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Spatial Multi-Criteria Analysis for Road Segment Cycling Suitability Assessment

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Abstract: The shift to low-emission mobility, embedded in a growing need for sustainable development, makes soft modes a highly promoted transport alternative in national and international mobility policies. Soft mobility modes, especially cycling, is an alternative capable of reversing the trend of private car use in urban areas, being one of the main strategies of Sustainable Urban Mobility Plans (SUMP). Several factors can influence travel mode choice, between them, demographic, economic, land use, travel distance and time, and climatic and physical factors are the most reported in the literature. This study presents a framework of the main European cycling strategies and focuses on the development of a methodological approach to assess the cycling suitability of existing road networks. The approach is based on a spatial multi-criteria analysis that combines population density, trip generation points service areas and road characteristics (hierarchy and slope). Consideration of the topography was particularly relevant in the cycling suitability model definition. The model was tested in the hillside city of Covilhã (Portugal) and compared with the recently planned and implemented city cycling network. The main conclusions point to the adequacy, flexibility, and applicability of the proposed model by municipalities, contributing to a more sustainable urban environment and healthier communities. Results obtained in the Covilhã case study also denote the possibility of implementing cycling mobility in hillside cities, especially using e-bikes. For future works, an expansion of the approach is proposed to include a detailed and sustained cycling network definition model and a process to assess cycling routes hierarchy/solutions.

Keywords: sustainable urban mobility; soft mobility; cycling; cycling suitability maps; spatial multi-criteria analysis

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1. Introduction

1.1. Framework

According to the World Business Council for Sustainable Development, sustainable mobility can be defined as the ability to meet society's need to move freely, gain access, communicate, trade, and establish relationships without sacrificing other essential human or ecological values, today or in the future [1]. The pursuit of this vision can only be achieved by protecting fundamental principles such as the natural environment; public health and safety; the population's travel needs; sustainable economy; social equity and overall well-being; ensuring energy efficiency and the long-term viability of transport systems with minimum infrastructure, access, and mobility costs.

For the European Union (EU) Council of Transport Ministers, the concept of sustainable mobility must comprise the following principles [2,3]:

- Respond to citizens', companies' and society's basic needs of access and development in a way that is safe and compatible with human health and environment preservation, while promoting equity in each generation and between generations.
- Be achievable, operating equitably and effectively, offering different transport choices, supporting a competitive economy and a balanced regional development.
- Limit emissions and waste to the planet's absorption capacity level using renewable energy at its generation rate and non-renewable energy at its substitution rate, minimizing the impact on land use and noise pollution.

As reported by the Transportation Association of Canada [4], a sustainable transportation system is a system that meets the access needs of present and future generations, uses renewable (inexhaustible) energy resources, does not pollute air, land, or water beyond the planet's capacity, is technologically possible, is economically and financially affordable, allows a desired quality of life, and supports local, national, and global sustainable development goals.

Presently, urban mobility is in debate when concerning sustainable city planning and citizens' quality of life. To be successful, it requires an overall view of the territory, namely its characteristics and constraints. One central issue for a more sustainable development has been the replacement of traditional motorized transport modes. To achieve more efficient and less polluting mobility systems, in the last decade, cities have been implementing policies supported by Sustainable Urban Mobility Plans [5], aiming to influence citizens' modal choice, namely using active modes integrated with other transport modes.

A successful change in travel behaviors depends on the creation of suitable conditions for this transition to occur, specifically in cities' spatial organization and their infrastructures, which should be suitable for active modes' use. The planning and design of cycling networks must meet the basic principles of continuity and coherence. They must also ensure safety to encourage citizens to use them, that is, they must be adequate and suitable for cycling travel [6].

This article aims to present an instrument to support the cycling suitability assessment of existing road infrastructure, having as a case study the city of Covilhã (Portugal).

To frame the proposed methodology, the concept of sustainable mobility, the EU and the Portuguese cycling strategy evolution, a review of the concept of bikeability and its assessment and the principles involved in spatial multi-criteria analysis are presented. The impact of slope in bikeability assessment and the role that e-bikes can play to overcome steeper slopes are also addressed. Finally, the methodology proposed to evaluate road segments cycling suitability using a spatial multi-criteria decision analysis is presented and applied to a case study.

1.2. EU and Portuguese Cycling Vision

Several important European documents focused on urban mobility were developed in the last two decades [7–10]. These strategic documents evolved from the discussion of the best approaches to improve urban mobility, to the definition of guidelines for a less polluting, smarter, safer, competitive, and resource-efficient transport system, resulting in a vision for sustainable urban mobility across the EU [8,11,12]. Of the considered documents, the first ones with a specific focus on promoting cycling culture in Europe appeared in 2017 [13,14].

Table 1 presents a summary of the main events concerning EU cycling policies.

The documents produced in the EU on urban mobility and cycling allowed the implementation of a significant number of national cycling strategies in European countries [22].

Following the European tendencies, in the first decade of the XXI century, Portuguese legislation and strategies were developed defining priorities for sustainable urban development and mobility policies implementation. These documents, which focused on less polluting modes, constituted a reference for the application of European funds [23,24]. In 2015, the government committed to the promotion of national green growth where cycling importance, as a particularly efficient urban mobility mode, was highlighted, aiming to increase its share in urban trips and its articulation with public transport modes [25]. Recognizing cycling as a fundamental part of the mobility chain, in 2019, more documents were published to promote cycling public policies [26,27].

Table 2 summarizes the main events concerning the Portuguese cycling scenario.

Table 1. European main events concerning cycling policies.

Year	Event	Brief Description
2007	Green Paper—Towards a new culture of urban mobility [7]	Defined a European agenda for urban mobility. Priority challenges: cities and towns decongested; greener cities and towns; smarter, affordable, and safe urban transport.
2009	Action Plan on Urban Mobility [15]	Proposed 20 measures to encourage and help local, regional, and national authorities in achieving their goals for sustainable urban mobility, including actions to promote cycling. The European Commission (EC) presented for the first time a comprehensive support package in the field of urban mobility.
2011	White Paper: Roadmap to a single European Transport Area—Towards a competitive and resource-efficient transport system [8]	Two explicit mentions to cycling in the 40 initiatives set out in the EU: efforts to deliver a 'zero-vision' for the number of road transport casualties, and the importance of promoting cycling as an alternative to car use. Acknowledges the importance of cycling in delivering clean and sustainable urban mobility and becoming an integral part of the urban transport system.
2013	Together towards competitive and resource-efficient urban mobility [11]	Sets out the concept of Sustainable Urban Mobility Plans (SUMP) on urban logistics and access regulations, deployment of Intelligent Transportation Systems (ITS) solutions in urban areas, and urban road safety. Promotes the development of strategies that can stimulate a shift towards cleaner and more sustainable transport modes, such as walking and cycling.
2014	Paris Declaration—City in motion: People first [12] From Amsterdam to Paris and Beyond: the transport, health and environment Pan-European programme [16]	Explicitly recognized the benefits of cycling in delivering sustainable economic development, reducing transport-related emissions, and promoting a more efficient transport system, whilst developing a Pan-European masterplan for the promotion of cycling.
2015	Declaration on cycling as a climate friendly transport mode [17]	Called the Commission to act on: integrate cycling into multimodal transport policy, including smart mobility, stressing the need to promote physical infrastructure and behavioral change programs; develop an EU-level strategic document on cycling; and set up a European focal point for cycling to serve as a one-stop-shop for relevant questions and facilitate exchange of best practices.
2016	Urban agenda for the EU—Pact of Amsterdam [9]	Established and noted that cycling was one of the elements to be focused on while delivering sustainable and efficient urban mobility.
	A European strategy for low-emission mobility [10]	The EU Commission refer to cycling in the section on action by cities, underlining the importance of local action and SUMP in enabling and encouraging cycling.
2017	Opinion of the European Committee of the Regions—An EU roadmap for cycling [13]	Established a set of policy recommendations, such as the inclusion of an EU Roadmap for Cycling in the Commission's Work Programme 2018 with actions to disseminate and raise awareness of cycling benefits and to promote a culture of cycling. Supported the development of a Pan-European Master Plan for cycling promotion.
	EU Cycling Strategy—Recommendations for achieving green growth and effective mobility in 2030 [14]	Designed to inspire the EC to develop its own European Cycling Strategy. Defined four central objectives: cycling as an equal partner in the mobility system; a 50% increase in EU bicycle use by 2030; a 50% decrease in EU killed and seriously injured cyclists by 2030; and increase the EU's investment in bicycles to €3 billion in 2021–2027 period and €6 billion for 2028–2034.
2018	Graz Declaration—Starting a new era: clean, safe and affordable mobility for Europe [18]	Discussed pathways leading to clean mobility. Acknowledged cycling as an equal mode of transport, developing a European strategic and supportive framework to promote and integrate active mobility in European funding and financing schemes.
2019	Directive (EU) 2019/1936 [19]	Revised the Directive 2008/96/EC on Road Infrastructure Safety Management (RISM), with dedicated guidance on road design quality requirements for "vulnerable" road users (cyclists, pedestrians, and powered two-wheelers).
2020	Sustainable and Smart Mobility Strategy—putting European transport on track for the future [20]	The strategy sets out a roadmap for European transport firmly on the track to sustainable and smart future mobility. It identifies 10 flagship areas with an action plan for future years, supporting the 2030 climate target plan. It aims for a 90% reduction in the transport sector's emissions by 2050, defining several initiatives to increase cycling mode share to achieve zero emissions, zero road fatalities, and first/last mile healthy mobility solutions.

Table 1. *Cont.*

Year	Event	Brief Description
2021	Pan-European Master Plan for cycling promotion [21]	The plan established several objectives to be implemented in the Pan-European region by 2030: - To significantly increase cycling in every country contributing to the overall target of doubling cycling in the region. - To extend and improve the infrastructure for cycling and walking in every country. - To significantly increase cyclists' safety in every country and to significantly reduce the number of fatalities and serious injuries in the region. - To integrate cycling into health policies, including those tackling noncommunicable diseases and obesity. - To integrate cycling, including cycling infrastructure, into land use, urban, regional and transport infrastructure planning

Table 2. Portuguese main events concerning cycling.

Year	Event	Brief Description
2005	ECOXXI Sustainability education program [28–30]	The program involved the identification of local sustainability indicators including sustainable mobility—indicator 18. This indicator evaluated the incentive to soft/active modes measured by the description of the three main actions to encourage soft/active modes implemented by a given municipality in the previous three years.
2007	Law no. 58/2007 National Program for Spatial Planning Policy (PNPOT) [23]	Framework of reference for other programs and territorial plans and a guiding instrument for strategies with territorial impact. A set of priority measures were established including the development of sustainable urban transport plans that aimed to reinforce the use of public transport and non-motorized mobility and improve the air quality, particularly in densely populated areas.
	Portuguese Sustainable Development Strategy (ENDS 2015) [24]	Defined the strategic objectives, priorities, and the most relevant vectors for accessibility and mobility. ENDS 2015 was the benchmark for the application to Community funds through the 2007–2013 period. It focused mainly on contributing to the reduction of air pollutants and noise, particularly in urban areas, and improving accessibility to citizens with reduced mobility.
2009	Resolution no. 3/2009—Recommendations for the National Plan for the promotion of bicycles and others soft transport modes [31]	The resolution established 6 objectives to achieve: (i) Percentage increase in cyclists in Portugal by 2012. (ii) Education actions for the use of safe transport modes. (iii) Teaching traffic rules and safe use of bicycles and other soft mobility modes at schools. (iv) Lobby to break down barriers to the use of soft mobility modes. (v) Support the integration of soft mobility modes in public transport systems. (vi) Promotion of cycle touring.
2012	ciclAndo—Plan for the promotion of bicycles and other soft modes [32]	Following the recommendations of resolution no. 3/2009, the plan defined 2 structuring strategic objectives framed in 5 areas of action with 17 operational goals.
	Portuguese Guidelines for Mobility [33]	Eleven guidelines for mobility were established constituting a set of instruments, plans and programs called the "Mobility Package". The package also contains a guide for accessibility, mobility, and transport in municipal spatial planning; a guide for preparing mobility and transport plans; a collection of technical/thematic brochures to support the preparation of mobility and transport plans, including a brochure on the principles for cycling networks planning and design; a guide for the elaboration of trip generation points mobility plans; and a guide on urban logistics.
2015	Resolution no. 28/2015—Green Growth Commitment [25]	This strategic document highlights the need to find alternatives to private car use and the importance of promoting the bicycle as a particularly efficient urban mobility mode, increasing its share in urban trips and its articulation with public transport modes.
2018	Bikeable Portugal 2030 [26]	The program's main objective was the identification of a set of favorable cycling scenarios in mainland Portugal to be integrated into an inter-municipal connectivity plan.
2019	National Strategy for Cycling Active Mobility 2020–2030 (ENMAC) [27]	ENMAC expects to reach 10,000 km of cycle paths by 2030, built through several investment initiatives; a cycling modal share of 7.5% in national territory and 10% in cities; and the reduction in road accidents involving cyclists by 50%. ENMAC foresees the implementation of 51 measures organized into 6 strategic dimensions.
	Roadmap for Carbon Neutrality 2050 (RNC2050) [34]	The government expects, by 2050, between 8% and 14% of short-distance mobility to be made using low-impact or active modes. This is considered one of the 5 main decarbonization drivers in the transport sector.

Table 2. *Cont.*

Year	Event	Brief Description
2020	Normative document for application to urban streets—Issue III—Geometric characteristics for non-motorized traffic streets [35]	The normative includes the cyclable road's theme, covering typologies, design and dimensioning, and measures to be applied in specific situations. The Normative can be considered a support document for ENMAC implementation.
2021	Regulation to support financially the acquisition of low emission vehicles [36] and for the implementation of bike park systems [37]	The incentive for the acquisition of low emission vehicles allocates financial support for individual persons and companies considering specific criteria. The financial support for the implementation of bike park systems aims to encourage the acquisition and installation of equipment for parking bicycles in places served by cycle paths, where "bicycle use" is notorious or in places where such use is intended to be stimulated, such as transport interfaces, schools, health services and other public services.
	National Climate Basic Law (Law 98/2021) [38]	The government assumes the compromise to promote cycling and pedestrian mobility (article 50—Sustainable Mobility)

Comparing the existing European and Portuguese regulations, plans and strategies, an increase was recorded in official cycling documents from 2015 onwards at the European level and from 2018 in Portugal. These findings point to a consolidation of policies to develop cycling as an urban mobility mode and to the existence of legislative conditions and financial instruments for its effective implementation.

1.3. Bikeability

The implementation of an effective sustainable urban mobility plan cannot be dissociated from soft mobility modes, and in particular from cycling. Municipalities have legislation and financial instruments to promote these modes and the main question became "how to encourage citizens to use this mode?". To answer this question, the quality of bicycle networks should be evaluated not based on one but on multiple factors, and more comprehensive methodologies to assess urban bicycle networks are essential to the operation and planning of modern city transportation [39].

In this context, the concept of bikeability can be defined as the extent to which the actual and perceived environment is conducive and safe for cycling [40]. According to Reggiani et al. [39], bikeability is the combination of objective and subjective factors and it integrates concepts such as bicycle comfort, suitability, friendliness, and accessibility.

Several methods and variables have been used for determining bikeability indexes. Among the most used methods, weighted regression, discrete choice, holistic approach and multi-criteria analysis using the additive or weighted linear combination method, and spatial analysis, can be highlighted [41–46].

A review of the literature identified the existence of cycling infrastructures and their characteristics (such as the presence, type and width of cycle paths, the existence of bike racks and routes sinuosity) [41,43,45–48]; land use [42,43,47,48]; population and behavioral and social aspects [42,43,45]; safety [43–45] and slope [41,42,44,45,48] as the most used variables. The variables that significantly influence the index values are, in most cases, the existence of dedicated cycling infrastructure, the network characteristics and safety.

The bikeability index determination approach varies from country to country, being related to the population's perception of the components that influence its suitability for bicycle use. For example, according to Arellana et al. [45], generalizing to developing countries on the American continent, bicycle use is mainly related to income. Low incomes push people to use bicycles, not by choice but because of the impossibility of resorting to other mobility options. In countries with higher incomes, people are more likely to use bikes due to health and environmental concerns.

1.4. Road Slope

Consideration of road slope in cycling systems modeling has not been consensual in the past. Empirically, slope appears to play an important role but few studies accounted for topography when estimating transportation mode choices [49–52]. The inclusion of slope in transport studies has risen significantly in the last two decades and findings point to a significant negative impact of slope on the attractiveness of non-motorized modes [50,51,53,54]. In fact, reports can be found on the positive impact of greater slopes, but these are generally related to experienced cyclists who value fitness-oriented routes [50,54,55].

In general, the ideal slope for conventional bicycle use should be the lowest possible, preferably less than 3% [56–59]. Conventional bicycles can be used in moderate slopes up to 5% while slopes greater than 8% are generally avoided.

Table 3 presents slope criteria for cycling adopted in several international design standards for conventional bicycles.

Table 3. Slope criteria for cycling (conventional bicycle).

Source	Slope	Description/Criteria for Cycling
Government of Catalonia Ministry of Town and Country Planning and Public Works—Manual for the design of cycle paths in Catalonia (2008) [60]	0 to 2%	No length limit
	4%	Up to 4 km
	5%	2 km
	6%	240 m
	10%	30 m
	25%	15 m
Portuguese Institute of Mobility and Land Transport (IMTT)—Cyclable Network: Planning and design principles (2011) [6]	0 to 3%	Level: Good for cycling
	3 to 5%	Gentle slope: Suitable for cycling up to medium distances.
	5 to 8%	Moderate slope: Inappropriate for long and medium distances.
	8 to 10%	Steep slope: Acceptable for very short distances.
American Association of State Highway and Transportation Officials (AASHTO)—Guide for the development of bicycle facilities (2012) [61]	0 to 5%	Shared use path: The maximum slope of a shared use path adjacent to a roadway should be 5%, but the slope should generally match the slope of the adjacent roadway. Slopes on paths in independent rights-of-way should also be limited to 5% maximum.
	>5%	Shared use path: Where a shared use path runs along a roadway with a slope that exceeds 5 percent, the side path slope may exceed 5 percent but must be less than or equal to the roadway slope.
	-	On-road facilities: If properly designed for motor vehicles, roadway design elements such as slope will meet or exceed the minimum design standards applicable to bicycles.
Transport for London—London cycling design standards (2014) [58]	0 to 3%	For cycle tracks, a maximum slope of 3% is recommended.
	3 to 5%	3% can rise to 5% over a distance of up to 100 m.
	5 to 7%	Where it is unavoidable, a slope of up to 7% over a distance of no more than 30 m is acceptable.
	>7%	In some circumstances, slopes steeper than 7% over short distances on a cycle route may be preferable to failing to provide the route at all.
	Comfort indicator: Uphill slope over 100 m >5% Basic cycling level of service 3 to 5% Good cycling level of service <3% Highest cycling level of service	
Austroads—Cycling aspects of Austroads Guides (2017) [59] Austroads—Guide to road design Part 6A: Paths for walking and cycling (2021) [57]	0 to 3%	Uphill: 3% is the desirable maximum slope for use on cycling paths.
	3 to 5%	Uphill and downhill: Slope to a maximum of about 5% and providing short flatter sections (20 m long) at regular intervals to give cyclists travelling, both uphill and downhill, some relief from the slope.
	>5%	Downhill: Slope steeper than 5% should not be provided unless it is unavoidable.

Table 3. *Cont.*

Source	Slope	Description/Criteria for Cycling
	Avoid	Slope greater than 10% over 50 m with horizontal curves or a slope of 12% over 50 m on a straight path.
CROW Design manual for bicycle traffic (2017) [62]	2 to 10%	Depending on slope height and length (slope severity/difficulty). $Z = H^2/L$ Z = slope difficulty H = slope height difference (m) L = slope length (m)
Böcker et al. (2020) [63]	<4%	Low slopes: Topography is not a limiting factor.
	4 to 8%	Moderate uphill slope: Topography does become a significant constraint.
	>8%	Cyclists generally avoid steep uphill and downhill slopes.
Cycle Infrastructure Design (2020) [64]	<5%	Maximum desirable slope—up to 30 m.
	8%	Absolute maximum slope.
Highway Design Manual—Chapter 1000—Bicycle transportation design (2020) [65]	<2%	Sustained slope.
	<5%	Maximum recommended slope.
Cycling Infrastructure—Auckland Transport (2021) [66]	<3%	Maximum desired slope.
	<5%	Undesirable because the ascents are difficult for many people to climb, and descents cause excess of speed.
	>5%	Recommended only for short sections.
Cycling by Design—Transport Scotland (2021) [67]	<3%	Providing cycle links on steep gradients will not provide the highest level of service for all users, and alternative routes should be considered where practical.
Geoprocessing and slope analysis of the cycling network of Londrina/PR (2021) [68]	<5%	Considered acceptable.
	>5%	"Warning points" for the implementation of infrastructure that helps cyclists in their travels.
	<8%	International references considered gradient slope of up to 8% as acceptable depending on the terrain and conditions offered to the cyclist.

These figures change when electric bicycles (e-bikes) are considered. The e-bikes are easier to use even with restrictions on the driver's physical condition, allowing to relativize the problems associated with steep slopes and the loads to be carried and to increase the area of influence of the daily trips to about 15 km [6,69]. Several authors refer that e-bikes have an advantage over conventional bicycles, mainly due to effort reduction in uphill routes [70], since speed, in general, does not differ more than 2 to 4 km/h when compared to conventional bikes [69,71–73].

Studies on conventional and electric bikes speed point to speeds of 18–20 km/h for 0% slope, 10–12 km/h for 5% slope and 8–11 km/h for 7% slope for conventional bikes, and 19 km/h for 0% slope, 16 km/h for 5% slope, 15 km/h for 7% slope and 13 km/h for >9% slope for e-bikes [74,75]. As expected, these differences are more evident on stepper uphill routes and almost zero in descent slopes. A study comparing bike and e-bike speeds showed that an increase of 1% in the street slope lowers speed by 0.39% for conventional bikes and by 0.29% for e-bikes, and that slopes above 6% decrease significantly downhill speeds for both types [75].

Still, recent research about the speed-slope relationship between conventional and electric bikes points out that the additional power from e-bikes is particularly helpful to maintain or increase average speed when cycling uphill [73,75], allowing us to conclude that the use of e-bikes can overcome the steeper slopes problem. Even when cyclists prefer longer routes to avoid steeper slopes, e-bikes present advantages by allowing longer trips in less time with the same effort [70,76].

By overcoming what is undoubtedly one of the greatest impediments to bicycle use in hillside cities, steep slopes, e-bikes help to materialize the concept of sustainable mobility in these areas [77,78].

1.5. Spatial Multi-Criteria Analysis

The definition of a cycling suitability index needs to include and quantify the influence of several factors to integrate the different dimensions that can affect the cycling mode choice. This integration can be achieved through Multi-Criteria Analysis (MCA), defined as a decision support technique that allows the comparison of different scenarios with multiple criteria, being in general the basis of most decision support systems [79]. The objective of this technique is to analyze the possibilities given a set of multiple criteria and objectives to be considered, which may be conflicting. The result is a ranking of alternatives according to their suitability for solving a specific problem.

Since the 1980s, MCA has been combined with GIS to optimize the decision-making process. When applied to alternatives and criteria that present spatial dimensions, MCA takes the name of spatial multi-criteria analysis [80,81]. The combination of the geographic database with the logical and mathematical relationships existing in map layers that enables the creation of new maps with new information results in decision support systems that allow making choices according to the produced analyses based on different situations, locations, and elements [82,83].

Among the different types of MCA, the Multiple Criteria Decision Analysis (MCDA) stands out for its use in problems with a spatial component, which allows combining geographic criteria and decision makers' preferences according to specified rules for sustained decision making [84,85]. The analysis seeks to support or assist in decision-making and not determine the solution to be taken [86,87].

The methods to adopt for criteria weights definition and combination are one of the main challenges in applying the MCA. According to Voogh [88], the priorities assigned to the various criteria can be translated quantitatively (weights) or through ordinal expressions (ordering) and can be performed through a preference analysis (questionnaires), a behavioral analysis or a hypothetical classification. Among the most used MCDA methods to assign a score to each criterion (weights) according to their relevance, those based on the ordering of criteria, scale of points and hierarchical analysis process (AHP) can be highlighted [81,89].

Regarding the most used methods to perform criteria combination and considering the context of GIS use, the weighted linear combination method and the ordered weighted average method are the most used. Of these, linear combination (additive models) is considered the basis of the MCDA, being the simplest, the most easily understood by decision-makers from different backgrounds and the most widely used form of value function method [86,87,90].

The MCDA based on linear additive models can be adopted to combine quantitative and Boolean criteria representing different degrees of adequacy of the considered factors (criteria). Each factor is multiplied by a weight, and the results are added together to obtain a multi-criteria solution that allows the ordering of options, from the most preferred to the least preferred option, serving as an aid for decision-makers [86,87].

2. Method

Since 2017, the Department of Civil Engineering and Architecture of the University of Beira Interior has developed, under the Master and Doctorate Programs in Civil Engineering and Master Program in Geographic Information Systems, several studies aiming at the definition of an evaluation process to assess the cycling and pedestrian suitability of urban road networks [91–95].

Regarding the use of bicycles, a methodological research approach was developed involving:

(1) A spatial multi-criteria cycling suitability model based on demographic data, trip generation points' location, type of bicycle (conventional and electric) and road network characteristics (slope, street hierarchy class and cross-section geometry).
(2) A cycling network definition model based on connectivity, network intersections, integration with other transport modes, parking, and safety.
(3) And a procedure for assessing cycling routes hierarchy/solutions.

Figure 1 presents the main steps involved in the research.

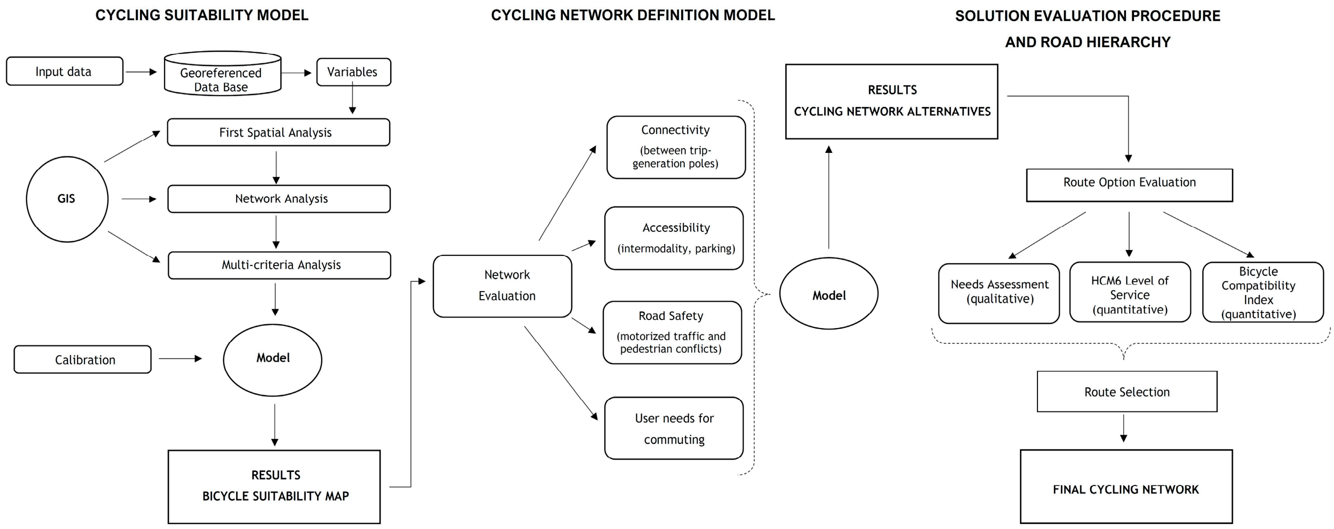

Figure 1. Methodological approach to plan cycling networks.

This article focuses on the first component of the proposed methodology, the cycling suitability model, which has been tested on the road network of the hillside city of Covilhã, Portugal [91].

The criteria considered in the suitability assessment of the network segments for conventional and electric bicycle use are population density, proximity to the main public facilities (trip generation points) and streets slope, hierarchy, and geometry (indirectly by hierarchy). For conventional and electric bicycle analysis, maximum slopes of 5% and 10% were considered, respectively.

The three criteria are combined based on a weighted linear method within a MCDA approach (see expression (1)) and the weights adopted are defined based on the opinion of a panel of urban mobility experts and local authorities. The trip generation points and population density criteria are calculated by pixel of the study area using expressions (2) and (3). Expression (2) allows to obtain the aggregate influence of the set of facilities considered in the generation of bicycle trips, weighted by the residents' stated preferences (workers). Population density is determined using expression (3). The values obtained in (2) and (3) are normalized using expression (4) and used in expression (1) to obtain a cycling suitability measure.

First, to feed the model, the collection and processing of spatial and alphanumeric information is performed. This information includes the road network, urban administrative boundaries and trip generation points' location vector data, raster digital terrain model ($\leq$5 m cell) and alphanumeric population data. Then, 3 types of data analysis can be performed using a set of tools available in GIS software. The analyses comprise an initial spatial analysis using geoprocessing tools (vector format), network analysis to define service areas based on time or distance (vector format) and spatial multi-criteria analysis (raster format). Finally, the calibration and evaluation of results are performed by a panel of urban mobility experts (academics and municipal representatives) and the results are transformed into vector format resulting in cycling suitability maps.

Expressions 1 to 4 present the model formulation.

$$CS_{i\_b} = (p_{TGP} \times TGP_{nor} + p_{PD} \times PD_{nor}) \times NS_i \quad (1)$$

where:

CS_{i_b} is the network cycling suitability, per pixel i on a 0–100 scale (very high $80 < CS_{i\_b} \leq 100$, high $60 < CS_{i\_b} \leq 80$, medium $40 < CS_{i\_b} \leq 60$, low $20 < CS_{i\_b} \leq 40$ and very low $0 < CS_{i\_b} \leq 20$ suitability), by bicycle type b (conventional bicycle or e-bike).

p_{TGP} and p_{PD} are the weights to be assigned to the trip generation points and population density criterion (defined by the panel of transportation experts and local authorities).

TGP_{nor} is the trip generation points criterion value (pixel, normalized).

PD_{nor} is the population density criterion value (pixel, normalized).

NS_i is the network value for segment i (0 for segments not adequate for cycling and 1 for segments adequate for cycling).

$$TGP = \sum_{j}^{n} \frac{w_n \times j_n}{n} \tag{2}$$

where:

TGP is the trip generation points criteria value (pixel, not normalized).

n is the number of sub-criteria (number of facility categories, such as health, educational, services, etc.).

j is the score assigned to the service areas representing the level of future cycling demand (defined as a function of travel time—scale of points).

w_n is the n sub-criterion's weight (defined from the inhabitants' stated preferences survey).

$$PD = \frac{RP}{A} \tag{3}$$

where:

PD is the population density criteria value in inhabitants/ha or inhabitants/km^2 (pixel, not normalized).

RP is the resident population of a considered urban area (pixel, inhabitants).

A is the urban area under study in ha or km^2. The A unit should be chosen according to the administrative territory division dimension considered (For example, neighborhoods (ha) or parishes (km^2)).

$$P_{nor\_i} = \frac{(P_i - P_{min})}{(P_{max} - P_{min})} \times 100 \tag{4}$$

where:

P_{nor_i} is the normalized pixel value for TGP_{nor} or PD_{nor}.

P_i is the not normalized pixel value for TGP or PD.

P_{min} and P_{max} are the criterion minimum and maximum values (not normalized).

The presented methodology's feasibility and operationalization were tested in a real case study.

3. Case Study

3.1. Study Area and Framework of Municipal Policies and Strategies

The city of Covilhã is located in Portugal's central region, on the southeast slope of Serra da Estrela Mountain, where the highest altitudes of mainland Portugal are found. The urban area has 36,500 inhabitants and presents altitudes ranging between 450 and 800 m. It is the seat of a municipality with a territory of 555 km^2 and around 52,000 inhabitants.

The city is characterized by two distinct occupations: the medieval village where the castle walls of Covilhã are located, deeply marked by the deployment slope and a narrow and irregular road structure, which has not suffered significant processes of urban fabric reorganization; and the most recent expansion area, whose development is conditioned by Cova da Beira Valley and Zêzere River.

The existence of two deep valleys, where streams Ribeira da Carpinteira and Ribeira da Goldra are located, and the rugged relief of the region, have contributed to the development of new urban areas away from the city center, resulting, in recent years, in a sprawl of the urban perimeter. This change caused a geographic dispersion of functions and facilities over 3 different altitude zones [96,97], raising problems with citizens' accessibility and contributing to the increase in private car use. According to data from the 2011 census, the municipality presents a high use of private transport for commuting (67.5%) when compared with the Portuguese national average (63.3%) [98].

Bearing in mind this scenario, a municipal goal of creating conditions for soft mobility was established by the local authorities in 2015. Within the scope of the financing framework established in the Partnership Agreement "Portugal 2020" between Portugal and the EC, the financing of operations related to urban mobility, in particular soft mobility, depended on the existence of a Sustainable Urban Mobility Action Plan (PAMUS). To achieve this goal, the municipality promoted the development of the Covilhã PAMUS, later integrated into the application for the city's Strategic Urban Development Plan (Covilhã PEDU) and the Beiras and Serra da Estrela PAMUS (PAMUS-BSE) [99]. PAMUS-BSE was developed for the Inter-municipal Community of Beiras and Serra da Estrela (CIM-BSE) territory, which comprises 15 municipalities, including Covilhã.

For the set of CIM-BSE municipalities, the 2001–2011 diagnosis within the scope of PAMUS-BSE revealed a decrease in the soft modes' share for commuting trips. It also showed a loss of 47% in pedestrian commuters and a bicycle share of only 0.6% [99]. The PAMUS-BSE considered that reversing this trend would primarily involve the improvement and expansion of the main pedestrian and cycling network in urban areas, not only to improve safety and comfort conditions, but also the attractiveness of the main connections between the trip generation points.

3.2. Analysis

To achieve the municipal soft mobility goal, since mid-2019 the city council of Covilhã has been undertaking the construction of the city's cycling network, complying with the PAMUS-BSE objective of creating a bicycle network combined with an e-bike sharing system in articulation with the city's public transport network. This system aims to promote the use of bicycles on commuting trips and the reduction in greenhouse gas (CO_2) emissions.

When completed, the planned city's cycling network will interconnect the main trip generation points in the urban area, covering a total extension of 17.59 km (Figure 2) considering street integration solutions based on street/road hierarchy and traffic flows. A special focus is placed on the connection between educational, residential, and commercial areas.

Four types of bike lanes are considered: bicycle lane in a unidirectional corridor with on-street parking, shared Bus-Bike lane in a unidirectional corridor, shared lane with traffic and pedestrians, and shared lane with traffic (streets with shared-lane marking placed in the travel lane to indicate where people should preferably cycle—pavement painting).

At the same time, the local academic community undertook several studies on the feasibility and implementation conditions to promote soft mobility in general, with particular emphasis on hillside cities. The criteria and suitability maps for Covilhã's urban perimeter obtained with the spatial multi-criteria cycling suitability analysis for conventional and electric bikes, according to the method described in Section 2, are presented in Figures 3–5. The study covered the entire road network of the urban perimeter parishes (430 km) and not just the urban center of Covilhã (intervention area considered by the City Council).

Facilities service areas were obtained through a network analysis performed with the ArcGIS® Network Analyst tool for network travel distances of 1000, 2500, 5000, 10,000 and >10,000 m. This analysis can also be performed as a function of travel time (see Table 4). The scores assigned to TGP service areas and weights allocated to each facility category, defined according to the performed survey's results, are shown in Table 4. Expression (2) was used to combine the service areas' scores with the facility category weights. Results obtained for population density and trip generation points criteria were normalized through a reclassification of values on a scale from 0 to 100 using expression (4). Regarding the road hierarchy and slope, considered as a constraint (binary variable), it must satisfy the logical condition: roads' hierarchical class = NOT arterial AND slope $\leq$ 5% for conventional bike analysis and roads' hierarchical class = NOT arterial AND slope $\leq$ 10% for e-bike analysis. Based on the findings of Flügel et al. [75] and Woodcock et al. [74], the average cycling speed considered for conventional (slope $\leq$ 5%) and electric (slope $\leq$ 10%) bicycle were, in both cases, 15 km/h.

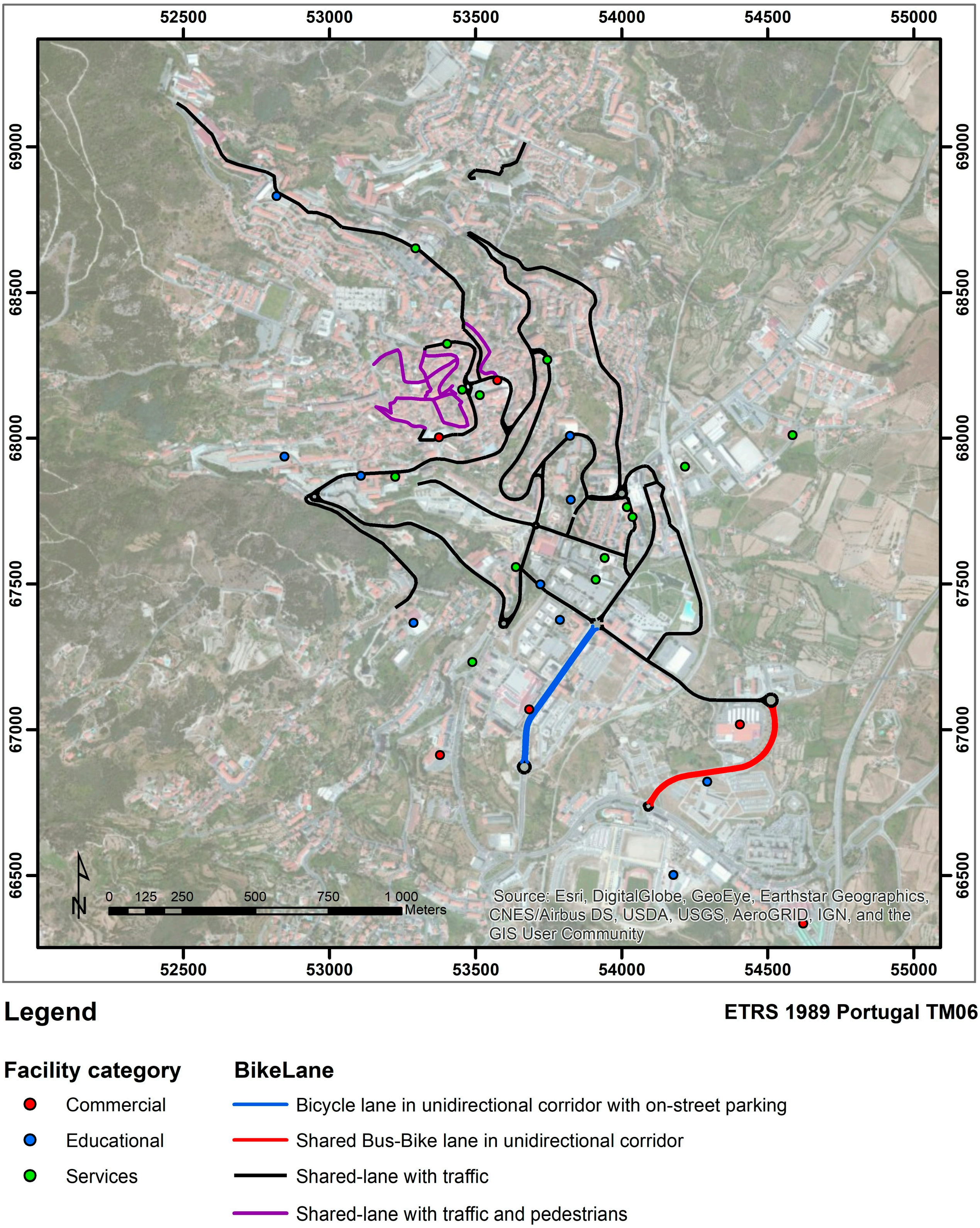

Figure 2. Covilhã's cycling network (adapted from [56]).

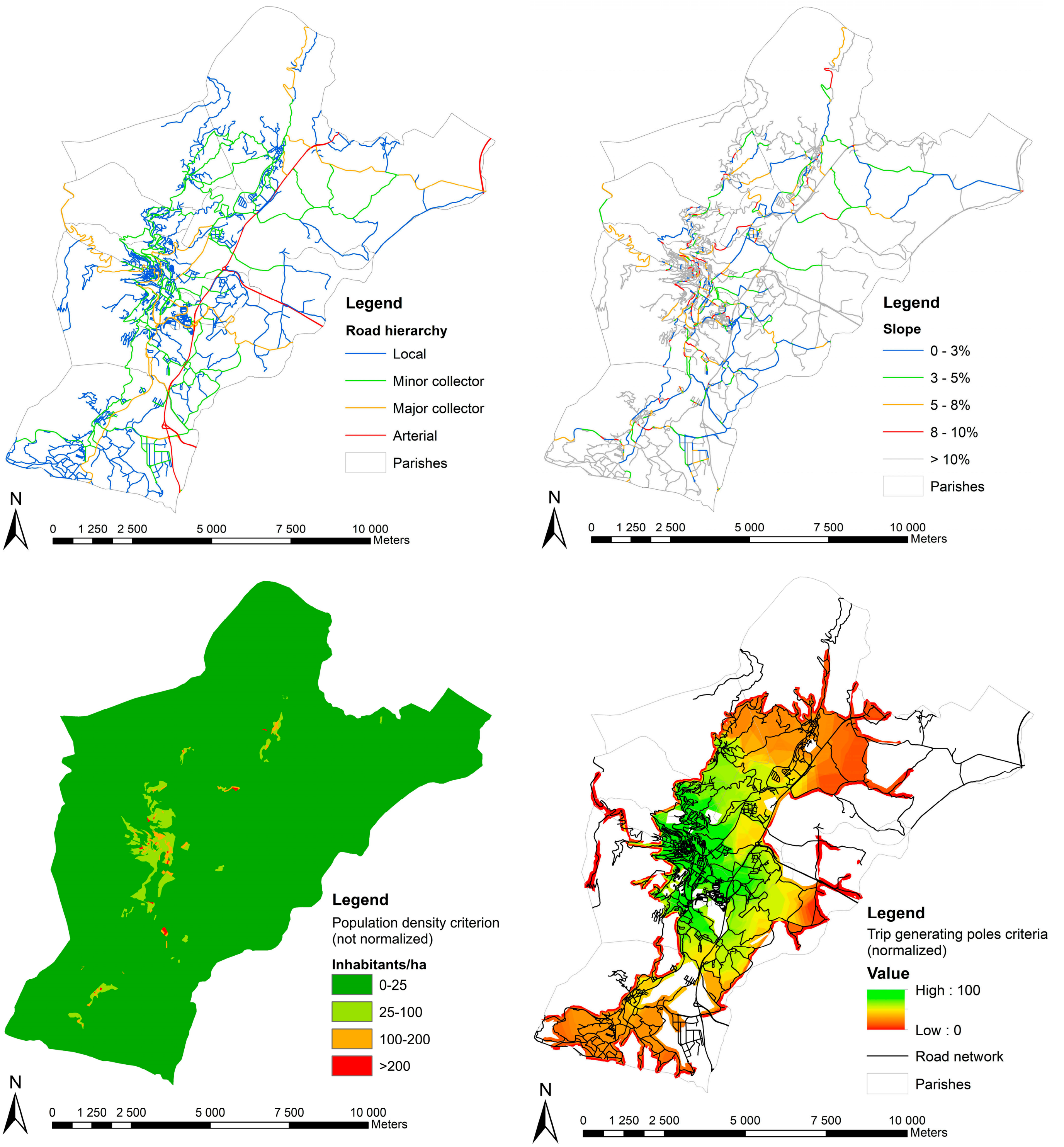

Figure 3. Covilhã's urban perimeter road hierarchy and slope, population density (not normalized) and trip generating poles analysis (normalized).

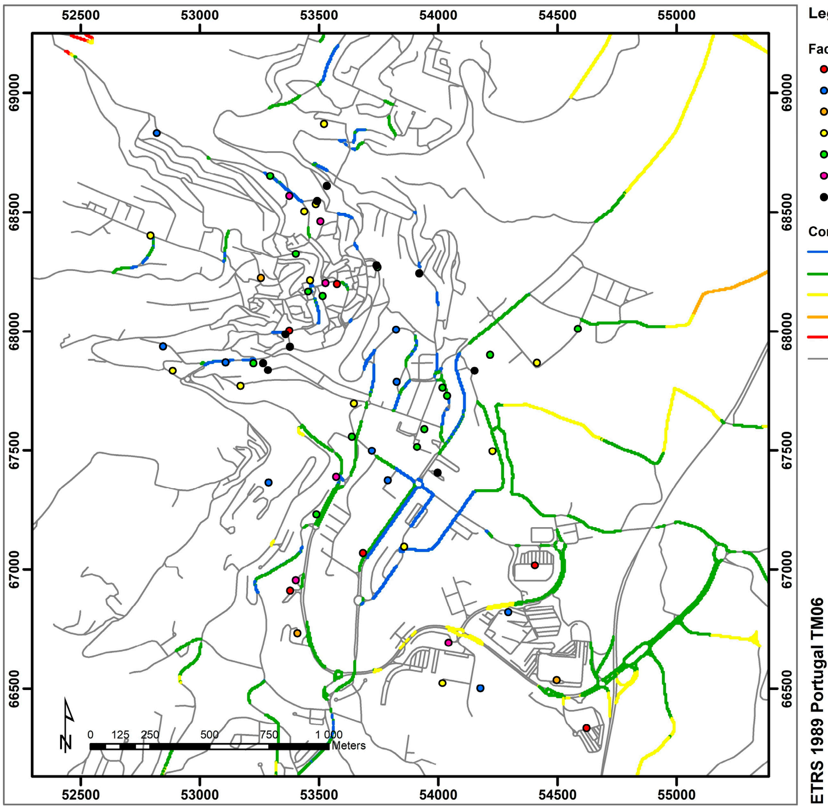

Figure 4. Covilhã's urban center: conventional cycling suitability map.

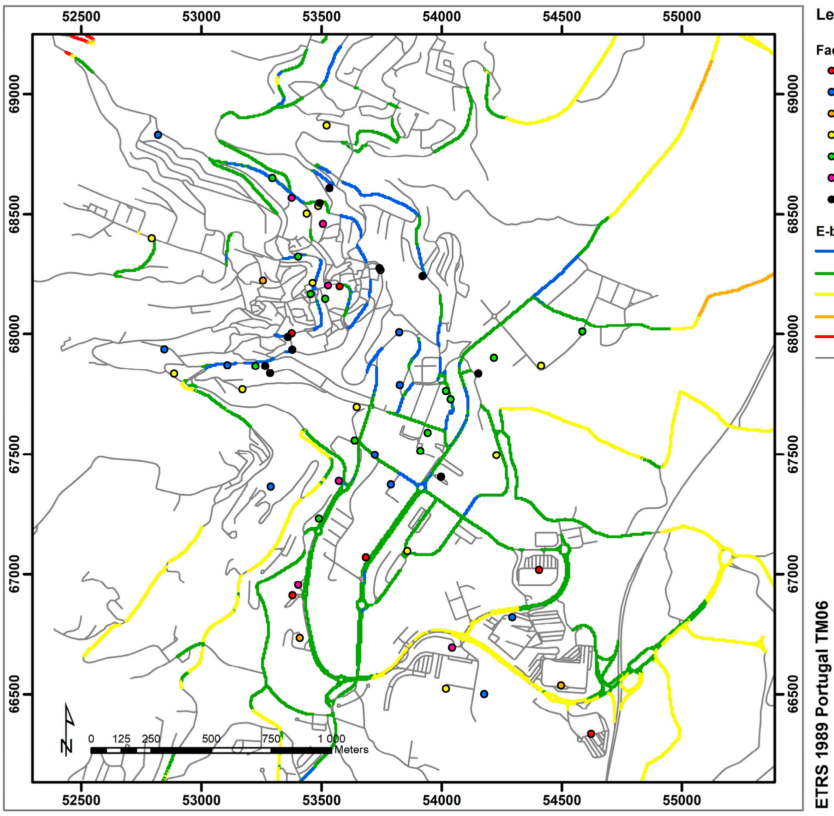

Figure 5. Covilhã's urban center: e-bike suitability map.

Table 4. Service areas scores and sub-criteria weights (facility category).

Service Areas		Score (0–100)	Facility Category	Weight
Travel Distance (m)	**Travel Time (min)**			
1000	0–4	90	Transportation	0.69
2500	4–10	75	Health	0.70
5000	10–20	50	Educational	0.79
10,000	20–40	1	Services	0.68
>10,000	>40	0	Commercial	0.71
			Tourism	0.80
			Culture	0.73
			Recreation	0.82
			Sport	0.78

The most appropriate combination of weights to be considered in expression (1) must be validated by transport and mobility specialists and municipal representatives. For the case study, the surveys carried out among Portuguese transport and mobility experts and Covilhã's municipal representatives pointed to weights of 70% and 30% for the trip generation points and population density criteria, respectively. The results of the proposed methodology application and weights are presented in Figure 4 for conventional bikes and in Figure 5 for e-bikes.

4. Results and Discussion

Suitability maps presented in Figures 4 and 5 show the set of street segments suitable for cycling without considering the network connectivity analysis. A total of 23% of Covilhã's urban perimeter road network is suitable for the use of the conventional bicycle (classification from very high to very low suitability), while for electric bicycle use, more suited to the city's topography, it is 34%.

Considering the road network segments with very high, high, and medium suitability scores, the overlap of the conventional and electric bikes' suitability networks with the planned Covilhã's cycling network is approximately 29% and 52%, respectively (Figure 6).

A preliminary analysis of the results to consider network connectivity revealed an increase in the e-bike network overlapping of 66% (Figure 6). The preliminary connectivity analysis only focused on the suitability results obtained for the use of e-bikes, since it is a more adequate solution for the city. Connectivity was evaluated to guarantee continuous and direct connections between trip generation points, access to transport facilities and low, very low or not suitable connecting road segments up to 150 m long.

Spatial location analysis of the planned and suitable segments confirms that both solutions point to the location of cycling routes in areas with high population density and trip generation points concentration, thus confirming the appropriateness of the proposed model.

For not suitable or low/very low suitability road segments longer than 150 m, but that guarantee connectivity needs, a more in-depth assessment is suggested. Since they are not suitable for e-bike use according to the criteria adopted, these road segments may need a deeper intervention to consider their inclusion in the cycling network.

Regarding the planned shared lanes with traffic and pedestrian (see Figure 2), which represents about 10% of the city's planned cycling network, the analysis revealed that it is not suitable for cycling circulation. It should be noted that the road segments in question are in the oldest part of the city center, where the roads are narrow, steep, and coated with natural stone (granite cubes). As this is a relatively small area near the town hall square with tourist interest, it is suggested to place bicycle racks and e-bike charging points in the square and interventions more oriented to improve the pedestrian infrastructure.

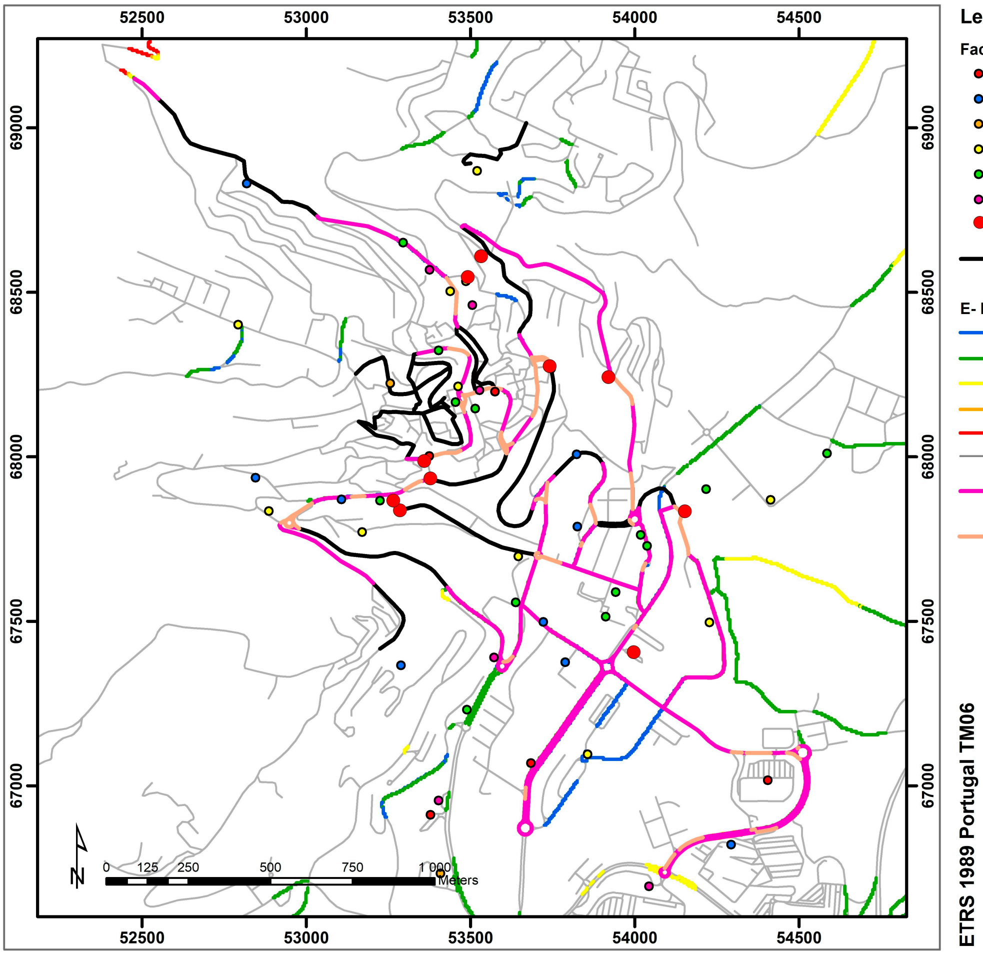

Figure 6. Overlapping of Covilhã's planned cycle network and e-bike suitability network (including a preliminary connectivity analysis).

5. Conclusions

Currently, the use of bicycles in daily trips is increasingly a reality, not only for economic and environmental reasons, but also because it is considered a faster alternative to private cars on short-distance urban journeys (up to 8 km). However, to be safe and attractive, it is necessary to raise awareness among the population and to adopt governmental and planning measures that guarantee comfort and safety conditions and an effective concern with cyclists' needs. These conditions must be considered when planning new cycling networks or adapting the existing road network to include cycling mobility.

Sustainable mobility has been a priority on the EU agenda since 2007. The definition of various policies and strategies, as well as the emergence of air quality legislation establishing greenhouse gas emission limits, provided the member states, including Portugal, with guidelines for the practice of a better urban mobility [100]. However, although soft modes are beginning to gain expression in Portuguese and other European cities, the private car continues to be the most used transport mode.

Decision support tools to assist urban space managers in cycling network planning are essential to promote more sustainable mobility behaviors and increase the use of bicycles on daily trips. The present study pretends to contribute to this goal through the creation of an instrument to evaluate the cycling suitability of road segments based on variables identified as relevant in the literature: population density, proximity to the main public facilities (trip generation points) and streets slope, hierarchy, and geometry. The selection of variables also considered the availability of official and public data for an effective tool application by the municipalities.

Choosing a spatial multi-criteria approach allowed to combine the selected variables, keep the approach flexible to incorporate the most appropriate criteria weights (which represent specific characteristics of each scenario under analysis), and include spatial relations using GIS.

The proposed methodology was validated by a case study in the urban road network of Covilhã city, Portugal. Since the urban perimeter is located on a hillside, the use of conventional and electric bicycles was analyzed.

The results obtained allow to conclude that 23% of the network extension is suitable for the use of conventional bicycles and 34% for the use of e-bikes. Of the five classes adopted to categorize road segments concerning cycling suitability level, only three were considered comfortable for urban commuting trips: very high, high, and medium suitability. Under this assumption, within the existing urban perimeter road network, 12.9% present comfortable conditions for the use of conventional bicycles and 19.1% for e-bikes.

The approach has also allowed an overlapping of the solution obtained in the case study with the cities' planned and implemented cycling network, validating the main routes suitable for cycling, and identifying road segments whose inclusion should be reassessed.

In future developments, the authors suggest the incorporation of models for cycling speed calculation (conventional and electric) as a function of road slope and the explicit inclusion of road cross-section geometric characteristics in the cycling suitability model. A more detailed and sustained development of the cycling network definition model and procedures is also proposed to assess cycling routes' hierarchy/solutions components.

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