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Bike-sharing stations: A maximal covering location approach

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ABSTRACT

The promotion of sustainable alternatives to motorized individual mobility has been seen in the past few decades as one of the cornerstones in a strategy to reduce the negative externalities related to the transportation sector. Bicycle sharing is increasingly popular as a sustainable transport system and the number of bike sharing schemes has grown significantly worldwide in recent years. One of the most important elements in implementation of these systems is the location of the stations. In fact the non-optimal locating of bike sharing compromises its success.

Municipalities or public–private partnerships are mostly responsible for implementing bike-sharing schemes. The public investment in bicycle mobility (particularly bike-sharing) is complex because it is always subject to a budget. The main concern for public investment is to maximize the benefits through the design and implementation of bike-sharing systems. This work sets out a methodology to help with the decision-making of bike-sharing systems.

The research work we present proposes using an optimization method to design the bike sharing system such that it maximizes the demand covered and takes the available budget as a constraint. It combines strategic decisions for locating bike-sharing stations and defining the dimension of the system (stations and number of bicycles) with operational decisions (relocating bicycles).

As an outcome, the model determines the optimal location of the bicycle stations, the fleet size, the capacity of the stations and the number of bicycles in each station, considering an initial investment lower than the given budget. In addition, it balances the annual cost of the system and the revenue assuming a possible supplementary budget from the system provider to cover any loss resulting from the shortfall between its operating cost and the revenue from the subscription charges.

A case study in Coimbra, Portugal, is presented and discussed.

1. Introduction

1.1. Bike-sharing systems

The first bike sharing system emerged in Amsterdam, the Netherlands, in 1965. Nowadays, a number of cities around the world have adopted public bicycle sharing systems as a transport option. According to the Bike Sharing World Map,[2] there are 813 bike-share programs in operation worldwide and 221 being planned or under construction.

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[2] The Bike-sharing World Map is provided by MetroBike, LLC based in Washington D.C. USA. It shows the bike-sharing systems all over the world and gives some basic information about them. See at: www.bikesharingworld.com, accessed in December 2014.

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The service includes picking up and dropping off a bicycle at different stations in an urban area, in coordination with other transport modes.

Four generations of bike sharing systems can be identified: free bikes, coin-deposit, information-technology-based and multimodal systems. The most recent generation of bike-sharing systems is demand-responsive and adapts the service to user needs. It considers the most recent improvements in technological mechanisms at the stations, bicycles that are easier to use and share, electric bicycles, bicycle relocations and the inclusion of several transport modes on the same access card (public transportation and car-sharing) (Demaio, 2009; Shaheen et al., 2010). The bike-sharing programs developed around the world in recent years are mainly based on third generation systems.

One of the most popular and extensive bike-sharing programs is Vélib' in Paris (France). It consists of a network of 1800 stations (a station every 300 m), and more than 20,000 bicycles are always available. China has the largest bike-sharing market. For example, Hangzhou city hall launched a public bicycle sharing system in 2008, the Hangzhou Public Bicycle. In 2011, the scheme had 60,600 bicycles with 2416 fixed stations, one every 200 m, in eight core districts (Shaheen et al., 2010). A 'user key' is needed to unlock the bicycles in the station and this is generated by inserting a credit card.

Most systems offer a choice of subscriptions: short-term subscription (1-day, 3-day or 7-day ticket), or long-term subscription (monthly or annual). Such systems have an important environmental impact by cutting energy dependence and decreasing greenhouse gas emissions and therefore they can help improve public health. They also have a positive impact on reducing car use. Furthermore, the implementation of bike-sharing schemes promotes private bike use itself and greatly enhances the image of cycling (Demaio, 2009; Fishman et al., 2014; Woodcock et al., 2014). In terms of strategic planning, bike sharing systems can be seen as a useful tool to improve the quality of city life and the urban environment by making better use of urban spaces (European Commission, 1999).

One of the most important elements in the implementation of these systems is the location of the stations. If they are poorly located, this compromises the success of the system. Bike-sharing systems are mostly introduced by municipalities or by public–private partnerships. Since public investment in bicycle mobility (particularly bike-sharing schemes) is always subject to a budget, the main concern for public investment is to maximize the benefits at the design and implementation stages. In this paper, we present an optimization model designed to determine the location of bike-sharing stations, assuming budget constraints but maximizing the demand covered. It could be a good tool to help urban managers implement a bike-sharing system by making the investment as effective as possible, and it represents innovation in this matter.

1.2. Literature review

Facility location is a strategic decision that depends on its preliminary goals. Locations can be selected efficiently with the support of a particular type of optimization model, called facility location models, whose decision variables represent the location, the capacity, the coverage area of any kind of facility, and, in this case, the relocation of bicycle stations (Daskin, 1995; Daskin, 2008; ReVelle and Eiselt, 2005).

Several objectives can be considered in a facility location model such as the minimization of the overall cost, the minimization of transportation costs, and the maximization of demand coverage. The first objective is dealt with through fixed-charge models, the second through p-median models, and the third through maximal covering models. Depending on whether capacity constraints apply to the facilities, the models are classified as capacitated or incapacitated.

In the case of bike-sharing stations, the literature reports different approaches to tackling the location of the stations with facility location models.

An optimization model is described in Lin and Yang (2011) who propose an integer nonlinear program that determines the optimal location of docking stations, the bicycle lanes needed and what routes should be taken from each origin to each destination. It is based on cost minimization and assumes a penalty for uncovered demand. This model does not consider the relocation of bicycles; it assumes that bicycles and free spaces are always available in the stations, but this oversimplifies the problem.

The model presented in Lin et al. (2011) incorporates bicycle stock considerations and is formulated as a hub location inventory model. The formulation presented is not computationally tractable and the authors propose a greedy heuristic method to efficiently find near-optimal solutions.

A mixed-integer linear program performed through a heuristic that optimizes the location of shared bike stations is presented in Martinez et al. (2012), assuming a fleet size and bicycle relocation calculation for a regular operating day. The main purpose of the method is to maximize revenue.

The literature contains other methodologies to define the location of the stations, without facility location models.

The authors of Romero et al. (2012) consider a simulation–optimization method that relates public bicycles to private cars. The methodology is essentially a bi-level mathematical programming model that optimizes the location of public bicycle stations.

A GIS-based methodology to estimate the potential trip demand and its spatial distribution, the location of the stations (using location-allocation models), the station capacity and demand profiling for stations is proposed in García-Palomares et al. (2012). Both the simple location problem and the relocation must be taken into account, and this balance of the bike-sharing systems problem, which considers the number of bicycles in each station and the optimal relocation routes, is discussed in Lu (2013), Raviv and Kolka (2013) and Sayarshad et al. (2012). The first, Lu (2013), sets out a robust fleet allocation model that generates the optimal daily allocation of bicycles to the stations and the redistribution flows of an implemented bike-sharing system, while minimizing the total cost. In Raviv and Kolka (2013), the authors present an inventory model to define the management of bike-sharing stations by introducing a user dissatisfaction function to assess the quality of the relocation service. The focus of the methodology is to find the initial inventory of the station that minimizes the dissatisfaction function. Finally, Sayarshad et al. (2012) provides an optimization model to plan the relocation of bicycles in bike-sharing systems in small communities, assuming the maximization of the total benefit to the company (function of revenue and costs).

All these works provide the background for our study, but they all miss some point in the real implementation of these systems. As we know, public investment requires the maximization of the benefit and, in the case of bike-sharing, it also involves maximizing the number of users.

The maximization of demand coverage is handled by maximal covering models, which are especially well suited to bike-sharing stations. These models were introduced by Church and ReVelle (1974) and their application makes it possible to determine the locations that maximize the covered demand, for a given number of facilities.

The approach we propose significantly improves earlier formulations by considering an available budget as a constraint and maximizing the benefits of the system by covering the demand.

The proposed model combines strategic decisions in the location of bike-sharing stations and establishing the system's size (stations and number of bicycles), with operational decisions (relocation of bicycles). More precisely, the model defines the optimal location of the bicycle stations, the fleet size, the capacity of the stations, and the number of bicycles in each station. It determines the initial investment and achieves a balance between the annual cost of the system and the revenue, and also considers a possible supplementary budget given by the provider of the system to cover losses resulting from the shortfall between its operating costs and revenue from the subscription fees. The city of Coimbra is used as a test bed.

There is a section on the optimization model for the design of a new bike-sharing network, as well as the assumptions upon which it is based. The model is then applied to the city of Coimbra (Portugal), and the data and results are presented. The last section discusses the model formulation and the future challenges of this research.

2. Modeling approach

The optimization model presented below addresses what we believe to be the key issues inasmuch as it defines the optimal design of a bike-sharing station network to maximize the demand covered while taking into account restrictions on the cost and level of service. It simultaneously determines the location of the stations, the number of bicycles that should be available in each station to maximize the demand (by defining the relocation operations across the zones), and the fleet size.

The optimization model must be coordinated with a demand study for the city or urban area, divided into zones. The demand is taken as the number of trips generated and attracted by each zone, and the zones must be small enough to guarantee walking distances inside each one. The zones must be as small as possible for the solution to have the highest accuracy possible. A sensitivity analysis must be done in each case to define this distance according to the locality and the available data, but it is recommended that no zone should exceed 500 m as maximum distance between any two point independently its shape. But if the zones are small it is highly unlikely that someone will use the sharing system to travel within a zone.

The day is divided into periods whose number must be compatible with the available data in each case study. It can also be justified by the frequency of relocation activities, because certain periods may be very demanding in terms of cost and human resources.

The objective of the model is to maximize the covered demand and the return on investment. On the revenue side, it considers a possible public investment contribution to the system and the revenue from the subscriptions and, on the expenses side, it considers the relocation cost and the maintenance cost (bicycles and stations).

The model is subject to capacity constraints to secure the coverage of demand, cost constraints based on net present value to satisfy the available budget, and domain constraints to ensure the viability of the variables.

The inputs of the model are: the demand for the system, maximum and minimum capacity of the stations, the price of the stations and bicycles and the relocations and maintenance costs, the total investment budget and the annual supplementary budget, as well as the discount and growth rate and the project's horizon years. As outputs, the model defines the number of stations in each zone, the capacity of the stations, the number of bicycles in each zone and to relocate in each time step, the fleet size, the annual revenue and the annual expenses.

The notation used to represent the sets, decision variables and parameters, used in the model, is given below, in order of appearance. The model can be solved with optimization software such as XPRESS®.

Sets:
J: set of demand zones, indexed by i and j
T: set of time periods, indexed by t
Decision variables:
x_{ijt}: proportion of covered demand from zone i to zone j in time step t
y_i: is 1 if the bike station in zone i is opened and 0 otherwise
r_{ijt}: number of bicycles relocated from i to j at time step t
v_{it}: number of bicycles in zone i at the beginning of period t (needed to meet the demand in that zone)
z_i: number of docks in zone i
Parameters:
u_{ijt}: demand from i to j in time step t
ib: initial budget
sb: supplementary budget to cover loss resulting from the shortfall between operating costs and revenue from charges
i: investment needed to the implementation of the system
z_{min}: minimum station capacity
z_{max}: maximum station capacity
Tv: total fleet size of the system
cb: unit price of a bicycle
cs^f: fixed cost of a station
cs^v: variable cost of a station
cr^f: fixed unit relocation trip cost
cr^v: variable unit relocation trip cost
cms: maintenance cost of the bicycle station, including depreciation per year
cmb: maintenance cost of each bicycle, including depreciation per year
fa: annual user subscription
fm: monthly user subscription
fd: daily user subscription
dr: discount rate
gr: growth rate
n: project horizon (years)
f: income from the subscriptions
c: costs of the project in the project horizon (n)
b: benefits of the project in the project horizon (n)

The problem of determining the maximum coverage solution for locating bike-sharing stations is represented by the following model:

$$\text{Max } Z = \sum_{i\in J}\sum_{j\in J}\sum_{t\in T}(u_{ijt} \times x_{ijt}) \tag{1}$$

Subject to:

$$v_{it} = v_{i(t-1)} - \sum_{j\in J} u_{ij(t-1)}x_{ij(t-1)} + \sum_{j\in J} u_{ji(t-1)}x_{ji(t-1)} + \sum_{j\in J} r_{ji(t-1)} - \sum_{j\in J} r_{ij(t-1)} \quad \forall i \in J,\ j \in J, \in T \tag{2}$$

$$v_{i,1} = v_{i,T} \quad \forall i \in J \tag{3}$$

$$z_i \leqslant z_{\max} \times y_i \quad \forall i \in J \tag{4}$$

$$z_i \geqslant z_{\min} \times y_i \quad \forall i \in J \tag{5}$$

$$v_{it} \geqslant \sum_{j\in J}(u_{ijt}x_{ijt}) \quad \forall i \in J,\ i \in J,\ t \in T \tag{6}$$

$$v_{it} \leqslant 0.75 \times z_i \quad \forall i \in J,\ t \in T \tag{7}$$

$$v_{it} \geqslant 0.25 \times z_i \quad \forall i \in J,\ t \in T \tag{8}$$

$$\sum_{j\in J} r_{ijt} \leqslant v_{it} \quad \forall i \in J,\ t \in T \tag{9}$$

$$Tv = \sum_{i \in J} v_{it} \quad \forall t \in T \tag{10}$$

$$i = \sum_{i \in J} (cs^f \times y_i + cs^v \times z_i) + cb \times Tv \quad \forall i \in J \tag{11}$$

$$i \leqslant ib \tag{12}$$

$$c = 365 \times \left[cr^f \sum_{i \in J} \sum_{j \in J} \sum_{t \in T} r_{ijt} + cr^v \sum_{i \in J} \sum_{j \in J} \sum_{t \in T} d_{ij} r_{ijt} + cms \sum_{i \in J} y_i + cmb \times Tv \right] \times \left(\frac{1 - \frac{(1+gr)^{(n-1)}}{(1+dr)^{(n-1)}}}{dr - gr} \right) \quad \forall i \in J,\ j \in J,\ t \in T \tag{13}$$

$$f = (fa \times 0.5 + fm \times 12 \times 0.2 + fd \times 365 \times 0.3) \times \sum_{i \in J} \sum_{j \in J} \sum_{t \in T} (u_{ijt} \times x_{ijt}) \quad \forall i \in J,\ j \in J,\ t \in T \tag{14}$$

$$b = (sb + f) \times \left(\frac{1 - \frac{(1+gr)^{(n-1)}}{(1+dr)^{(n-1)}}}{dr - gr} \right) \tag{15}$$

$$-i - \left(\frac{c}{(1+dr)^1} \right) + \left(\frac{b}{(1+dr)^1} \right) \geqslant 0 \tag{16}$$

$$\sum_{j \in J} x_{ijt} \leqslant 1 \quad \forall i \in J,\ t \in T \tag{17}$$

$$x_{ijt} \leqslant y_i \quad \forall i \in J,\ j \in J,\ t \in T \tag{18}$$

$$x_{ijt} \leqslant y_j \quad \forall i \in J,\ j \in J,\ t \in T \tag{19}$$

$$r_{ijt} \geqslant 0 \quad \forall i = j \in J,\ t \in T \tag{20}$$

$$x_{ijt} \geqslant 0 \quad \forall i \in J,\ j \in J,\ t \in T \tag{21}$$

$$y_i \in \{0, 1\} \quad \forall i \in J \tag{22}$$

$$v_{it}, z_i, r_{ijt} \in \mathbb{N} \quad \forall i \in J,\ j \in J, t \in T \tag{23}$$

The objective function (1) of this linear program maximizes the demand covered by the bike-sharing system.

Constraint (2) defines the number of bicycles available at a station in zone i in time step t, which is the balance of the bicycles available in the previous time step (difference between the bicycles leaving station i and arriving at station i), as well as the bicycles relocated from or to station i, assuming that the number of bicycles at the beginning and the end of the day is the same, constraint (3).

The capacity of any station is always the same as (or lower) than an established maximum capacity of the stations, constraint (4), and higher than a minimum, constraint (5). The number of bicycles available in station i in time step t has to be enough to meet the demand, constraint (6).

According to some manufacturers,[3] the stations should always have some free parking places to ensure movement between stations and some bicycles to cover the demand. In fact, experience shows that free spaces must always be 25% of the station capacity, thus at the beginning of t the number of bicycles in station i must be 75% of the capacity of that station, constraint (7), while there must be more than 25% of bicycles, constraint (8). But during each period of time the model considers the possibility of fluctuations in the number of bicycles/parking spaces available.

The number of bicycles to be relocated from station i is lower than the number of bicycles in the station, constraint (9). Eq. (10) determines the total fleet of the system.

The investment is the sum of the cost of the bike sharing stations (defined as a function of the number of docks) and the cost of the bicycles (assuming that the implementation costs are included), Eq. (11), and the investment must be lower than the initial budget available ib, constraint (12).

The annual cost of the system includes the relocation cost, the maintenance cost and the vehicle depreciation cost, Eq. (13).

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[3] Portuguese manufacturer (Miralago).

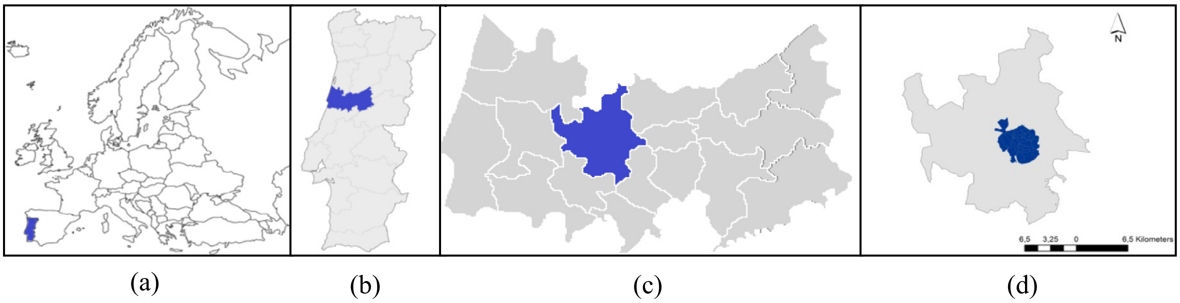

Fig. 1. Location of: (a) Portugal within Europe, (b) Coimbra district within Portugal, (c) Coimbra municipality within the district, and (d) study area within Coimbra municipality.

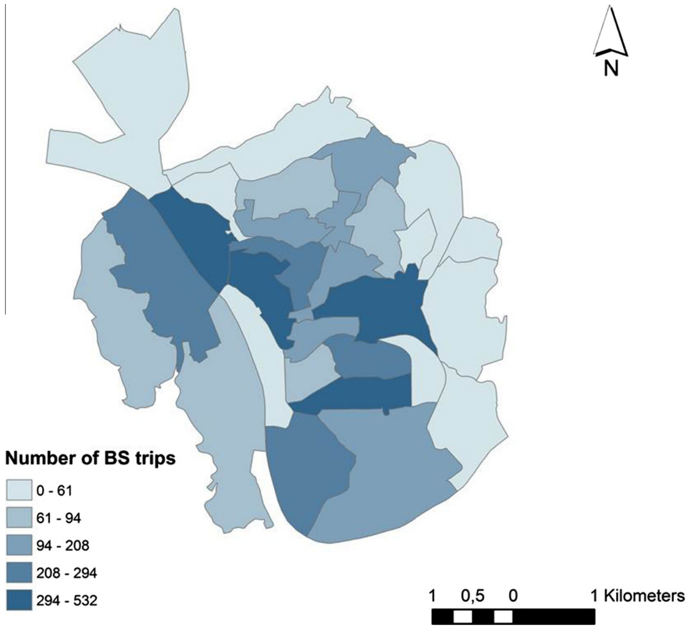

Fig. 2. Main results of the demand study in (19) – number of bike-sharing origin and destination trips.

The income from subscriptions is determined from the annual and daily subscriptions, Eq. (14); it is estimated that on a daily basis 50% of the users have annual, 20% monthly and 30% daily subscriptions.[4]

The benefits consider the supplementary budget (from public or other bodies) to cover any loss resulting from the shortfall between operating costs and the revenue from the daily charge, Eq. (15). The net present value for this problem must be greater than 0 to ensure a good investment, constraint (16).

The proportion of the demand from i to j that can be covered is no more than 1, constraint (17). Constraints (18) and (19) state that demand can only be served by installed bike stations.

Finally, Eqs. (20)–(23) specify the domain of the decision variables.

Where it is possible to have smaller zones (census block size for instance) and thus meet the requirements presented above, the model locates no or one station per zone, thereby enabling the decision maker to choose easily where to locate the station in the zone.

However, special care should be taken where the zones defined by the demand study are not small enough to be considered in the terms specified; in other words they are big enough to have more than one station and the need to ride a bicycle within the zones is accepted, using the bike sharing system. In these cases, the model must not consider $y_i \in \mathbb{N} \forall i \in J$ and Eq. (22) because it limits the number of bicycle stations to one per zone. Therefore, we did not consider this restriction in the case study presented in the next section.

[4] According to the manufacturers in this sector.

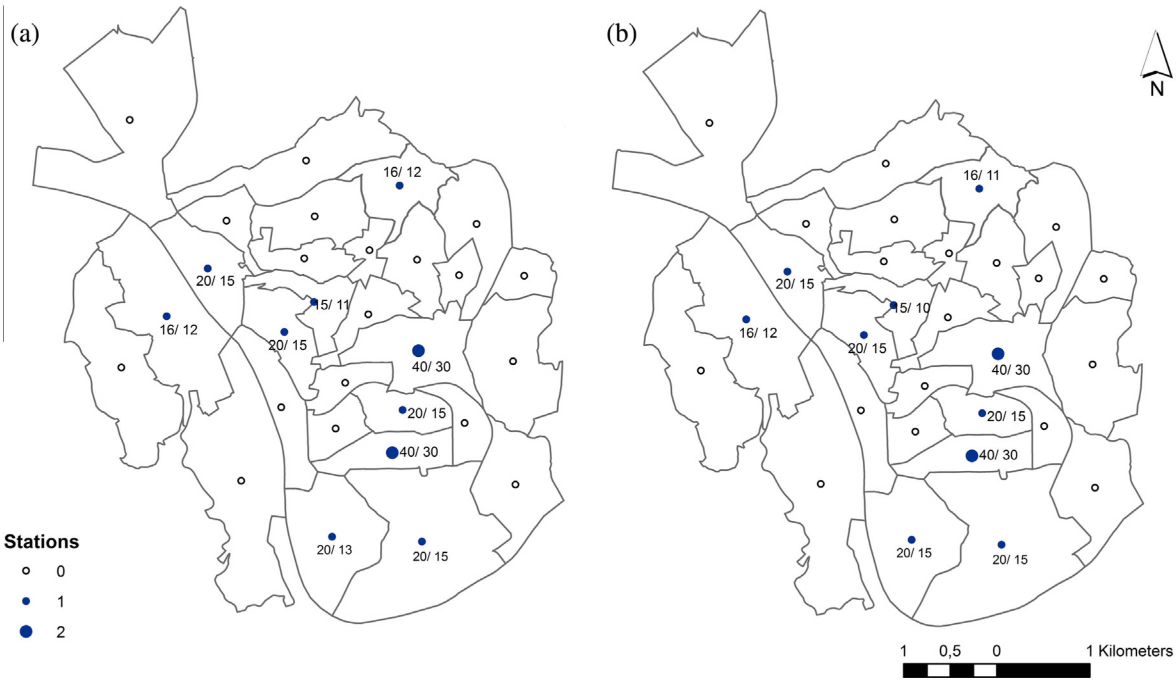

Fig. 3. Solution of scenario 1 (number of docks/number of bicycles in time step 1): (a) time steps 1, 2, 3 and 5 (b) time step 4.

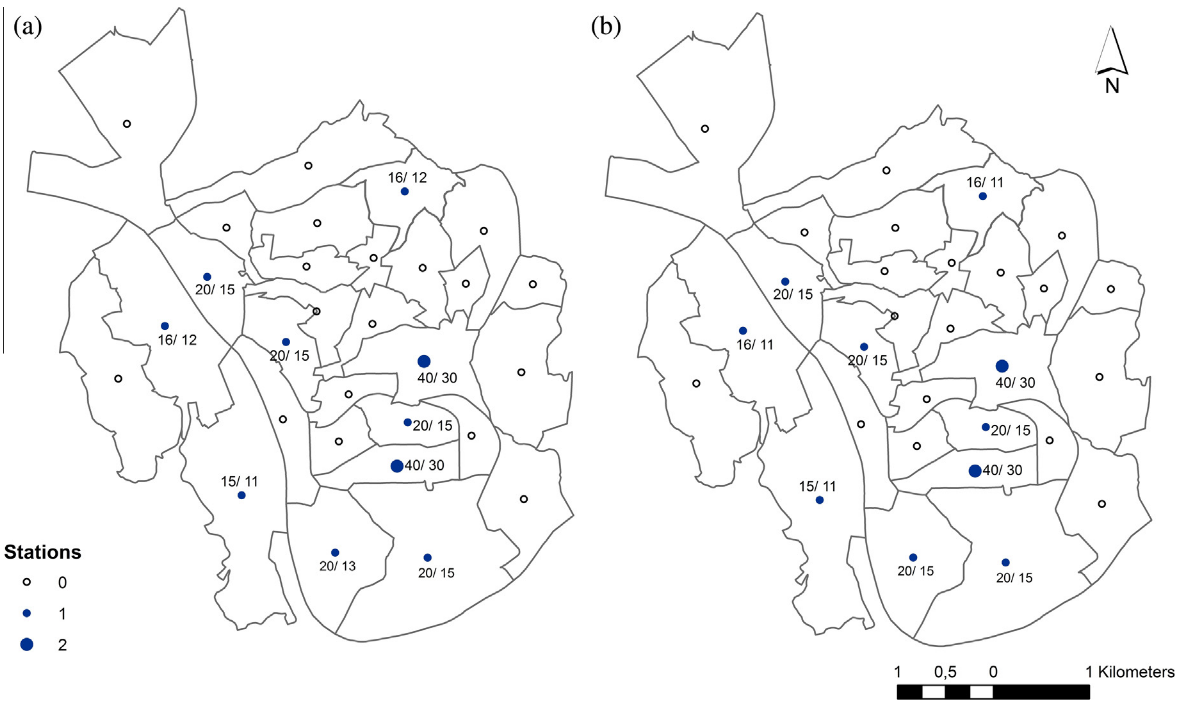

Fig. 4. Solution of scenario 2 (number of docks/number of bicycles in time step 1): (a) time steps 1, 2, 3 and 5; (b) time step 4.

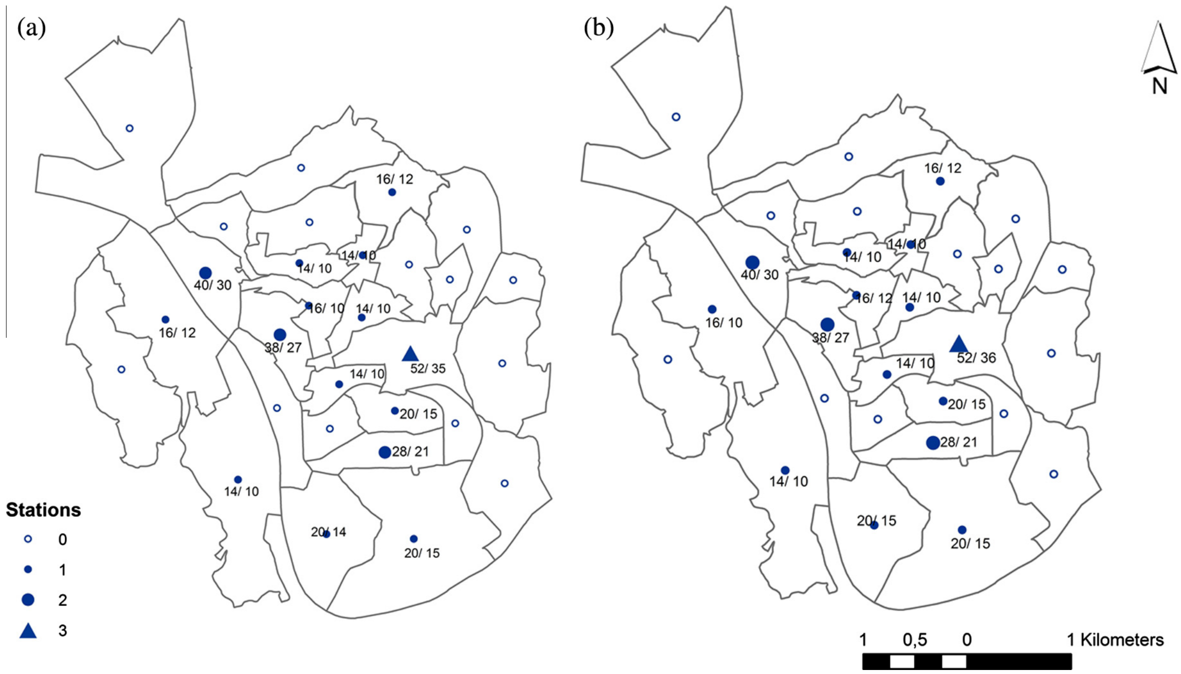

Fig. 5. Solution of scenario 3 (number of docks/number of bicycles in time step 1): (a) time steps 1, 2, 3 and 5; (b) time step 4.

3. Case study

3.1. Description

The methodology was applied to the city of Coimbra, Portugal, Fig. 1. Coimbra is located in the center of Portugal (Fig. 1) and it had a population of more than 140,000 in 2011 census. It has a large student population – the University of Coimbra has approximately 30,000 students – an important factor that could strengthen the potential for using a bike-sharing scheme (Baltes, 1996; Handy et al., 2010), in spite of the geographical characteristics, as explained below.

In 2008, according to a study (TIS.pt, 2009) to determine the mobility patterns of Coimbra's population based on surveys, 42% of households had one car and about 45% had two or more cars, emphasizing the high motorization rate in the city – 522 cars per 1000 inhabitants compared with 473 cars per 1000 inhabitants in Europe in 2009 (figures from Eurostat). Most daily trips are made by car (69%), and the bicycle is of very low importance. Anyway, this study shows the bicycle as a forthcoming option, since 57% of trips are of less than 4 km.

The municipal urban public transport services include buses, trolleybuses and one elevator. The mobility study says that 18% of daily trips in Coimbra are taken in public transport.

The mobility study divided the municipality of Coimbra into 61 traffic zones, 29 of which cover the urban area of Coimbra. The latest strategic plans for the city stress some points with implications for cycling, which is a good sign that attitudes may be changing (Parque Expo, 2012; Regulation no. 255/2012, 2012).

At present Coimbra does not have the infrastructure to make the bicycle an optional transport mode, in an optimized way. There is a lack of bike lanes and other facilities for bicycles, and the generally hilly terrain suggests that Coimbra is not suitable for cyclists. However, the study on potential demand (Frade and Ribeiro, 2014) showed that more that 70% of the road network is suitable for cycling using normal bikes, according to the relation between the grade and extent of the roads presented in another study (AASHTO Executive Committee, 1999). This fact, together with the high percentage of daily trips of less than 4 km, makes Coimbra a potentially suitable city for cycling.

A previous study on the demand for a future bike-sharing system in Coimbra is presented in Frade and Ribeiro (2014). It estimates the potential demand for bike-sharing systems based on the relation between the target public (based on other case studies) and the users' trip characteristics (travel time and purpose of the trip) as well as the physical characteristics of the city (hills). Its main results (Frade and Ribeiro, 2014) regarding bike sharing trips are presented in Fig. 2, assuming the traffic zones from the mobility study in TIS.pt (2009). According to the same study, 2291 of the daily trips (from a total of 122,253 trips) can be done using bicycles from the bike sharing system, which is 2% of the trips.

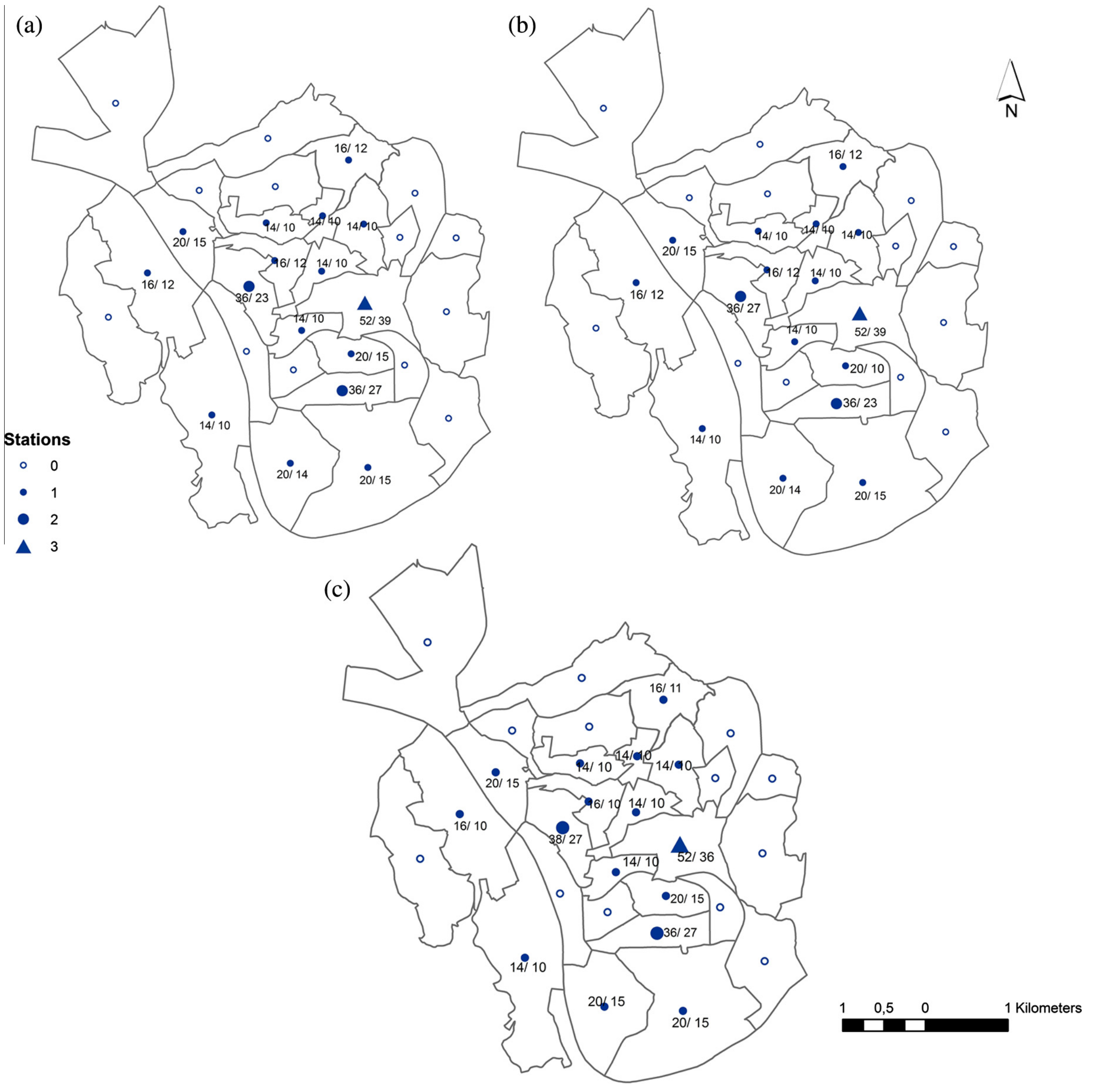

Fig. 6. Solution of scenario 4 (number of docks/number of bicycles in time step 1): (a) time steps 1, 2 and 5; (b) time step 3; (b) time step 4.

Table 1
Comparison between scenarios.

		Scenario 1	Scenario 2	Scenario 3	Scenario 4
Initial investment		€200,000	€200,000	€300,000	€300,000
Annual supplementary budget		€0	€50,000	€0	€50,000
Optimal solution	Daily trips covered	545	547	750	757
	Stations located	12	12	20	20
	Total of docks	227	227	334	336
	Total of bicycles	168	168	243	240
	Total investment	€199,900	€199,900	€299,900	€300,000
	Annual expenses	€183,956	€234,667	€251,085	€303,820
	Annual revenue	€202,874	€203,686	€279,534	€332,160

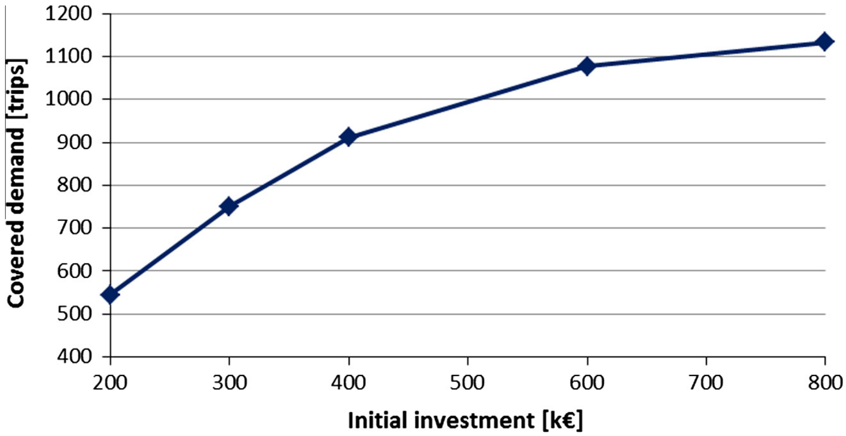

Fig. 7. Relation between the initial investment and the covered demand.

In the application presented below, we assume a more optimistic scenario and demand is 2.5 times the demand defined in this study, thus 5728 of the daily trips can be done using bicycles from the bike sharing system, which represents 5% of the total of trips.

3.2. Application

The traffic zones considered are too large to satisfy the assumption that there are no bike-sharing trips inside the zone. Thus, as stated above, constraint (25) is not considered in this application. Five time steps are assumed in order to adjust to the available data.

The maximum bike capacity of the stations is assumed to be 20 and the minimum 10, because it is usually quite hard for bike-sharing systems to acquire land for stations with a capacity over 25 bicycles.

The cost of a station will depend on the number of docks. The fixed cost is taken to be €3000 with the price increasing by €500 per slot. The unit price of a bicycle considered in our study is €300[5] and other costs assumed were: the fixed relocation cost of €0.1, the variable relocation cost of €0.01 (per bicycle to be relocated), the annual maintenance costs of €100 per station and €50 per bicycle. A discount rate of 5% per year, a growth rate of 2% and a 15-year project horizon were assumed.

In scenario 1, the initial budget is €200,000 and there is no annual supplementary budget. The annual subscription is €40, the monthly subscription €10 and the daily subscription €3.

The optimal solution given by the model is presented in Fig. 3. It covers 545 daily trips and locates 12 stations in the blue[6] traffic zones. The zones have between 15 and 40 docks (227 in total) and the fleet has 168 bicycles in the system. The total investment is €199,900 (less than the available budget), the annual expenses are €183,656 and the annual revenue from the fares is €202,874 (more than the annual expenses). Fig. 3 shows the location of the stations, the number of docks in each zone and the number of bicycles in the first time step.

In scenario 2, the previous assumptions are the same but we assume an annual supplementary budget of €50,000. The best solution, presented in Fig. 4, covers 547 daily trips and locates 12 stations in the blue traffic zones, with only one station per zone. The zones have between 15 and 40 docks (227 in total) and there are 168 bicycles in the system, as before. The initial investment is €199,900, the annual expenses amount to €234,667 and the annual revenue from the charges is €203,686. In terms of station location, the solution is the same as for scenario 1.

In scenario 3, the initial budget is increased to €300,000, there is no annual supplementary budget and all the other inputs are to the same as for scenario 1. The optimal solution covers 750 daily trips, locates 20 stations, the zones have between 14 and 52 docks (334 in total), and the fleet contains 243 bicycles. The initial investment is €299,900 and the annual expenses are €251,085 with annual revenue from the charges being €279,534. The location of the stations is presented in Fig. 5.

The last scenario (scenario 4) is similar to scenario 3 but the annual supplementary budget is €50,000. The optimal solution shown in Fig. 6 covers 757 trips, locates 20 stations and the zones have between 14 and 52 docks with a fleet size of 336 bicycles. The initial investment is equal to the budget (€50,000), the annual expenses are €303,820 and the annual revenue from the charges is €282,160.

Table 1 shows the comparison between the scenarios. We can conclude that by increasing the annual supplementary budget the covered demand increases, as expected. Moreover, if the initial investment is increased the solution covers a greater number of trips.

[5] According a Portuguese manufacturer, bicycles cost between €250 and €600.

[6] For interpretation of color in Fig. 3, the reader is referred to the web version of this article.

The relation between the initial budget and the covered demand is explored by solving several scenarios, with a higher initial investment and not considering an annual supplementary budget. The results of the variation are presented in Fig. 7. As expected, the amount of covered demand increases with an increasing initial investment.

Most bike-sharing systems are funded by the government or supported by advertising and sponsorship contracts. The opportunity to have a more precise idea of the relations between investment and demand covered can therefore be very useful when it comes to drafting agreements between local authorities and sponsors.

4. Conclusion and future work

The methodology described above makes it possible to determine the location of bike-sharing stations within an urban area and to relate such locations to the demand estimated by means of a maximum coverage model that also considers constraints related to the budget and the level of service. It can provide urban managers with good insight into the design of a bike-sharing scheme. The comparison of different scenarios can help decision makers to choose the best solution for their town or city. In fact, it is not fair when implementing these schemes to make a huge initial investment if there is no money to sustain them, so the balance between initial investment and maintenance costs must be included in a bike-sharing system optimization model.

The results of the Coimbra case study show the model performs well. It indicates the best zones to locate the bike-sharing stations according to the criteria used.

Actually, the model locates the stations per zone without giving the exact location of the station in the zone. For better accuracy in the definition of the exact location of the stations, this model can be coordinated with another that minimizes the distance between people and stations and considers the exact possible locations to the stations.

Demand was defined based on recent studies by the same authors (Frade and Ribeiro, 2014), but in future research it will be also influenced by the level of the service, i.e. proximity of the stations, number of available bicycles and the cost to the user, as a dynamic component of the model. The demand should also change over the time, in light of the project horizon. It will also consider the demand for bike-sharing services resulting from interaction with public transport services (considering public transport users who could potentially use public bicycles). Other technology will also be involved, such as electric bicycles within a framework of internet of things (IoT) in the system. The authors are now working on these steps.

From the strategic planning point of view, the implementation of bike-sharing systems has other benefits for the city that this model does not take into account, such as the reduction of trips made by car, health benefits to the population and a general improvement in the quality of city life and the urban environment. There are other costs to be considered, too, such as labor costs.

We believe that the methodology outlined here can provide urban managers with good insight into where bike-sharing stations should be located in their towns, and therefore it contributes significantly to the future planning of bike-sharing systems.

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