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From Traditional to Electrified Urban Road Networks: The Integration of Fuzzy Analytic Hierarchy Process and GIS as a Tool to Define a Feasibility Index—An Italian Case Study

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Abstract: To achieve sustainable development in the road sector, the use of Electric Vehicles (EVs) appears as a positive response to transport emissions. Among the available technologies, dynamic charging seems to overcome the main weakness points of EVs, even if it requires that traditional roads (t-roads) be equipped with a system providing electricity for EVs. Thus, so-called electrified roads (e-roads) must be implemented into the urban road networks. Since it is not possible to electrify all roads simultaneously, and also to consider the demand needs of citizens, a selection criterion is essential. This research describes and develops a simple, self-explanatory, repeatable, and adaptable selection criterion aimed at helping city managers in prioritizing the roads of an urban network to be upgraded from t-road to e-road status. This method belongs to the so-called Multicriteria Spatial Decision Support Systems (MC-SDSS)—processes useful for solving spatial problems through the integration of multicriteria analysis (Fuzzy Analytic Hierarchy Process, F-AHP) with a geo-referenced data management and analysis tool (GIS). The developed algorithm is based on several criteria related to the infrastructure/transport, social and environmental areas. The result of the implemented method is a Feasibility Index (*FI*), able to prioritize the roads most eligible to be upgraded as e-roads, as also verified by its application on the urban area of Milan (Italy).

Keywords: electrified road; dynamic charging; Multicriteria Spatial Decision Support Systems (MC-SDSS); Geographic Information System (GIS); Fuzzy Analytic Hierarchy Process (F-AHP)

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1. Introduction

From the perspective of sustainable development, vehicle electrification appears as a favorable response to high levels of Green House Gas (GHG) emissions generated by the road transport sector. In fact, as demonstrated by Figure 1 from [1], the amount of CO_2 equivalent, measured in millions of metric tons, related to transport increased by 33.18% from 1990 (726.5 million metric tons) to 2019 (967.5 million metric tons). Moreover, road transport is the most critical mode considering the whole transport sector, as reported in Figure 2, also from [1].

However, electrification requires both new vehicles (Electric Vehicles—EVs) and appropriate charging infrastructure networks. According to the available scientific literature, batteries can be recharged using both conductive and contactless technologies in both static and dynamic ways. Among the battery charging techniques available on the automotive market, on-the-road (dynamic) charging seems to overcome the main points of EV weakness which, otherwise, prevent its widespread diffusion, namely, high initial cost, long charging time, limited diffusion of static charging stations and range anxiety (short range) [2,3]. In this way, EVs can recharge their batteries while traveling. Therefore, traditional roads (t-roads) must be equipped with technologies that continuously provide electricity for EVs, developing the so-called electrified roads (e-roads). Since it is not possible to electrify all the infrastructures of a road network at the same time (for economic reasons, construction aspects, etc.), the current research develops a simple, self-explanatory, repeatable, and adaptable method able to define a priority list of roads that can be electrified, considering infrastructure/transport, social and environmental criteria.

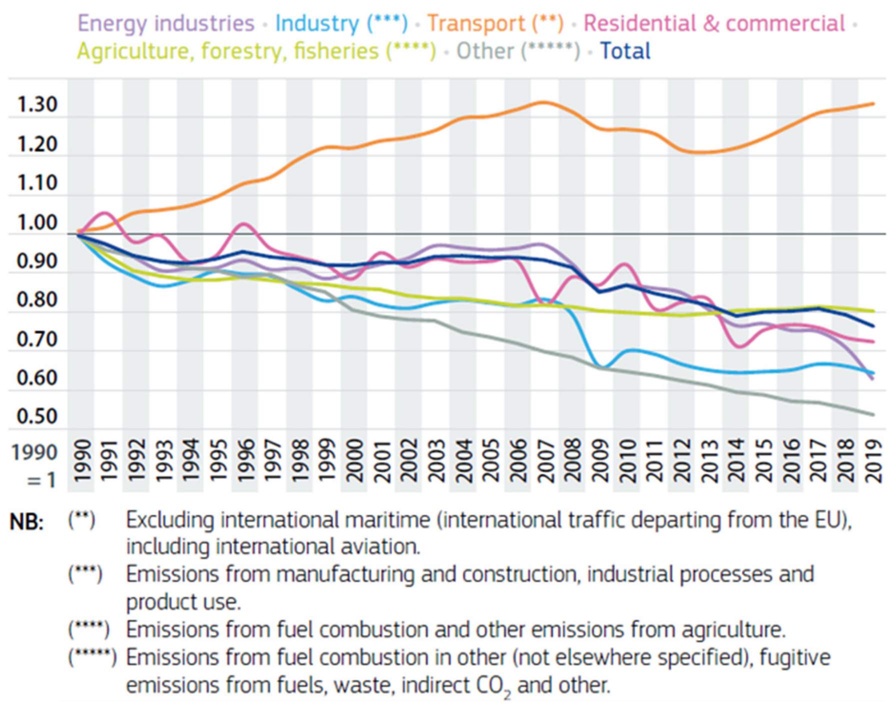


Figure 1. Million metric tons of CO_2 equivalent in EU-27 from 1990 to 2019 divided by sectors; from [1].

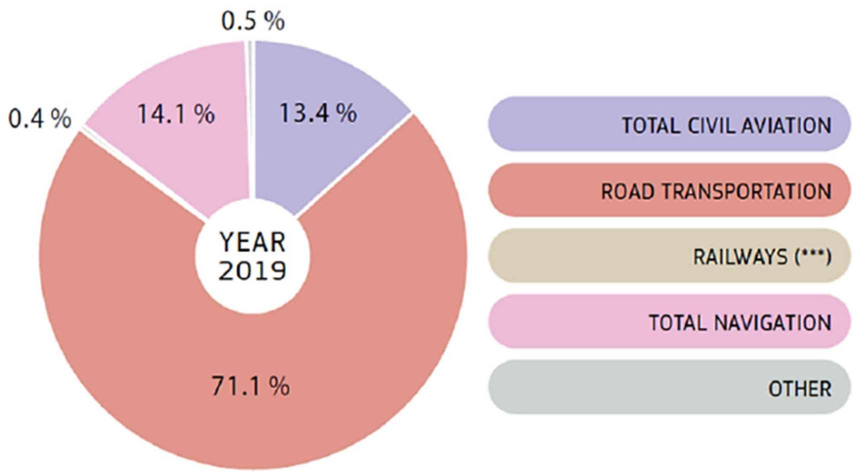


Figure 2. GHG emissions [%] from transport in EU-27 during 2019, divided by modes; (***) excluding indirect emissions from electricity consumption; from [1].

2. Literature Review and Objectives

In the available scientific literature, only a few studies improve methods to identify the best location for charging stations or wireless charging lanes, such as [4–9]. For example [4] shows an algorithm to optimize EV charging sites, on the basis of different parameters, such as parking, car/pedestrian traffic, street furniture, etc. The study described in [5] defines a method for dynamic charging lane deployment based on traffic and vehicle speed, using an entropy minimization problem. In other cases, such as [10], a suitable location is chosen in an arbitrary way, without implementing a decision-making process.

In addition to the previous methods, the so-called Multicriteria Spatial Decision Support Systems (MC-SDSS) is another tool able to solve spatial problems. Briefly, MC-

SDSS solves such spatial problems through the integration of multicriteria analysis with a geo-referenced data management and analysis tool, such as GIS (Geographic Information System) [11]. This is because, on one hand, multicriteria analysis is able to assess and prioritize different alternatives; on the other hand, GIS allows the managing and processing of spatial information [11]. Therefore, an MC-SDSS is potentially an optimal method to support long-term integrated planning for sustainable development [11], without replacing the role of the decision maker [12]. It is clearly confirmed by several examples of MC-SDSS that can be found in the available scientific literature [11–16].

The implementation of an MC-SDSS is the most suitable method to tackle the aforementioned problem, since it can be adapted to a dynamic road network. In fact, some examples in the available literature consider fixed paths (as in the case of local public transport) and attempt to implement a method to optimize these paths.

Moreover, two points of strength mark the MC-SDSS: the choice of the best parameters for the urban context of analysis and the definition of weight values (to be assigned to each parameter) in line with decision-maker policy.

Since MC-SDSS is a decision-making process, according to Simon's model, it is possible to find four main phases, as follows [12,17]:

- *Intelligence*: the problem is structured and the related descriptive criteria are defined. Data of each criterion are collected and processed;
- *Design*: development of the multicriteria structure, in which the relationships between criteria are described: both normalization and weighting process are performed; regarding the latter, the collection of public/general opinion regarding the main defined problem is currently based on surveys;
- *Choice*: the different alternatives are compared and assessed for achieving the right solution, answering the question posed by the main problem;
- *Review*: due to the subjectivity of some steps above described, a sensitivity analysis is performed to increase the decision model reliability and robustness.

The research herein discussed adopts the MC-SDSS as a suitable method in order to both identify and prioritize the upgrading from t-road to e-road of an urban road network, referring to the city of Milan (Italy) as a case study (Figure 3).

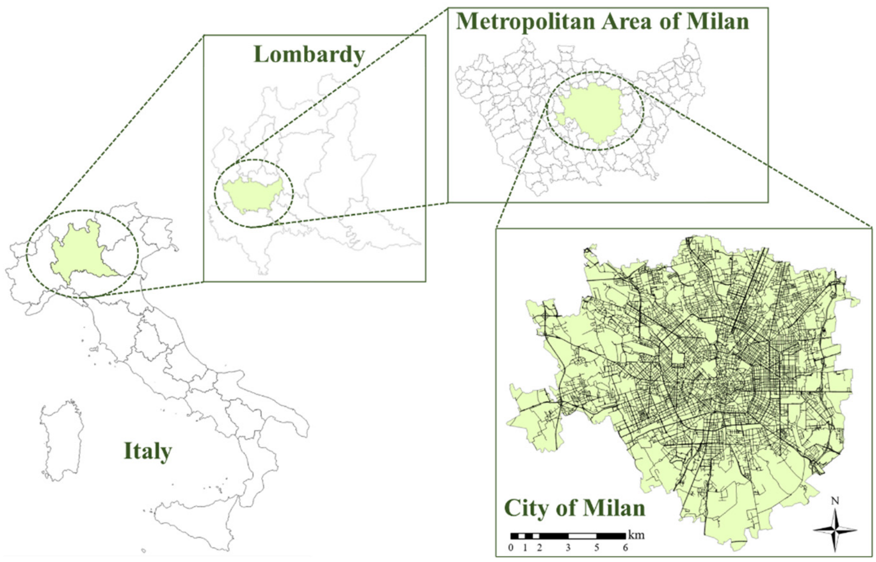


Figure 3. Location of the city of Milan in Italy.

As mentioned above, multicriteria analysis was used to compare different alternatives (t-roads), prioritizing them according to a score (the Feasibility Index—*FI*) assigned to each road. A specific algorithm (weighted sum) was developed to calculate the *FI*, based on several criteria related to infrastructure/transport, society and environment. A hierarchical relationship exists between these criteria; this is the reason the algorithm uses weights. The higher *FI*, the higher is the feasibility of upgrading a t-road to an e-road. The criteria definition is the main improvement compared to the available state of art, in which the descriptive parameters are related to transport only (such as traffic and vehicle speed). The criteria adopted in the present investigation are the results of both quantitative and qualitative analyses, in order to take into account that an e-road (or an e-road network) must improve the overall quality of the context. Thus, it must be able to be exploited by a large number of users, while also considering the spatial distribution for each criterion. For this reason, GIS is a key tool for solving the decision process. A flow chart of the decision-making process related to the identification of the potential e-roads is presented in Figure 4.

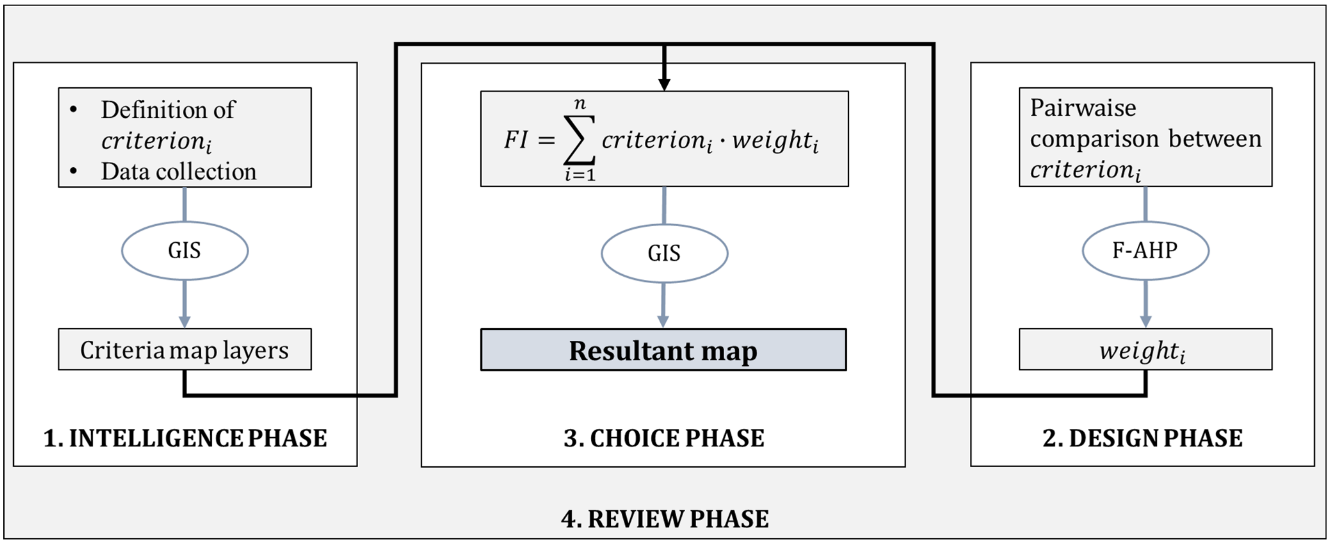


Figure 4. Flowchart of decision-making process related to identification of potential e-roads.

According to the decision-making process phases, the current paper is planned as follows. In Section 3, the descriptive criteria are detailed and the corresponding map layers related to the city of Milan, as a case study, are shown. The Fuzzy Analytic Hierarchy Process (F-AHP) is described in Section 4, in order to define the hierarchical importance of each criterion. Section 5 shows the final map of the case study (Milan road network), in which the developed *FI* is reported. In Section 6, the sensitivity analysis results are disclosed. Finally, conclusions are drawn in Section 7.

3. Intelligence Phase: Criteria Definition, Data Collection and Processing

During this phase, the problem was shaped and the related descriptive parameters were defined. The data for each criterion were collected and processed in order to obtain the criteria maps.

The analyzed criteria are shown in Table 1, according to both the area of interest and the methodology applied for data processing. Regarding data collection, two important considerations were necessary:

- From a theoretical point of view, the analysis must consider data in a wider area than that considered as a case study (the city of Milan), according to [4]. However, data related to the surrounding areas close to Milan suffer from a lack of information and are not as precise as those from Milan. Therefore, the data considered in the case study are from the city of Milan, except for "Air Quality", as discussed in the following;
- The year of analysis is 2019, since 2020 data (even when accessible) were affected by the COVID-19 pandemic.

Table 1. Criteria definition and description.

Criterion		Area of Interest	Methodology of Data Processing
Road Characteristics	RC	Infrastructure/transport	Linear
Vehicle Density	VD	Infrastructure/transport	Areal
Traffic	T	Infrastructure/transport	Areal
Key Infrastructures	KI	Infrastructure/transport	Buffer
Primary Attraction Centers	PAC	Society	Buffer
Secondary Attraction Centers	SAC	Society	Buffer
Air Quality	AQ	Environment	Areal—Thiessen polygon
Natural Reserves	NR	Environment	Buffer

The starting GIS map was the road network map of the city of Milan [18]. However, this basic map was revised, by removing unpaved roads, private roads, roads inside parking lots and pedestrian paths. It is important to note that each GIS road (representing the carriageway axis) comprises various lines. The total number of lines is equal to 53,929. On the basis of this map, all the criteria were processed.

The criteria descriptions are listed as follows. More details about each parameter, such as classification intervals and the related values, are given in Table 2.

- Road Characteristics (RC): this criterion describes Italian road categories according to [19]: A (extra-urban and urban), B (extra-urban), D (urban) two carriageways and four lanes; E (urban), C (extra-urban) single carriageway and two lanes; F (urban and extra-urban) local/rural roads. The values were set to promote urban environment and lower travel speeds, with the goal of maximizing the vehicle-charging efficiency [5,10,20].
- Vehicle Density (VD): this parameter examines the vehicles (number of vehicles per km^2) within the city of Milan. Information about vehicle distribution within the city is difficult to find, because of privacy issues. Therefore, vehicle density was correlated to the population density (*PD*) of each Milan neighborhood [21], as shown in Equation (1). This assumption implies that the greatest number of vehicles occurs where the greatest number of people live. Since EV number is limited compared with the total vehicle fleet (in Italy, during 2019, EV accounted for 0.057% of the total [22]), VD considers all vehicles without making a distinction between EV and vehicles with other power supplies.

$$PD_{neighborhood} : PD_{Milan} = VD_{neighborhood} : VD_{Milan} \quad (1)$$

  By extension, roads acquire the vehicle density value of the neighborhood ($VD_{neighborhood}$) in which they are located. Once the vehicle density was computed, four intervals were defined to which to assign parameter values, as shown in Table 2 (*intelligence phase* column). These VD intervals were obtained using the Jenks natural breaks method [23,24]. The values were set to promote high density urban areas, assuming that a high density entailed a higher number of e-road users. Moreover, since each GIS road is made of various lines, it is possible to have a road characterized by various parameter values (VD_i). Therefore, in order to obtain one value for each road (VD_{road}), a length weighted mean is applied, as shown in Equation (2).

$$VD_{road} = \frac{\sum VD_i \cdot lenght_i}{\sum lenght_i} \quad (2)$$

- Traffic (T): this criterion considers the Annual Average Daily Traffic (AADT) traveling on each road. Although the ideal scenario would directly correlate the observed traffic with the road, it was not possible to create an intersection between the network containing the traffic data (traffic data map) and the road network of the city of Milan, due to technical issues. Therefore, an approximation was made by correlating the traffic to both road category (according to [19]) and neighborhood. By intersecting the traffic data map and the neighborhood map, an average value for AADT was calculated according to road category and neighborhood, then it was located into the road network map according to road category and neighborhood. Thus, four intervals were defined to which to assign parameter values, as shown in Table 2 (*intelligence phase* column). Also in this case, T intervals were outlined using the Jenks natural breaks method. Moreover, in line with the previous parameter, the value for each road (T_{road}) was calculated by adapting Equation (2).

- Key Infrastructures (KI): this parameter includes point- infrastructures of strategic interest for the city of Milan, whose importance attracts high levels of traffic. In this context, KI are Park-and-Ride facilities [25] and the city airport (Linate) [26]. The parameter values were defined as follows:
  1. based on the distance as the crow flies from the center of the strategic infrastructure (the shorter the distance, the greater the value);
  2. based on the strategic infrastructure density (the greater the number of strategic infrastructures, the greater the value).

  The adopted data processing methodology is known as "multiple/multi ring buffer" (GIS software). By extension, roads acquire the parameter value according to their position in the "multiple ring buffer" geometry. An example of the methodology is shown in Figure 5a. Moreover, in line with the previous parameters, the value for each road (KI_{road}) is calculated by re-arranging Equation (2).
- Primary Attraction Centers (PAC): this criterion involves facilities whose importance attracts high levels of vehicle traffic: hospitals, pharmacies, schools and railway stations [27–30]. In line with KI, the parameter values were defined using the "multiple ring buffer" methodology (Figure 5), in which roads close to numerous PAC assume higher values. Once again, the value for each road (PAC_{road}) was calculated by re-arranging Equation (2).
- Secondary Attraction Centers (SAC): this criterion includes museums, large sales structures (e.g., malls), sports facilities and significant locations for the city of Milan (i.e., Milan Cathedral, Monumental Cemetery, etc.) [26,31–33]. In line with the previous parameters, the values were defined applying the "multiple ring buffer" methodology. Additionally, the value for each road (SAC_{road}) was calculated by re-arranging Equation (2).
- Air Quality (AQ): this parameter considers the average annual nitrogen oxide (NO_2) emissions into the atmosphere, in comparison with the threshold imposed by [34], equal to 40 $\mu g/m^3$. The reasons leading to NO_2 evaluations are listed as follows:
  1. road transport is the main cause of NO_2 emissions in major European cities [35,36];
  2. NO_2, in urban areas, can act as a precursor for the formation of other pollutants, such as $PM_{2.5}$ and, in combination with solar irradiation and ozone [35,36];
  3. NO_2 can have a harmful effect on human health, as it leads to an increase in respiratory problems and an increase in the likelihood of lung cancer [35,36];
  4. the high number of NO_2 monitoring sites.

  Since it is complex to assign an air quality parameter to each road [37], mostly because air quality is influenced by several factors (e.g., weather conditions, industry, overlapping effects of different roads in the same area), data by spot-monitoring sites already working in the city area were used [38]. The detected NO_2 values were correlated with the area surrounding the monitoring site, in order to obtain a homogeneous polygon characterized by the same emission values. The adopted data processing methodology was the so-called Thiessen polygon method [39–41]. Thus, the monitoring site value is representative of the area defined by the polygon (Figure 5b). Since there are only five NO_2 monitoring sites inside the city of Milan, the analysis was extended to a wider area which included several other cities in the Metropolitan Area of Milan (i.e., the Municipalities of Arconate, Cassano d'Adda, Cinisello Balsamo, Magenta, Rho, Sesto San Giovanni, etc.). Three AQ intervals were defined to which to assign parameter values, as shown in Table 2 (*intelligence phase* column). The greater the air pollution, the greater the parameter value. Contrary to the previous criteria, AQ intervals were obtained using a manual classification method. By extension, roads acquire the AQ values of the polygon in which they are located. The value for each road (AQ_{road}) was calculated by adapting Equation (2).

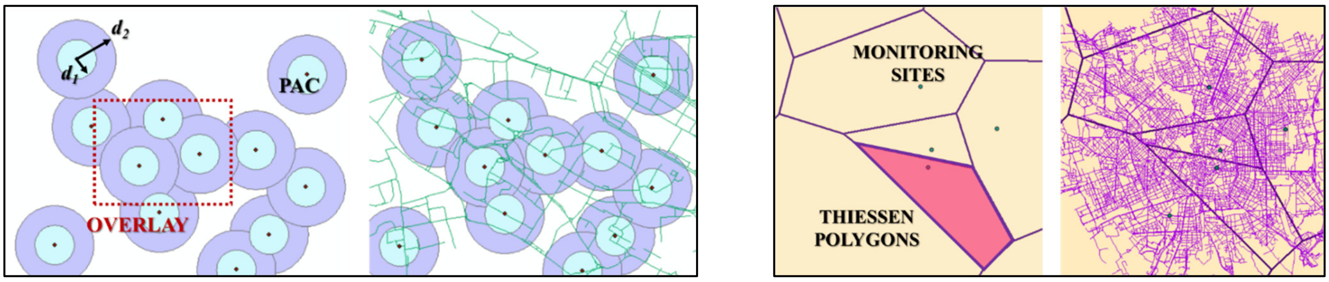
- Natural Reserves (NR): this criterion deals with parks and protected areas located in the city of Milan [42]. In line with KI, PAC and SAC, the adopted methodology for data processing was "multiple ring buffer". The difference between NR and the aforementioned parameters is the geometry; in fact, in this case, an areal distribution implies a concentric area (instead of concentric circle). According to the previous criteria, the value for each road (NR_{road}) was calculated by adapting Equation (2).

Table 2. Criteria classification intervals during both intelligence and *review phase*.

Criterion	**Classification Intervals**			**Value**
	Intelligence Phase		**Review Phase**	
	Italian Road Categories [19]	Area		
	Manual			
RC	A	Urban	No change	0.500
		Extra-urban		0.500
	B	Extra-urban		0.700
	C	Extra-urban		0.700
	D	Urban		1.000
	E	Urban		1.000
	F	Urban		1.000
		Extra-urban		0.700
VD	Number N of vehicles per km^2 [vehicles/km^2]			
	Jenks natural breaks		Manual	
	$N \leq 2491.991442$		$N \leq 4.000$	0.125
	$2491.991443 \leq N \leq 4704.604518$		$4.001 \leq N \leq 8.000$	0.250
	$4704.604519 \leq N \leq 7274.732464$		$8.001 \leq N \leq 12.000$	0.500
	$N \geq 7274.732465$		$N \geq 12.001$	1.00
T	Average Daily Traffic ADT [vehicles/day]			
	Jenks natural breaks		Manual	
	$ADT \leq 7948.635082$		$ADT \leq 4.000$	0.125
	$7948.635083 \leq ADT \leq 17{,}231.855022$		$4.001 \leq ADT \leq 8.000$	0.250
	$17{,}231.855023 \leq ADT \leq 45{,}069.874999$		$8.001 \leq ADT \leq 16.000$	0.500
	$ADT \geq 45{,}069.875000$		$ADT \geq 16.001$	1.000
KI	Straight distance d from key infrastructure [m]			
	Manual		No change	
	$d \leq 500$			0.500/key infrastructure
	$500 < d \leq 1000$			0.250/key infrastructure
	$d > 1000$			0.000

Table 2. *Cont.*

Criterion	**Classification Intervals**		**Value**
	Intelligence Phase	**Review Phase**	
PAC	Straight distance *d* from attraction center [m]	No change	
	Manual		
	$d \leq 150$		0.100/attraction center
	$150 < d \leq 300$		0.050/attraction center
	$d > 300$		0.000
SAC	Straight distance *d* from attraction center [m]	No change	
	Manual		
	$d \leq 150$		0.100/attraction center
	$150 < d \leq 300$		0.050/attraction center
	$d > 300$		0.000
AQ	Average annual emission *E* of NO_2 [$\mu g/m^3$]		
	Manual	Manual	
	$E \leq 40$	$E \leq 19$	0.250
	$41 \leq E \leq 45$	$20 \leq E \leq 39$	0.500
	$E \geq 46$	$E \geq 40$	1.000
NR	Straight distance *d* from natural reserves borders [m]	No change	
	Manual		
	$d \leq 500$		0.500/natural reserve
	$500 < d \leq 1000$		0.250/natural reserve
	$d > 1000$		0.000

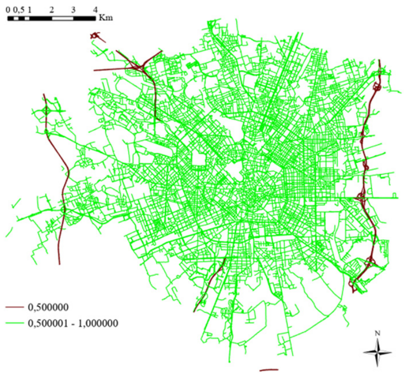
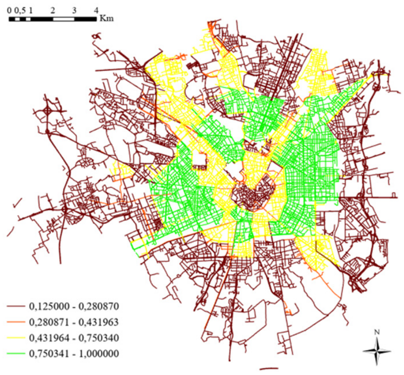
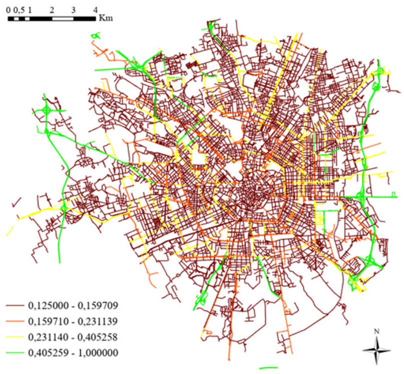
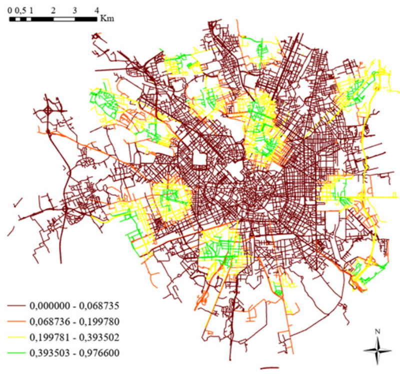
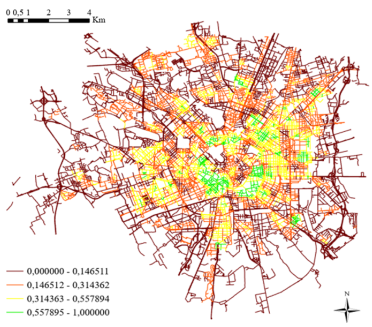
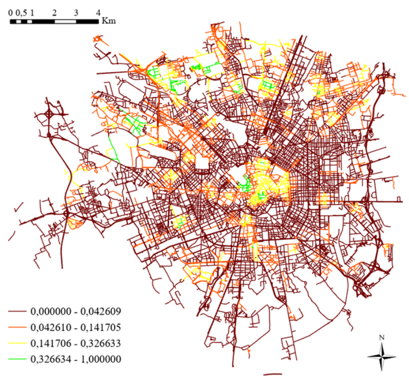
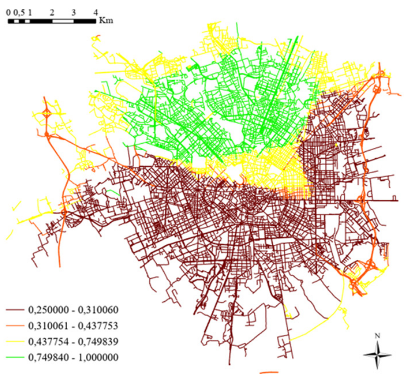
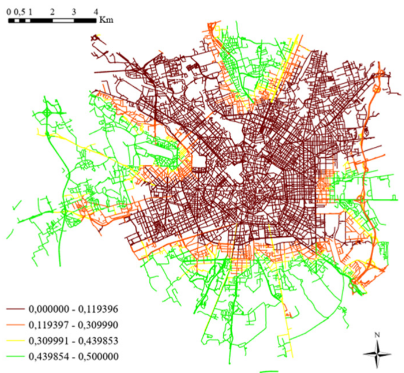


(**a**) (**b**)

Figure 5. Data processing methodology (**a**) Multiple Ring Buffer; (**b**) Areal—Thiessen Polygon.

The criteria maps are reported in Table 3: green-colored roads are characterized by higher parameters values, while dark red-colored roads show lower values. The four intervals (as shown in the legend) were obtained using the previously mentioned Jenks natural breaks classification method.

Table 3. Criteria maps of the city of Milan.

Infrastructure/ transport	Road Characteristics 	Vehicle Density 
	Traffic 	Key Infrastructures 
Society	Primary Attraction Centers 	Secondary Attraction Centers 
Environment	Air Quality 	Natural Reserves 

4. Design Phase: Fuzzy Analytic Hierarchy Process

During this phase, the multicriteria structure was developed by defining the relationships between criteria. The Analytic Hierarchy Process (AHP) used in this research is the most popular among the multicriteria methods provided by the scientific literature [16]. It is based on the Thomas L. Saaty procedure, in which the evaluation of alternatives is performed using pairwise comparison of criteria and a numerical scale of importance, as reported in the first column of Table 4.

Table 4. Pairwise comparison scale in F-AHP method.

Intensity of Importance (AHP Method)	Linguistic Variables	Triangular Fuzzy Number (*l*, *m*, *u*)	Reciprocal Triangular Fuzzy Number $(l, m, u)^{-1}$
1	Equal	(1, 1, 1)	(1,1,1)
2	Weak	(1, 2, 3)	(1/3, 1/2, 1)
3	Moderate	(2, 3, 4)	(1/4, 1/3, 1/2)
4	Moderate plus	(3, 4, 5)	(1/5, 1/4, 1/3)
5	Strong	(4,5, 6)	(1/6, 1/5, 1/4)
6	Strong plus	(5, 6, 7)	(1/7, 1/6, 1/5
7	Very strong	(6, 7, 8)	(1/8, 1/7, 1/6)
8	Very strong plus	(7, 8, 9)	(1/9, 1/8, 1/7)
9	Extremely strong	(9, 9, 9)	(1/9, 1/9, 1/9)

Since AHP is affected by problems of uncertainty and ineffectiveness in the description of human behavior, the introduction of fuzzy theory is currently used to improve the procedure by modelling vagueness of human expression [16]. In Fuzzy AHP (F-AHP), proposed by Dr. Lotfi Zadeh (1965), the numerical scale consists in Triangular Fuzzy Numbers (TFNs), instead of the so-called crisp numbers. A TFN is characterized by a group of three real numbers (l, m, u)—lower, medium and upper, respectively—describing the so-called membership function $\mu_A(x)$, as shown in Equation (3). The decision maker performs the pairwise comparisons using linguistic expressions (2nd column of Table 4), that are translated into TFN (3rd/4th column of Table 4) in a second phase.

$$\mu_A(x) = \begin{cases} \frac{x-l}{m-l}, & l \leq x \leq m \\ \frac{u-x}{u-m}, & m \leq x \leq u \\ 0 & otherwise \end{cases} \tag{3}$$

The matrix $\widetilde{A}$ of the pairwise comparison between the n parameters is shown in Equation (4), using TFN, from a theoretical point of view.

$$\widetilde{A} = (\widetilde{a}_{ij})_{nxn} = \begin{bmatrix} (1,1,1) & (l_{12}, m_{12}, u_{12}) & \ldots & (l_{1n}, m_{1n}, u_{1n}) \\ (l_{21}, m_{21}, u_{21}) & (1,1,1) & \ldots & (l_{2n}, m_{2n}, u_{2n}) \\ \vdots & \vdots & \ddots & \vdots \\ (l_{n1}, m_{n1}, u_{n1}) & (l_{n2}, m_{n2}, u_{n2}) & \ldots & (1,1,1) \end{bmatrix} \tag{4}$$

where:

$\widetilde{a}_{ij} = (l_{ij}, m_{ij}, u_{ij})$ and $\widetilde{a}_{ij}^{-1} = \left(\frac{1}{u\,ji}, \frac{1}{m\,ji}, \frac{1}{l\,ji}\right)$; for $i, j = 1, \ldots, n$ and $i \neq j$ Based on these judgments, it is possible to calculate the fuzzy weight $\widetilde{w}_i$ of each alternative, by adopting one of the methods available in the scientific literature. In the current research, the geometric mean method—presented by Buckley (1985) and shown in Equation (5) from a theoretical point of view—was used, since it is characterized by computational friendliness [16].

$$\widetilde{w}_i = \widetilde{r}_i \otimes (\widetilde{r}_1 \oplus \widetilde{r}_2 \oplus \ldots \oplus \widetilde{r}_n)^{-1} \tag{5}$$

where:

$\widetilde{r}_i$ is the fuzzy geometric mean value, calculated with Equation (6).

$$\widetilde{r}_i = (\widetilde{a}_{i1} \otimes \widetilde{a}_{i2} \otimes \ldots \otimes \widetilde{a}_{in})^{1/n} \tag{6}$$

In order to convert the TFN $\widetilde{w}_i$ to crisp value w_i, the de-fuzzification method of Center of Area (COA) is adopted, as presented in Equation (7). Weights normalization is then carried out to obtain the final values.

$$w_i = \left(\frac{l + m + u}{3}\right) \tag{7}$$

The last step is consistency validation, that ensures the coherence of the decision-making process [16,43], by calculating the Consistency Index (*CI*)—Equation (8). The matrix $\widetilde{A}$ is consistent if *CI* is equal to 0. However, if *CI* differs from 0, the Consistency Ratio (*CR*) can be computed by Equation (9). The consistency is verified if *CR* is less than 0.1.

$$CI = \frac{\lambda^{max} - n}{n - 1} \tag{8}$$

$$CR = \frac{CI}{RI} \tag{9}$$

where:

λ^{max} is the maximum eigenvalue of the comparison matrix;

RI is the Random Index that varies with the matrix dimension (number of parameters).

In the current research, the number of analyzed parameters n is equal to 8, as already discussed (Table 2). The theoretical steps described above are contextualized to the case study of the city of Milan and are summarized in Tables 5 and 6.

Table 5. Fuzzy pairwise comparison matrix.

	RC	VD	T	KI	PAC	SAC	AQ	NR
RC	(1; 1; 1)	(1/4; 1/3; 1/2)	(1/9; 1/9; 1/9)	(1/3; 1/2; 1)	(1/7; 1/6; 1/5)	(1/6; 1/5; 1/4)	(1/9; 1/8; 1/7)	(1; 2; 3)
VD	(2; 3; 4)	(1; 1; 1)	(1/7; 1/6; 1/5)	(1/4; 1/3; 1/2)	(1/5; 1/4; 1/3)	(1/4; 1/3; 1/2)	(1/6; 1/5; 1/4)	(1; 2; 3)
T	(9; 9; 9)	(5; 6; 7)	(1; 1; 1)	(4; 5; 6)	(2; 3; 4)	(3; 4; 5)	(1; 2; 3)	(7; 8; 9)
KI	(1; 2; 3)	(2; 3; 4)	(1/6; 1/5; 1/4)	(1; 1; 1)	(1/4; 1/3; 1/2)	(1/3; 1/2; 1)	(1/4; 1/3; 1/2)	(2; 3; 4)
PAC	(5; 6; 7)	(3; 4; 5)	(1/4; 1/3; 1/2)	(2; 3; 4)	(1; 1; 1)	(1; 2; 3)	(1/4; 1/3; 1/2)	(5; 6; 7)
SAC	(4; 5; 6)	(2; 3; 4)	(1/5; 1/4; 1/3)	(1; 2; 3)	(1/3; 1/2; 1)	(1; 1; 1)	(1/4; 1/3; 1/2)	(4; 5; 6)
AQ	(7; 8; 9)	(4; 5; 6)	(1/3; 1/2; 1)	(2; 3; 4)	(2; 3; 4)	(2; 3; 4)	(1; 1; 1)	(7; 8; 9)
NR	(1/3; 1/2; 1)	(1/3; 1/2; 1)	(1/9; 1/8; 1/7)	(1/4; 1/3; 1/2)	(1/7; 1/6; 1/5)	(1/6; 1/5; 1/4)	(1/9; 1/8; 1/7)	(1; 1; 1)

Table 6. From fuzzy to normalized weight.

Criteria	Fuzzy Geometric Mean Value	Fuzzy Weights	De-Fuzzified Weights	Normalized Weights
RC	(0.27; 0.33; 0.43)	(0.02; 0.03; 0.05)	0.03	0.03
VD	(0.40; 0.52; 0.69)	(0.03; 0.04; 0.08)	0.05	0.05
T	(3.05; 3.88; 4.61)	(0.2; 0.33; 0.51)	0.35	0.32
KI	(0.59; 0.82; 1.15)	(0.04; 0.07; 0.13)	0.08	0.07
PAC	(1.32; 1.77; 2.28)	(0.09; 0.15; 0.25)	0.16	0.15
SAC	(0.92; 1.26; 1.71)	(0.06; 0.11; 0.19)	0.12	0.11
AQ	(2.19; 2.85; 3.64)	(0.15; 0.24; 0.41)	0.27	0.24
NR	(0.23; 0.28; 0.39)	(0.02; 0.02; 0.04)	0.03	0.03

As regards the consistency verification, *CI* is equal to 0.093 (λ^{max} = 8.65). Therefore, *CR* is computed and it is equal to 0.065 (considering *RI* is equal to 1.41 [43]). Thus, the judgement is consistent (*CR* < 0.1).

5. Choice Phase: Resultant Map Indicating Feasibility Index

During the *choice phase*, the criteria maps obtained in the *intelligence phase* were merged in a final map by using the algorithm presented in Equation (10), answering the question posed by the main problem. The implemented algorithm is a weighted sum of the criteria described above that allows the Feasibility Index (*FI*) to be computed. *FI* is a numerical score to be assigned to each road in relation to the feasibility (suitability) of converting a traditional road into an e-road. *FI* varies from 0 (worst case) to 1 (best case, in which the road transformation is highly recommended).

$$FI = \sum_{i=1}^{n} criterion_i \cdot weight_i \tag{10}$$

where:

n is the total number of criteria;

$criterion_i$ is the value of the criterion i, as defined in Table 2;

$weight_i$ is the weight of the criterion i, as defined in Table 6.

In detail, each road is characterized by eight values related to the eight criteria; the criteria values of each road are multiplied by the corresponding weight (defined in Table 6), as summarized by way of the example in Table 7.

Table 7. Example of the adopted procedure for *FI* calculation.

		Value_Road		
		ID_Road	**Criteria**	**Criteria × Weight**
Criteria	RC	000000000096	1	0.03
	VD		0.25	0.0125
	T		0.125	0.04
	KI		0	0
	PAC		0.136662	0.020499
	SAC		0	0
	AQ		0.25	0.06
	NR		0	0
IF_000000000096				0.162999

The final map of the city of Milan is shown in Figure 6, in which green-colored roads (23.25% of the total network) are characterized by higher *FI* values and dark red-colored roads (22.03%) show lower *FI* values. The four intervals shown in the legend were obtained using the Jenks natural breaks classification method.

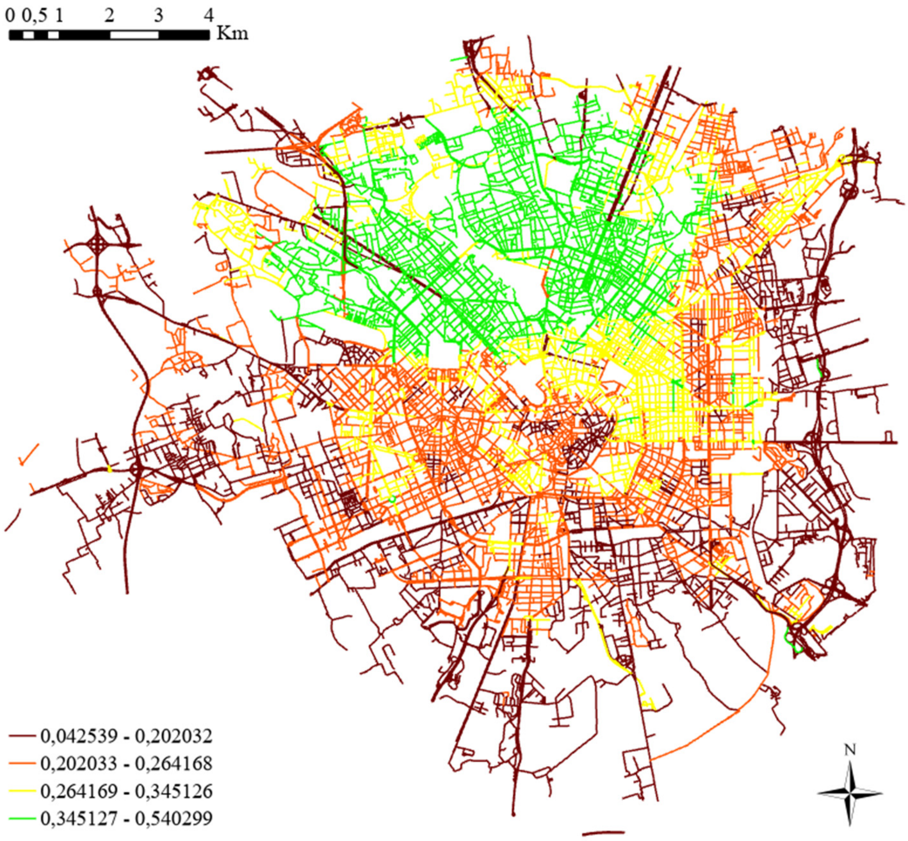


Figure 6. Final map of the city of Milan with the indication of Feasibility Index.

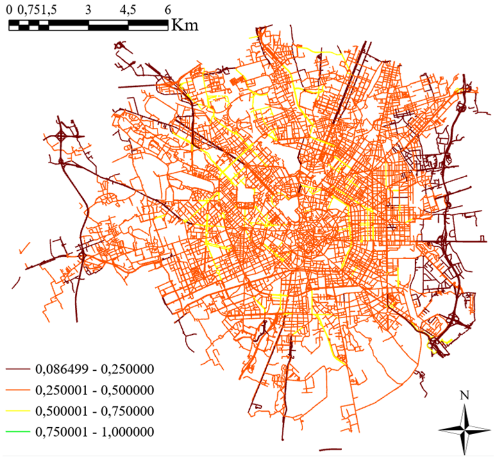
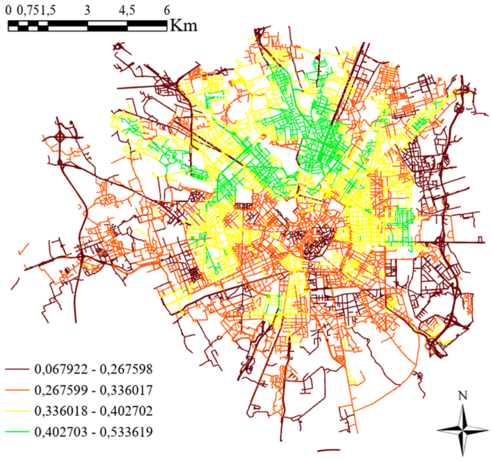
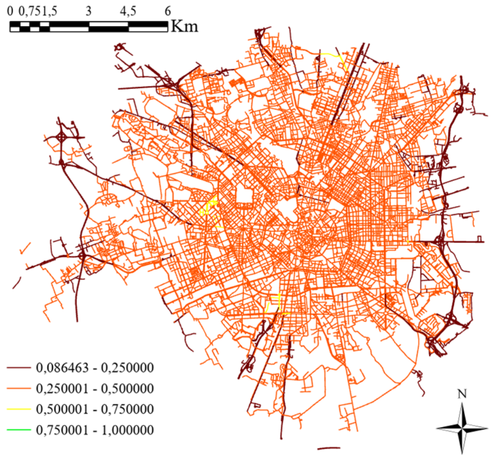
6. Review Phase: Choice of the Best Solution

Due to the subjectivity of the steps described above, a sensitivity analysis was performed in order to make the decision model more relevant and trustable. Therefore, three more scenarios were considered, varying both the criteria classification intervals and the criteria weights.

Three parameters (Vehicle Density, Traffic and Air Quality) were involved in the revision of the classification intervals, as reported in Table 2. It is important to note that the parameter values remained unchanged; only the interval to which these parameters are assigned varied. The other five criteria assumed the values of the *intelligence phase* (as reported in Table 2) in the same classification intervals. As regard weight variation, the criteria were considered to be of equal importance. Therefore, the criteria weights were set as equal to 0.125 (from 1/8).

By combining these two modifications, the final maps of the city of Milan with *FI* indication were obtained, as shown in Table 8, according to classification intervals and weights. When the manual intervals are considered (*review phase* column), the *FI* values in the legend are divided in four equal ranges (0.25 in width); in the other case (*intelligence phase* column), the four intervals in the legend are divided using the Jenks natural breaks method. In any case, green-colored roads are characterized by higher *FI* values, while dark red-colored roads have the lowest *FI* values.

Table 8. Final maps of the city of Milan with the indication of Feasibility Index in different scenarios.

		Criteria Classification Intervals	
		Intelligence phase: natural breaks + manual	*Review phase*: manual
Criteria weights	F-AHP	Figure 6 (base case)	
	$w = 0.125$		

The choice of both the criteria classification intervals and the weights is crucial to reach the final goal, as depicted in the maps of the city of Milan (Table 8). By comparing all these maps, the best solution is that shown in Figure 6 (classification method used in the *intelligence phase* and weights according to F-AHP), in which significant differences in the road network are appreciable.

7. Conclusions

From the perspective of sustainable development, the use of Electric Vehicles (EVs) appears as a favorable response to high emissions generated by the road transport sector. Among the available technologies, on-the-road charging seems to overcome the main points of weakness (e.g., high initial cost, long charging time, range anxiety, etc.) which prevent the widespread diffusion of EVs. Therefore, traditional roads (t-roads) must be equipped with technologies that provide electricity for EVs, developing the so-called electrified roads (e-roads). Since it is not possible to electrify all roads simultaneously (for economic reasons, construction aspects, etc.), this research develops a simple, self-explanatory, repeatable and adaptable method to prioritize the upgrading interventions of the road network (in which urban t-roads can be converted into e-roads). This method belongs to the so-called Multicriteria Spatial Decision Support Systems (MC-SDSS). These systems are procedures for solving spatial problems through the integration of multicriteria analysis

(Fuzzy Analytic Hierarchy Process, F-AHP) with a geo-referenced data management and analysis tool (GIS). The implementation of an MC-SDSS is the most suitable method to address the above problem since it can be tailored to a dynamic road network. In fact, the choice of the descriptive parameters/weight values can be adapted to the urban context of analysis according to decision-maker policy.

The method allows the calculation of the Feasibility Index (*FI*), that is a score—defined by an algorithm—to be assigned to each road according to the feasibility (suitability) of upgrading interventions.

As a result of the performed analyses, the main conclusions can be drawn as follows:

- The algorithm for the *FI* calculation is based on criteria related to infrastructure/transport, society and environment, in order to strengthen the multidisciplinary framework of the proposed technology; moreover, the option of considering sectors other than the common one (infrastructure/transport area) allows the development of a more detailed algorithm, gaining advantages in the final outcomes.
- The use of F-AHP improves the definition of hierarchical importance among the investigated parameters.
- The implemented method is a useful tool for the decision-maker to prioritize the upgrading interventions of the road network. In particular, the decision-maker can adapt the hierarchical importance among parameters according to their judgement (tailored-made weights).
- The map of the parameter "Road Characteristics" (RC) is marked as a green-colored road network, with a reduced number of roads in red. Therefore, a parameter constructed in this way is of little significance for the assessment of road geometric characteristics.

The variation in the criteria classification intervals affects the final map more than does the variation in the criteria weights, as shown during the last step of the MC-SDSS (*review phase*).

As a further proposal, the *FI* algorithm can be improved by adding more parameters, such as criteria related to both energy supply and interaction between an embedded charging system and underground utilities. In addition, a survey about the hierarchical importance between parameters can be conducted in order to collect the assessment/acceptability opinions of both a panel of experts and potential users of the designed system.

Finally, it is important to note that both the parameter choice and weight values depend on the urban context of analysis. Therefore, it is essential to identify a city, which is open to performing real-scale tests in order to confirm the proposed methodology.

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