Transport Research Arena 2014, Paris

Cognitive mapping and multi-criteria analysis for decision aiding: an application to the design of an electric vehicle sharing service

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Abstract

The paper presents a model for the design of an electric car sharing service for the city of Milano. Several options of service configurations have been analysed and evaluated according to indicators, to measure the performance of such options in respect to relevant dimensions (i.e., economic and financial costs and revenues, mobility, social benefits, environmental effects). We set up a multicriteria decision analysis, structured by means of cognitive maps. Causal networks to estimate the effects of the options have been identified and instantiated by means of simulation techniques and other qualitative and quantitative models. The focus of the paper is on the development and use of the causal maps and their integration with a multicriteria method. The use of cognitive maps allowed to capture the multiple values of the problem and the value trees of stakeholders objectives. The proposed method can be useful in general for design and planning of mobility service, especially at a strategic level.

Keywords: cognitive maps; multi-criteria analysis; electric vehicle sharing; service design.

Résumé

Le document présente un modèle pour la conception d'un service de partage de voiture électrique pour la ville de Milan. Plusieurs options de configurations de service ont été analysés et évalués en fonction d'indicateurs pour mesurer la performance de ces options en ce qui concerne les dimensions pertinentes (ie la viabilité économique et financière, la mobilité, les prestations sociales, les effets environnementaux). Nous mettons en place une analyse multicritère d'aide à la décision, structuré par des cartes cognitives. Des réseaux aléatoires pour estimer les effets des options ont été identifiées et instancié au moyen de techniques de simulation et d'autres modèles qualitatifs et quantitatifs. L'objectif de ce document est le développement et l'utilisation des cartes aléatoires et leur intégration avec une méthode multicritère. L'utilisation des cartes cognitives a permis de capturer les valeurs multiples du problème et les arbres de valeur correspondant aux objectifs des preneurs de décision. La méthode proposée peut être utile en général pour la conception et la planification des services de mobilité, en particulier à un niveau stratégique.

Mots-clé: Les cartes cognitives, l'analyse multi-critères, le partage de véhicules électriques, la conception des services.

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1. Introduction

The earliest origins of car sharing, understood as an organized form of shared use of the car, can be traced back to 1948 when an association started a service in Zurich (Shaheen et al., 1999). In the following years, particularly in the 70s and 80s, several car sharing systems were set up, but still on a small scale, with poor results (Shaheen et al., 1998). The original idea has been gradually replaced by an offer structurally organized according to strict business criteria, in order to achieve economies of scale, which resulted in increased benefits to users in terms of low rates and diversification of the available fleet. The concept of vehicle sharing has been characterized in different ways, over the years and depending on local conditions (Barth & Shaheen, 2002; Shaheen & Cohen, 2007). The most important factor for the success of car sharing is represented by the difficulty of reaching a critical mass of users to ensure an economic balance (Brook, 2004), hence the frequent need for public support. The two main barriers for the use of the service consist in the distance from the origin and the stations, and the concern of not having always available a vehicle (Katzev, 2003).

Within this framework, the project Green Move designed and tested an electric vehicle-sharing system for the city of Milano, in an attempt of overcoming the obstacles that limit the diffusion of both electric vehicles and traditional car-sharing initiatives. The project aims to involve and integrate a multiplicity of key actors of the Milano mobility system and to balance different dimensions of sustainability. Green Move[†] involves eight different departments and research centers of Politecnico di Milano: DEIB (information communication technology), DIG (economic and stakeholder analysis), DAStU (travel demand analysis), DICA (geographical information systems), Fondazione Politecnico (administrative management), Design (service design and communication), DMAT (mathematical models), and Poliedra (evaluation and environmental analysis). The main idea behind Green Move is to create a flexible service of vehicle sharing, based on electric cars and open to a wide range of different typology of users. The system will be made easily accessible thanks to an add-on device, the Green e-Box (Alli et al., 2012), a bridge between the user, the vehicle and the control center, that allows any vehicle to join the service network. In this way, single users, private companies and associations may share their personal car or fleet (peer-to-peer approach).

Figure 1 presents the overall articulation of the Green Move project. Within the first phase the research team performed three main activities: best practice and literature review, context analysis and service idea identification (Villari & Luè, 2013). The second phase of the project, the strategic design, focuses on the strategic design of different service configurations, chosen among the most effective in terms of user needs fulfillment. Based on such activities, four specific service configurations (condominium based service, network of services, the new business fleet, peer-to-peer) have been identified (Arena et al., 2012). The third phase concerns, on one hand, the technology necessary to manage the physical system (Alli et al., 2012; Bianchessi et al., 2013; Panigati et al., 2012) and, on the other hand, the elaboration of the most effective and efficient solutions, taking into account different dimension of sustainability (environment, finance, mobility, social). As regards the latter phase, we set up a multicriteria decision analysis, structured by means of cognitive maps. Causal networks to estimate the effects of the options have been identified and instantiated by means of simulation techniques and other qualitative and quantitative models. The last phases concern the implementation of a pilot in Milan to test the results and the elaboration of final recommendations concerning the implementation of a car sharing service.

This paper specifically focuses on the development and use of the causal maps and their integration with a multicriteria method. Section 2 synthetizes a literature review we made on decision aiding methods and causal maps. Section 3 describes how we applied such method for the design of an electric car sharing in Milano. Section 4 concludes the paper.

[†] The Green Move project has been co-financed by Regione Lombardia through the “Fondo per la promozione di accordi istituzionali - Bando accordi istituzionali”.

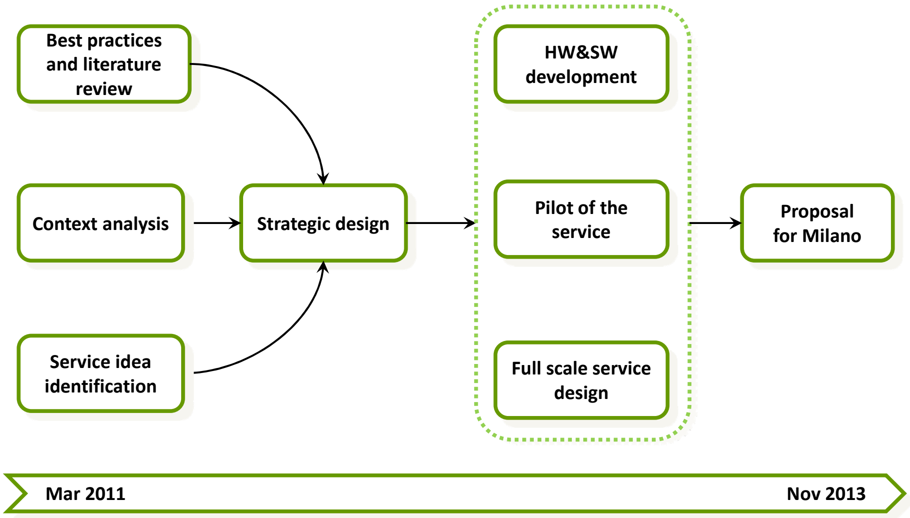

Fig. 1. Phases of the Green Move project

2. Decision aiding methods and causal maps

Decision aiding methods aim at supporting the decision-maker in the process of making a choice. In an idealized decision problem, one person (the decision-maker) chooses among specific and well described alternative options, evaluated according to an unique and defined objective (evaluation criterion). Moreover, the decision-maker has the whole information, i.e. he knows the performance for each option, according to the evaluation criterion. Operational research classically deals with this kind of problem (Hillier & Lieberman, 2005), formalizing a decisional problem through a mathematical problem and finding the optimal solution (or an approximation, if the computation time is to long for finding the optimal solution).

The problem of designing a vehicle sharing service, however, is characterized by the presence of many objectives to be pursued that are in conflict with each other. For example, the expansion of the territorial coverage (an objective to be maximized) will increase the investment and operational costs (an objective to be minimized). It is not easy to compare and choose in a situation characterized by many evaluation criteria. Different methodologies have been designed, in order to classify and rank the options according to the set of criteria that the decision-maker considers relevant (Figueira et al., 2005). In first approximation, it is possible to identify two main categories of methods, characterized by a different approach:

- definition of an utility function (or of an overall satisfaction function) to aggregate the different criteria. Two examples are represented by the Multi Attribute Utility Theory (Keeney & Raiffa, 1976), and the Analytic Hierachy Process (Saaty, 1990).
- pairwise comparison of the different alternatives, using concordance and discordance criteria. An example is represented by the outranking (Electre) methods (Roy, 1996).

In addition, non-deterministic variables may change the outcome of the evaluation. These variables refer to

- the information regarding the reference scenario (e.g., what will be the regional transport policies to improve air quality in Milan? Is the cost of an electric vehicle going to decrease in the next decade?)
- the estimation of the effects of alternatives (e.g., magnitude of the reduction of air pollutants due to the introduction of the service).

So, the classical operational research methodologies are not suitable for this process, because they need a completely-structured problem and a fully-rational decision-maker. In fact, in this particular case, even the decision-maker (and the analysts that support the decision-maker) does not have all the information necessary for a complete definition of the problem, which is a fundamental step for the decision process. The use of even sophisticated models is not effective if the definition of the problem is imprecise or not complete and can, paradoxically, help to solve a problem that is not the decision maker's one. Within such framework, decision aid methods can support the *structuring process* of the service design in order to link the process to quantitative, or, at least, clearly expressed, criteria.

The preliminary questions that can help in the design of the service in this preliminary phase are: who is the decision maker?, who is involved?, who will be affected or influenced by the decision?. Moreover, the problem involves many actors with different interests. In the first instance, we can identify:

- public administration, interested in minimizing the impacts on the environment and to improve accessibility of an area;
- users, interested in a good quality of service, in a high capillarity of the service and in low fares;
- the service provider, primarily interested in profit.

In addition to these key figures, we can identify other stakeholders who may be more or less interested depending on the kind of configuration of the service (e.g., producers of energy from sustainable sources, in the case of an electric car sharing service).

The second step of the structuring process consists in the definition of: reference scenarios, evaluation criteria, and options to be evaluated. The options' identification (in this case: the definition of the options for the service configuration) is one of the most sensitive aspect. It has been verified that, often, mobility experts define and choose the alternatives in coherence with their own experience about "what has already worked" (Hull & Tricker, 2005). A representative number of meaningful alternatives is the precondition for a consistent decision process (Colorni et al., 1999). Depending on the specific decision problem, different approaches are possible, such as the ones proposed by Bana e Costa (2001), Kelly et al. (2008) and Jones et al. (2009).

Within such approach, we used the *cognitive maps* tool, which has been so far used mainly in psychology and behavioral sciences, management (Fiol & Huff, 1992; Langfield-Smith, 1992), political sciences (Eden & Ackermann, 2004) and business (Kwahk & Kim, 1999). A prime aim of cognitive maps is to graphically represent the ideas of an individual through a network of interrelated concepts. Moreover, it allows to build a shared vision of the decision problem in a group of persons and facilitate the identification of values and their conflicting elements that may have an impact on the consequence of decision (Eden, 1988). Cognitive mapping, widely used in problem-structuring (Mingers & Rosenhead, 2004), permits a rich representation of decision-makers' views through modeling of complex chains (causes and effects) (Eden, 2004), and may help in identifying possible new better actions (Montibeller & Belton, 2006). In the use, cognitive maps have a limited capacity of inference. The following methods are examples to improve it:

- fuzzy cognitive maps, which go extend in the direction of semi-qualitative outputs (Glykas, 2012; van Vliet et al., 2010);
- qualitative probabilistic networks, where the links of the map denote a probabilistic dependence (Wellman, 1994).
- Bayesian networks, probabilistic directed acyclic graphical models to draw inferences (Nadkarni & Shenoy, 2004);
- decision maps, a framework to integrate scenario and multi-criteria analysis (Comes et al., 2011).

Our objective was to develop an multi-criteria evaluation structured by means of cognitive maps (see Fig. 2). In this sense, previous attempts for integrating cognitive maps have not reached the expected results (Comes et al., 2011; Kpoumié et al., 2012; Montibeller & Belton, 2006; Montibeller et al., 2007).

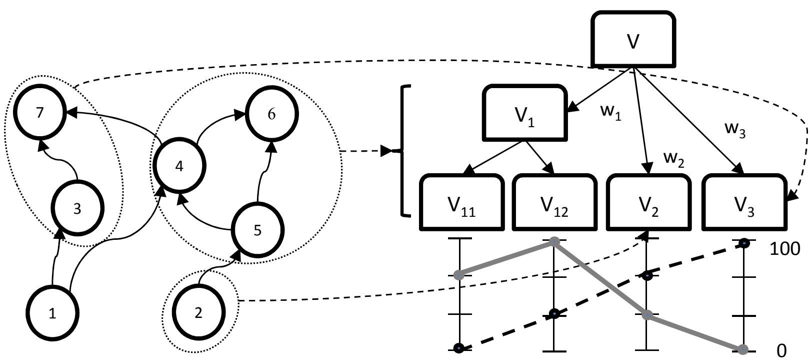

Fig. 2. An example of value tree of a multi-criteria analysis, structured from a cognitive map. Elaborated from Montibeller and Belton (2006).

3. Assessment of the configuration options

The design of a full scale electric car sharing service for the city of Milano has been carried out by identifying different configuration options, taking into account parameters related to performances (e.g. capillarity, price, accessibility), additional services (e.g. baby car seat, navigation system), technology (e.g. booking services, road toll device, lock and unlock system), etc. In order to support the identification and selection of the options most promising in terms of the overall level of sustainability (economic, social and environmental), we studied the possible effects of such parameters on the mobility system. In order to identify such effects, we used cognitive maps, elicited by means of interviews and workshops made with the researchers with different expertise of the Green Move team and territorial stakeholders. The result is shown in Fig. 3, which represents a cause-effect chains, tracks the complex interactions among the parameters for each option and the effects.

The left part of the graph is represented by the configuration parameters, whose combination identifies different service options. The configuration parameters are connected to some intermediate nodes, that depend on the specific service configuration (e.g. number of vehicle stations and number of users), and, in turn, determine the value of performance indicators. Performance indicators measure the extent to which the objectives of the system are achieved; in this way, different service configurations can be compared based on their results in relationship to performance indicators and the consequent level of fulfillment of the objectives.

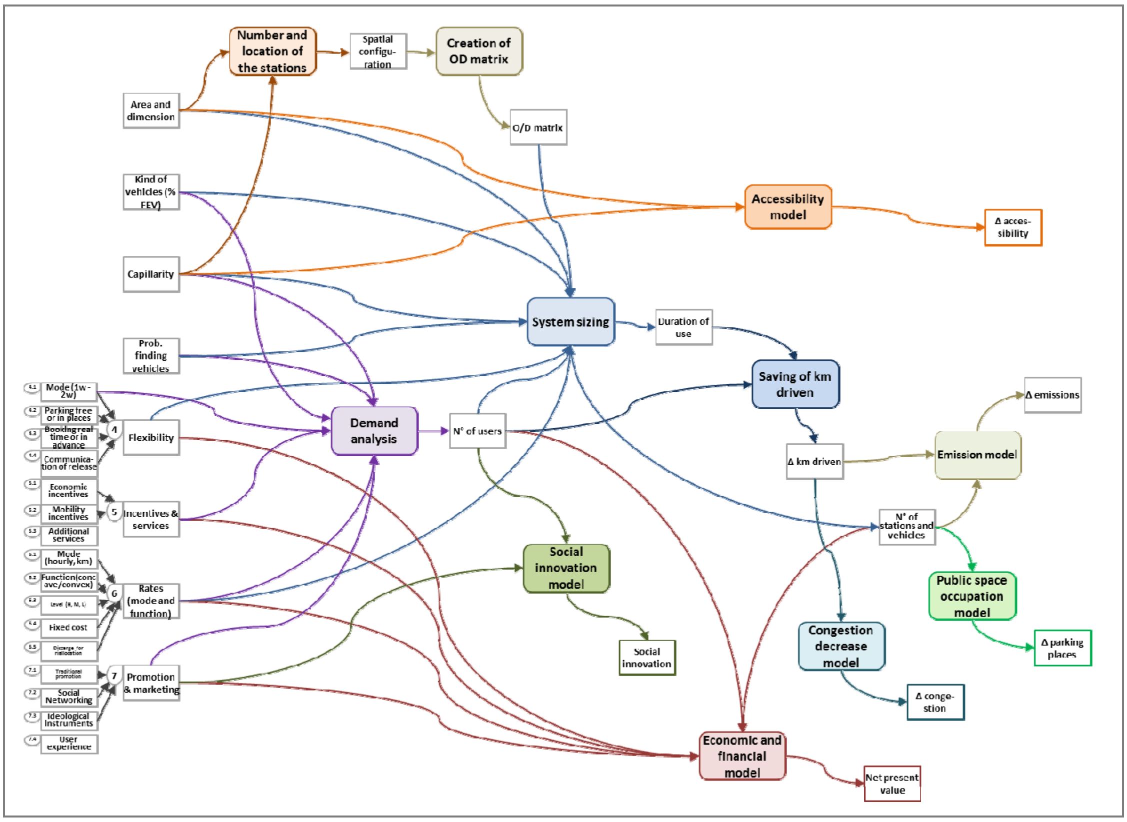

Fig. 3. Theoretical system modelling of service configuration

For the estimation of the indicators, the formalization of a set of models has been required. In the system model presented in Fig. 3, for example, the nodes *capillarity*, *probability of finding a vehicle*, *flexibility*, *incentives and services*, *rates* and *promotions* influence the node *number of users*. However, not all the influences identified in the theoretical design have been converted into mathematical relations because of the complexity of the relations existing in the reality. The result of this simplification is presented in Fig. 4. Considering the example above, we were able to identify and quantify - through a stated preference model (Ben-Akiva & Lerman, 1985) - the influence of a limited number of parameters, i.e. spatial localization, spatial flexibility, probability of finding a vehicle, and annual and hourly rates.

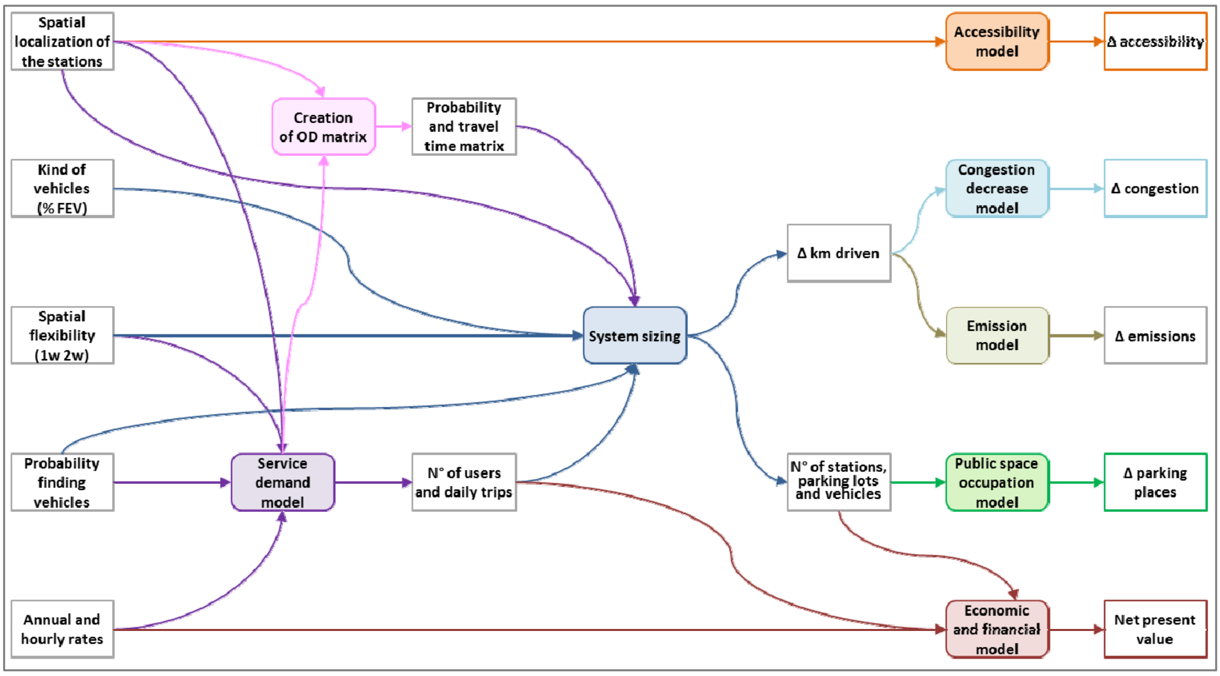

Fig. 4. System modelling of the service configurations implemented.

The parameters used in the implemented system modelling are briefly described below:

- *Spatial localization of the stations*: it represents the spatial configuration of the service in terms of localization of the stations on the urban area. The capillarity, i.e. the distance between one station and another, is function of this parameter as well as the number of users potentially served by the service: in fact the attractiveness of a station towards a potential user it is function of his distance to the station. The spatial localization influences directly the accessibility by the users of the urban territory.
- *Kind of vehicles* (% FEV): it characterizes the composition of the car sharing fleet in terms of engine technology (electric and internal combustion engine). Electric vehicles need not negligible time for recharging (and dedicated recharge stations) and the use of them imply a difference sizing of the vehicle fleet.
- *Spatial flexibility* (1w 2w): with an 1-way service the user is allowed to leave the vehicle in a station other than where the vehicle was picked up; with a 2-ways he is forced to make round-trip travel, bringing the vehicle back to the station of picking. The parameters influences the system sizing.
- *Probability finding vehicles*: it is an expression of the level of service given to the user. Higher is the probability of finding a vehicles for users, higher, obviously, is the level of the satisfaction of users' requests.
- *Annual and hourly rates*: price charged to the users for the vehicle's usage. It consists of two different components: an annual rate (i.e. a subscription costs), and an hourly rate (i.e. a usage fee), paid for each use.

For the definition of the spatial localization of the stations, three different areas have been outlined: City Centre, Ring Road Area and Municipality Borders. For each area, we defined three values of the average distance between stations: 500, 1.000 and 2.000 meters. Not all the possible configurations have been evaluated because they have been preliminarily evaluated as no interesting (for example, the configuration with stations every 2.000 meters in City Centre, no station in Ring Road Area and stations every 500 meters in Municipality Borders). Table 1:lists the 18 considered combinations and Fig. 5 depicts one of the possible spatial configuration.

Table 1: The considered spatial configurations

N°	City Centre	Ring Road Area	Municipality Borders
1	500	-	-
2	500	500	-
3	500	500	500
4	500	500	1.000
5	500	500	2.000
6	500	1.000	1.000
7	500	1.000	2.000
8	1.000	-	-
9	1.000	1.000	-
10	1.000	1.000	500
11	1.000	1.000	1.000
12	1.000	1.000	2.000
13	1.000	2.000	2.000
14	2.000	-	-
15	2.000	1.000	500
16	2.000	1.000	1.000
17	2.000	2.000	-
18	2.000	2.000	2.000

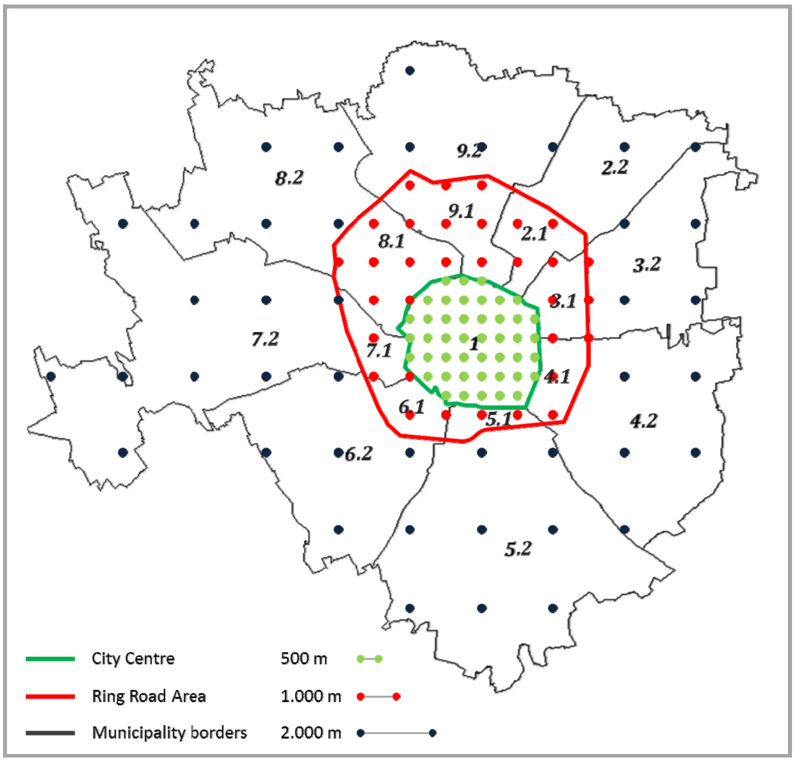

Fig. 5. Example of one spatial configuration. Density is higher in City Centre (the distance among station is 500 m), than in Ring Road Area (1.000 m) and within Municipality borders (2.000 m)

For the annual and hourly rate, the combinations considered in the evaluation phase are listed in Table 2. As it is possible to be seen in the table, not all the possible combinations of rates have been considered, even if quite extreme alternatives have been evaluated, such as the number 1 and the number 8.

Table 2: The considered combinations of annual and hourly rates

N°	Annual rate (€/year)	Hourly rate (€/hour)
1	0	7
2	0	15
3	50	5
4	50	7
5	50	15
6	100	3
7	100	5
8	100	7

The performance indicators identified for measuring the achievement of the options' objectives are:

- accessibility - variation of the level of accessibility to the urban mobility system;
- congestion - variation of the congestion level on the road network;
- local and global emissions - quantity of pollutant and of greenhouses gas emissions;
- parking places - variation of the public space occupied by private car;
- net present value - economic performance of the car sharing service.

The final step consists is the option evaluation, which is carried out by means of a multi-criteria analysis, in order to take into account possible conflicting objectives. Different service options can be compared based on their effects and the consequent level of fulfillment of the objectives. We implemented the *Electre tri* sorting method (Dias et al., 2002; Mousseau et al., 2000), in order to sort the options in categories and to elaborate a proposal. Moreover, the evaluation of the options will be conducted taking into account the points of view of different stakeholders.

The implemented model is able to design and size the main dimensions for a car sharing service, considering both internal combustion engine vehicles and electric ones. The model, starting from a limited number of significant configuration parameters, estimates a set of indicators and evaluates the economic, environmental and social performances of the designed service. At the present stage of the project, the evaluation model still lacks of the implementation engines of some models. So, we have not yet implemented the actual evaluation of the options for the city of Milan.

4. Conclusion

The paper presents a model for the design of an electric car sharing service for the city of Milano. This decision situation comprises a comprehensive set of stakeholders with possibly conflicting and unstructured views. In such an ill-defined decision context, it is crucial that the decision problem is structured in order to build consensus among stakeholders' objectives. In order to support the design of the configurations, we set up a multicriteria decision analysis, structured by means of cognitive maps. Such structuring phase supported the mutual understanding between the researchers with different expertise and the territorial stakeholders, and the identification of causal networks to estimate the effects of the options. The use of cognitive maps allowed to capture the multiple values of the problem and reduce their conflicting aspects. Moreover, their use was useful to define the estimation models and the multicriteria analysis by the mean of value trees of stakeholders objectives. The considered multi-criteria assessment is able to take into account the points of view of the territorial stakeholders, expressed mainly by their quantification of the importance of the different dimensions (criteria) and the possible support they may provide for the setup of the service. The proposed method can be useful in general for design and planning of mobility service, especially at a strategic level.

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