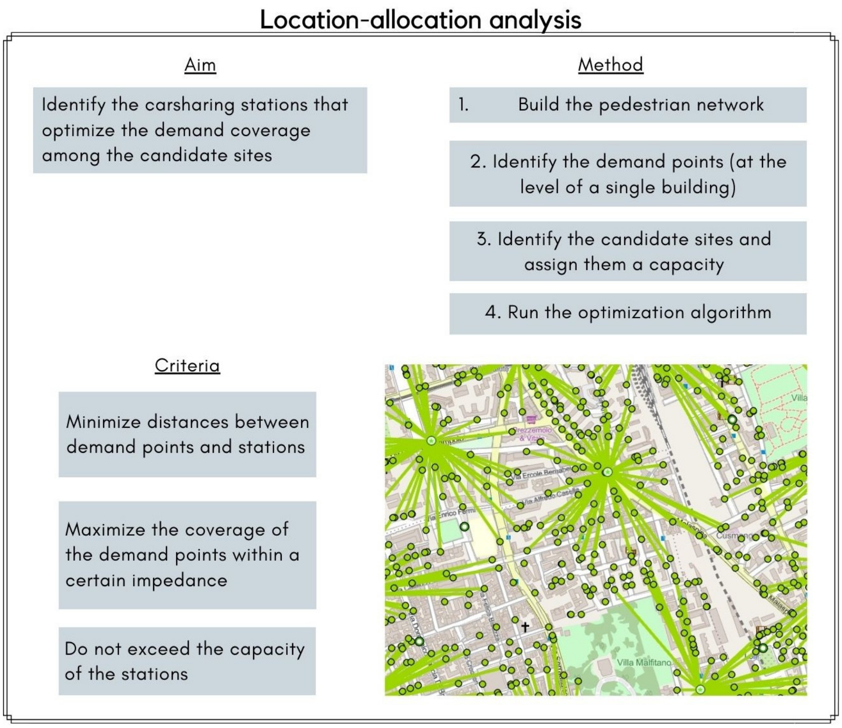

Figure 6. Location-allocation analysis.

The optimal distribution of stations of a station-based carsharing service in an urban area falls into the category of problems that private companies and public administrations face when they want to provide a service that is as accessible as possible to the users belonging to their target group: we generally speak of location-allocation problems. This type of problem includes, for example, the location of a new school, hospital, fire station, public access office, or the opening of a new store or goods distribution center. Problems of this type are both mathematical and geographical in nature. The more general formulation of these problems is as follows: suppose we have a set of n points distributed in a space, a numerical weight associated with each point, and a set of m points without a predetermined position, then the location-allocation problem consists of finding the position in space of points m (location) and associating each point n or part of it with a point m (assignment) in such a way that a certain objective function is optimized.

Among the location-allocation problems, finding the optimal location of carsharing stations can be considered as a coverage problem and a capacitated facility location problem. In this case, M potential locations for carsharing stations are identified on a graph with N nodes (buildings). Each node of the graph is associated with a demand that needs to be satisfied, but each station has a specific capacity: namely, carsharing stations have a limited number of parking spaces and cars that can be found there. Therefore, each station can only answer a certain number of requests at a time: the demand that exceeds the capacity of one station must be forwarded to another station that can be reached within a walkable distance.

The optimal solution must aim to satisfy the demand of each node by placing the carsharing stations at some of the M candidate locations and allocating the demand coming from the nodes to these stations without exceeding their capacity. The assignment of demand to stations must be conducted in a way that pursues the further goal of minimizing the distance between the demand node and the station to which it is assigned.

Because of the strong geographic nature of this family of problems, location-allocation problems have long been among the analyses that geographic information systems can perform using their functions and algorithms. An example of this is the ArcGIS software that we used in our case study to perform this type of analysis (version: ArcGIS Pro 2.7).

The "Maximize Capacitated Coverage" command can be used to solve location-allocation problems for facilities with capacity limits for a given network. The software requires the following data as input:

- Geographic location of candidate sites, imported as a georeferenced layer, with their capacity as an attribute, i.e., the demand they can serve.
- Pedestrian network as line layer with arches representing sidewalks and crosswalks.
- Demand points, that is, a layer of points representing residential buildings, georeferenced and having as attribute the demand they express.
- Maximum number of stations that the algorithm must deliver as a result.

The identification of candidate sites was conducted in the previous phases of the methodology in a GIS environment. Each site must now be assigned a capacity that the software algorithm considers to be the maximum value of demand that can be allocated in the station. This capacity was therefore set in terms of the maximum number of residents that belong to the target user group that live near the candidate station and that can be served by it, based on the number of cars assigned to it.

The pedestrian network can be modeled as an undirected weighted graph, with arches representing sidewalks and crosswalks to consider users' ability to walk on the streets in both directions where they need to pick up or leave the shared vehicle. It is important to ensure that the algorithm can only assign demand to candidate stations that are within a distance that is at most equal to the maximum distance that carsharing users are willing to travel to access the service. For this purpose, a "cutoff" can be defined, i.e., a network distance limit between the demand points and the candidate station; beyond this limit, the algorithm cannot connect the demand points to the candidate station and cannot assign the demand to the station.

The demand points are the places from which this demand is generated: buildings contain users. Therefore, it is necessary to know, for each residential building, the number of people belonging to the target group living in this building. The GIS software allows the estimation of the demand expressed by the single building from the number of inhabitants of the grid cells through some geoprocessing operations.

Before starting the algorithm, some of the candidate sites can be set as required sites: these are candidate locations that the algorithm absolutely must select. If the carsharing company has identified locations where it intends to install a carsharing station, for example, because they are close to strategic poles to be served, these locations can be imported as required stations. It is necessary to specify the number of stations that the algorithm must provide as a result. Therefore, in order to obtain an optimal result, various simulations must be performed by varying the number of stations.

A result can be considered optimal if the sites selected by the algorithm serve 95% of the demand that would have been met if the total number of candidate sites resulting from the site selection analysis had been considered.

The result of the algorithm is the selection of those locations that optimally meet the demand and minimize the distances between the demand points and the stations, taking into account the capacity of the stations. Thus, the first result is the optimal distribution of stations, which ensures that most of the demand is satisfied without exceeding the capacity of each station. A second outcome of the procedure is that for each location that the algorithm selects to allocate carsharing stations, it estimates the demand that it will serve.

3.6. Verification of the Capacity of the Carsharing Stations and the Fleet Size

The location-allocation analysis allows demand to be allocated at each selected station. It is therefore appropriate to follow up this analysis by reviewing the fleet size and the number of parking spaces assigned to each selected station in light of the demand values assigned by the algorithm. In fact, due to proximity to other selected sites, some stations will serve a smaller number of users than they were assigned prior to the site assignment analysis: In this case, these stations can be downsized, reducing the number of parking spaces and requiring a smaller number of vehicles.

As a result of the method, we obtain a carsharing service with an optimized number of stations, parking spaces, and cars to meet the potential demand and make the main POIs accessible.

3.7. Fare Structure

The rates of station-based services generally vary according to the distance traveled, the rental time, and the type of vehicle rented. In order to incentivize users to use shared cars more, the rates can be structured dynamically. In accordance with the methodology developed here, operators could vary the rates according to the type of station ("origin-oriented", "mixed", "destination-oriented", and serving a large attractor poles). In particular, the following criteria could be followed:

- The rental of cars positioned in a "destination-oriented" station or in a station serving a large attractor pole could be discounted if the destination of the carsharing trip, stated during the booking phase, was an "origin-oriented" station or a "mixed" one.
- The rental starting in an "origin-oriented" or "mixed" station could suffer a malus, i.e., an increase in the fare, if the destination of the carsharing trip is a "destination-oriented" station or a station serving a large attraction pole.
- In all other cases, the base rate may apply.

The application of this criterion would favor the fleet relocation by the users, thus reducing the costs that the company would have to incur to carry out this operation on a daily basis.

4. Case Study

In order to apply the methodology to a case study, we chose the city of Palermo, where a station-based carsharing service, called amiGo, operates. This service has 159 cars (last data referred to December 2021) and 83 stations (April 2024). We compared the existing service with the service resulted from the application of the methodology.

A grid of cells with each side 500 m long was created in the GIS software, covering the whole city area. We considered cells with 500 m as side length, which is the maximal walking distance typically accepted by carsharing users [41].

The profile of the average carsharing user was obtained from a customer satisfaction survey conducted in 2017 [42]. The target group is composed of people between 30 and 59 years old, with a high school diploma or college degree and an occupation that guarantees an above-average income. Therefore, the following variables and their weights were considered in the suitability analysis:

- The percentage of the male resident population (2.5%, positive influence).
- The number of residents aged between 30 and 59 (20%, positive influence).
- The number of residents with university degrees (25%, positive influence).
- The number of residents with high school diplomas (5%, positive influence).
- The number of unemployed residents (25%, negative influence).
- The number of resident families with annual income between EUR 28,200 and EUR 38,299 (5%, positive influence).
- The number of resident families with annual income between EUR 38,300 and EUR 55,191 (15%, positive influence).
- The number of resident families with an annual income exceeding EUR 55,192 (2.5%, positive influence).

The weights were determined in a discussion with managers and technicians of the carsharing company and university professors. We performed the suitability analysis using the Business Analyst toolbox in ArcGIS: the software uses an apportionment algorithm to find the population data within each grid cell. The results of the suitability analysis can be seen in Figure 7.

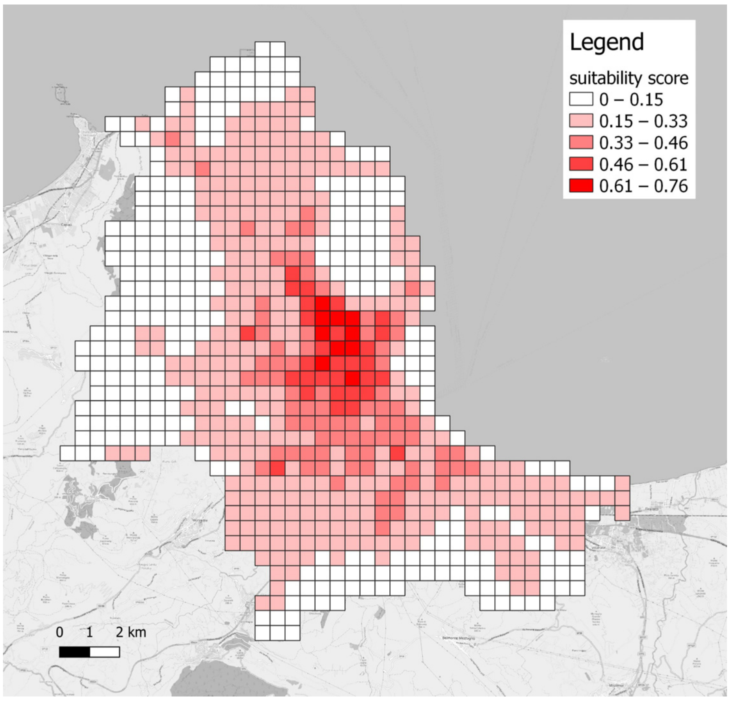

Figure 7. Suitability score map.

As can be seen in Figure 7, no cell in the grid reaches a value of 1. A value of 0.33, which is one-third of the full value, was chosen as the threshold for the adequacy assessment. The number of cells that met this threshold was 130.

For the site selection analysis, 341 POIs were identified in the area (Figure 8). According to the criteria considered in the site selection model, 170 candidate sites were identified: 40 sites as “origin-oriented” stations, 96 sites as “mixed” stations, 30 sites as “destination-oriented" stations, and 4 sites as carsharing stations serving major points of attraction (three shopping centers and the commercial area along Via Ugo La Malfa). For some of these sites, a walkability analysis was performed to better determine their location.

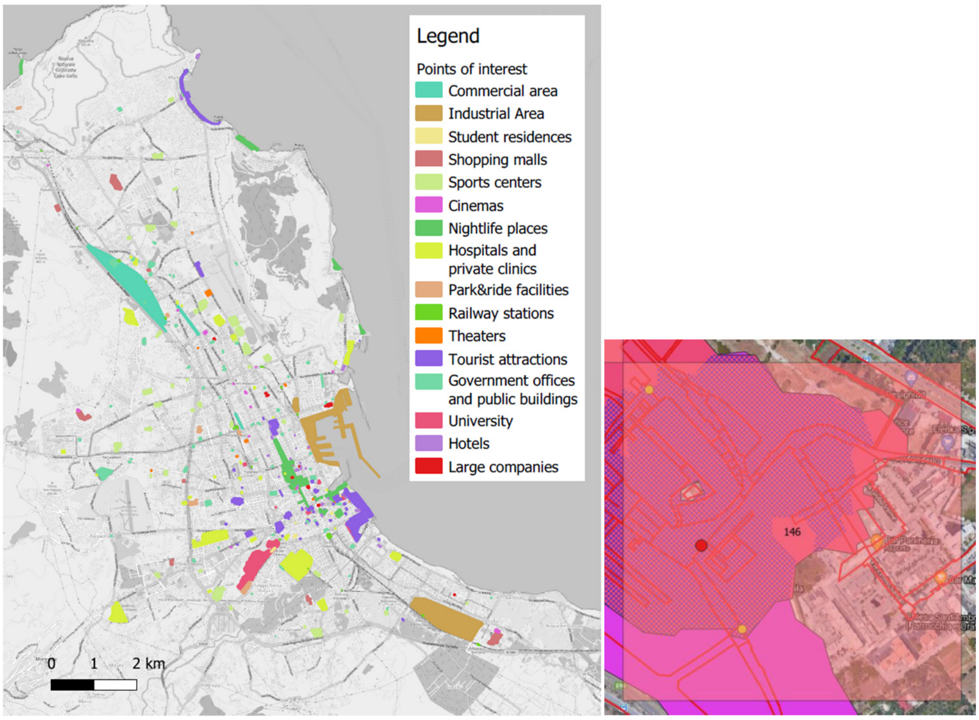

Figure 8. POIs (on the **left**). Example of site selection analysis (on the **right**): identification, through the pedestrian catchment areas (light purple and pink) of POIs (yellow points), of the area (dotted, dark purple) where the inclusion of the candidate site can be evaluated. The candidate site (red point) is located according to centrality, visibility, and space availability.

The capacity assessment allowed for the allocation of vehicles and parking spaces to candidate sites, according to the carsharing stations type. For the "origin-oriented" and "mixed" stations, the number of requests that the station must be able to satisfy was determined based on the number of people belonging to the target group who live in the cell where the station is located. We used a multinomial logit model and calibrated it for the city of Palermo based on a stated preference survey involving about 500 respondents and considering four different travel modes: private car, public transport, carsharing, and carpooling [42].

We considered travel time, travel cost, parking cost, parking time, and number of cars in household as attributes. The fare structure adopted in this case study is the same fare proposed by amiGO in order to offer a financially sustainable carsharing service; the prices are in line with other carsharing operators in Italy, which have more vehicles and stations [19]. Considering the target group, we assumed a probability of using carsharing equal to 8.5% and an average frequency of rentals of once a month, considering amiGO carsharing data and experience with services in other cities [38,42]. We also assumed that each car is used on average by only one user per day. Considering these assumptions, we evaluated the number of requests and the corresponding number of cars that each carsharing station must accommodate. The sizing process led to 27 additional stations, resulting in a total of 197 candidate sites with 388 cars and 618 stalls.

A location-allocation analysis was then performed in ArcGIS. The Municipality of Palermo provided a shapefile with the buildings and their characteristics, such as the volume and the number of floors. Considering only the residential buildings, we apportioned the population data of each census area among buildings within it proportionally to their volume. Several simulations were run, varying the number of stations that the algorithm must provide as a result.

The optimal result was obtained with 150 stations (Figure 9), which can serve 95% of the residents belonging to the target group who would be served considering all 197 candidate locations. Therefore, the fleet size and the capacity of stations were verified based on the number of users that the algorithm assigns to each station. In the preliminary sizing of the fleet, a total number of 317 vehicles was assigned to the 150 locations selected by the algorithm. Given the demand for the stations, it was determined that 297 vehicles would be sufficient. In addition, it was possible to verify the sizing of the stations in terms of the number of parking spaces. During the preliminary sizing phase, a total number of 560 parking spaces was assigned to the 150 candidate locations selected by the algorithm. Due to a lower number of vehicles to be accommodated in some of the selected stations, only 547 parking spaces are required.

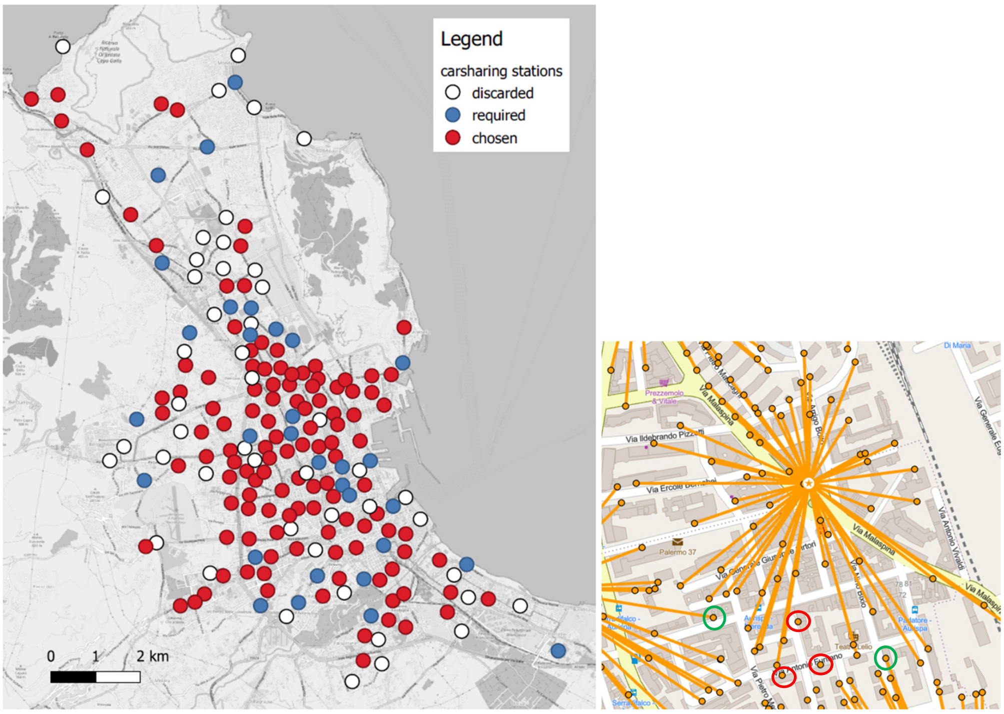

Figure 9. Results of the location-allocation analysis (150 stations) (**left**) and demand assigned to each station (**right**). Some demand points (red) are not assigned to any station, and others (green), although they are within the pedestrian catchment area of one station, are assigned to nearby stations due to proximity.

Finally, the methodology resulted in a station-based carsharing service characterized by a fleet of 297 cars, 150 stations, and 547 parking spaces. Currently, the carsharing service of the city of Palermo has 159 cars, 83 stations, and just over 300 parking spaces. Therefore, there is an undersized carsharing supply, with about 45% fewer stations and 46% fewer cars compared to those resulting from the model. Indeed, the current number of amiGO members is about 55% of the carsharing potential demand. Therefore, the current service fails to cover the entire city area, leaving some POIs and some areas capable of generating demand unserved. This result is in line with the findings of the customer satisfaction survey carried out in 2017: a weakness of the service is certainly the availability of the vehicle near POIs, so that 57% of users find it difficult to rent a shared car in the preferred station and in the preferred time [42]. Moreover, considering the current service, only 38% of inhabitants live within 500 m from a carsharing station, and the number of carsharing members in Palermo is very low compared to those of other Italian cities [19]. The optimal result determined by the new method can represent a useful yardstick for the company to undertake a service optimization process. The optimal result is also of great interest for carsharing companies that want to introduce a new station-based carsharing service in the city.

5. Conclusions

Although services such as carsharing are now present in many cities, they do not always manage to break through the mobility habits of those who live in the cities where they are introduced. Being complex systems, several factors contribute to the success or the failure of these services: the fleet size, the location of the stations, the fare structure; if not carefully designed, these aspects can easily turn into critical elements. Moreover, being closely connected to the territorial context in which they are introduced, they can find smooth roads or walls that are difficult to break down. The fast development of competing modes such as e-scooter sharing and ride-hailing services, combined with a poor design of these aspects, can easily lead to the shutdown of services.

This paper aims to develop a design process following a holistic approach to govern the complexity of these services: a methodology for designing station-based carsharing services was developed in a GIS environment. GIS, with their ability to process data with geographical references, have proved to be effective tools for designing all the elements of a carsharing service step by step. It has been shown how, through GIS software, it is possible to carry out suitability analyses in order to identify the most suitable areas to locate carsharing stations based on the socioeconomic characteristics of those who reside in those areas; it is possible to precisely identify the sites where to locate the parking spaces reserved for the service, taking into account not only the generated demand but also the potential destinations, different user groups, and the likely purposes of travel; it has been shown that, through GIS software, problems of location-allocation can be easily solved, finding the optimal distribution of the carsharing stations that can guarantee maximum coverage of the demand. This article also highlighted how important it is to investigate the relationship between carsharing and pedestrian accessibility, since the latter strongly affects the demand that this service manages to intercept. As far as the authors know, walkability has found, for the first time, the right place in the design process of the carsharing service, since we underlined that, during the first and last stretch of the trip, carsharing users share the travel experience with pedestrians, depending primarily on the quality of the pedestrian environment that surrounds carsharing stations.

Furthermore, the developed methodology is of considerable support not only to companies that want to design a new service but also to those companies that need to optimize a service already operating in a city: the result of the methodology can be compared with the supply of the existing service to understand the latter's criticalities and find possible solutions. Considering the case study, a practical implication of our research is that the carsharing company in Palermo should consider increasing the number of stations to cover new areas capable of generating demand, increasing, at the same time, the number of vehicles to prevent the resulting increase in the number of users from making cars less available to them, not allowing for profitability.

However, there are still some limitations in our research. In finding the optimal locations for the carsharing stations and the optimal fleet size for the one-way service, our methodology does not consider a cost–benefit analysis. A higher cost for increasing the fleet size and the number of stations requires a higher number of requests by users to redeem this cost. However, an increase in the number of users following the introduction of new stations, their new location, and the new fleet size could lead to the financial sustainability of the service, also considering the environmental benefits due to the reduction in kilometers traveled by carsharing users that we calculated in the city of Palermo [5]. Further studies will be undertaken by conducting a sensitivity analysis on suitability criteria and optimizing the methodology considering the problem of a fleet of electric vehicles requiring charging stations.

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