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Integrating sustainable criteria through an AHP-GIS method to allocate mobility hubs using open data sources.

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Study Project

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Exposé - Study Project

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Title: Integrating sustainable criteria through an AHP-GIS method to allocate mobility hubs using open data sources.

Background:

As the world is on the verge of a climate crisis, the transportation sector, as one of the largest contributors [1], is seeking for more sustainable approaches in policies and planning strategies necessary to adapt to this challenge [2]. In general, the concept of sustainability refers to a balance between the social, environmental, and economic domains [3]. However, in transportation, it have focused mostly on the economic and, until some extend, on the environmental aspects, leaving aside social concerns related to the transport field [4] [5].

Such contradictions might lead to disparities in how different social groups benefit from transportation, or by contrast, how they are affected. Inequalities in the transport field might lead to social exclusion, limiting participation, and increasing deprivation among disadvantaged groups [6][7][8][9]. In this social regard, there are two important concepts. The first one, horizontal social equity, referring to the uniform distribution of resources for all (also known as egalitarianism) and vertical social equity, which corresponds to the distribution based on the needs of the different social groups (or also called social justice) [10] [11]. Within this last concept, two additional categories are pertinent, one is the allocation of resources based on the individual's income and position in the stratified society and a second one referring to resources distribution based on mobility needs and abilities of each individual [10].

In line with the previously mentioned sustainable strategies, local authorities and transport planners are working on the enhancement of transport modes with lower or minimal environmental footprint (e.g. cycling, walking, sharing services, and public transport) [2]. With such changes, new transportation concepts, such as mobility hubs have become an attractive approach. These are physical convergence points for sharing services (bicycles, e-scooter, cars, etc.), public transport, and active modes that are thought to provide a seamless inter and multimodal mobility [12]–[15]. Additionally, mobility hubs can integrate complementary features to increase the attractiveness of such modes and potentially make them more convenient for users in terms of time savings, flexibility, and ease of use. For example, mobility hubs can incorporate information, signage elements, as well as retail options, and supporting commercial services [15][16]. The integration of such features is not only thought to ensure seamless connection between the various transport modes but also to use mobility hubs as placemakers to enrich the public realm; contributing to social safety and accessibility topics [12], [13].

To know more about the planning process, the literature review done so far concerning the design and implementation of mobility hubs covered other types of transport stations (bus stations, bike-and-ride, or park-and-ride), since the field of mobility hubs is more limited. Even though a vast number of the sources addressed social criteria, they mainly refer to physical accessibility aspects [12], [14]–[20]. Namely, they often relate to design features such as barrier-free, security for the users, comfort, and the provision of inclusive signage [10] – coinciding with the second type of vertical equity (movement needs and abilities). Other addressed social equity aspects focused on individuals' income referring to integrated and economically accessible payment fares [12]. However, in terms of the location planning process, the literature consulted only vaguely mentions the importance of creating mobility hubs accessible to all social groups [12], [18]. Another example found in the literature correspond to a suitability analysis integrating aspects related to social equity and resiliency of communities to help planning authorities place new mobility hubs [21].

Regarding the other neglected pillar of sustainability, environmental indicators are usually not weighted-in when planning the location of new mobility hubs. The problem with this goes beyond environmental aspects, as the effects of poor environmental quality in specific areas might significantly affect less-privileged segments of the population [22]. Therefore, it would make sense to consider spatial environmental data during the location planning (e.g., concentration of pollutants with high global warming potential). Nonetheless, the consulted guidelines and methodologies showed no proof that such criteria are typically considered.

Mobility hubs have emerged to encourage more sustainable mobility behaviors and to improve the public realm. The reviewed guidelines and related papers mainly focused on efficiency criteria, such as population and activity density and land-use diversity, when addressing the allocation of mobility hubs. However, up to this point, none of the literature sources combine the criteria of the 3 sustainability pillars to identify potential locations for this new mobility concept.

Goals:

Although mobility hubs have emerged as new strategies supporting more sustainable transport alternatives, the allocation process has overlooked environmental and, specially, social considerations. This study project intends to complement this gap by integrating environmental and social equity aspects as weighting factors for selecting potential locations for mobility hubs. Therefore, the main objective is to create a method that combines the social equity, environmental criteria with existing efficiency principles for the allocation of mobility hubs.

Methodology:

A further in-depth literature review is one of the initial methodological steps to identify the specific criteria for each of the three categories to be considered when finding a potential location for the mobility hubs. Based on those findings and the data availability, the information will be analyzed, classified, and treated through a geographic information system (GIS) approach

The criteria will be differentiated into three categories: social equity, environment, and efficiency. Potential indicators include income:

- Equity criteria: migration background, housing costs, education level, income and/or deprivation index.
- Environmental criteria: concentration of air pollutants, noise levels, and transport mode share.
- Efficiency criteria: population density and points of interest (POIs).

The final list of criteria will be defined during the development of the literature review and based on the available spatial data. Through an analytical hierarchy approach (AHP), each criterion will be assigned a weight considering the input of different experts in the field. Some possible experts might be representants from the academia, experts involved in the SmartHubs project, representants of transportation organization, decision makers, among others. Subsequently, a GIS multi-criteria analysis (GIS-MCA) will be used to identify and visualize potential locations for the mobility hubs. The data will be visualized in the form of heatmaps, representing suitable locations for the mobility hubs.

Expected results:

The expected result of this project is the identification of suitable potential locations for mobility hubs through a methodology that simultaneously integrates aspects of social equity, environmental quality, and typically efficiency criteria associated with high demand. This study project is expected to contribute to the decision-making process by providing a visual ranking of the suitable locations.

Supervision:

The candidate will present to his supervisor Dr.-Ing. David Durán Rodas a draft of the structure for her study project report and a work plan two weeks after this approval. Other supervision meetings will be planned with the candidate when necessary. The Chair of Urban Structure and Transport Planning supports the candidate with the contact to relevant actors and or experts if needed. After two weeks of the submission of her study project report, the candidate must defend it by means of a presentation (20 minutes) and the following discussion. The results are responsibility of the author. The Chair does not take responsibility for those results.

Dr.-Ing. Benjamin Büttner

Dr.-Ing. David Durán Rodas

Hereby, I confirm that this document, corresponding to the report of the study project for the MSc. Environmental Engineering program, is my own work and I have documented all sources and material used for its creation.

Munich, 9 May 2022

María Fernanda Navarro Ávalos

May 2022

Study Project – MSc. Environmental Engineering

Integrating sustainable criteria through an AHP-GIS method to allocate mobility hubs using open data sources.

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Abstract

The transport planning sector now faces the challenge of reducing car dependency and related emissions. Following the current global agenda on sustainable development, transportation systems should reduce greenhouse gases (GHG) and be more equitable and accessible for all the population. Mobility hubs are a relatively new approach that enhances sustainable modes and can help mitigate those issues. They are nodes where multiple modes are available. Although mobility hubs are becoming an appealing strategy for developers, there is not enough information addressing the allocation process beyond the usual focus on rentability, and, vaguely, on social equity and environmental concerns. To fill this gap, this study proposes a method that integrates sustainability criteria to select a location on the macro-level for new mobility hubs. The method encloses a pre-selected list of social equity, environment, and demand efficiency criteria, corresponding to those most frequently mentioned in the literature. The pre-selected list is thought to be used as a reference when consulting open spatial data sources to select a final set of criteria. A group of experts is then consulted to define weights to those final criteria applying the analytical hierarchy process (AHP). Then, using a Geographic Information System (GIS) software, the spatial data is treated and combined with the weights to create a suitability map showing the area under study ranked from least to most suitable to guide the allocation process. Thus, the level of suitability is based on the assigned weighted values by the experts. This study used the city of Munich as a case study. Seven final criteria were considered for the AHP, namely low car ownership, unemployment rate, elderly population, nitrogen dioxide concentration, traffic noise levels, population density, and density of points of interest. The contacted experts were practitioners and researchers from academia with expertise on mobility hubs. The AHP results showed a strong prioritization of the criteria related to demand efficiency, namely, population density and points of interest (POIs) density, both together with almost 60% of the weights. Following the results from the suitability map, the most suitable areas for the placement of mobility hubs are found in the city center, where there is a higher concentration of POIs and populations. Still, suitable areas can also be found in more peripheral locations.

Keywords: *mobility hubs;analytical hierarchy process; allocation; sustainable transport.*

1. Introduction

As the world is on the verge of a climate crisis, the transportation sector, one of the major culprits, requires a transformation towards more sustainable mobility options. Recent efforts from governments and developers, especially in Europe, focus on reducing car dependency by enhancing public transport, active modes, shared services and on-demand options [1], [2].

In general terms, sustainability accounts for the balance of environmental, social, and economic costs and benefits. Therefore, a sustainable transport system is not only cost-effective over time, but it should also adopt new low-emission models and ensure equal opportunities for the entire population; in fact, this is one of the targets of the Sustainable Development Goals (SDGs). Specifically, SDGs' targets 9.1 and 11.2 refer to accessibility and affordability for everyone [3]. This strictly represents the core of social equity, which Greene and Wegener point to as an intrinsic component of sustainability [4]. The importance of social equity in transport is based on the fact that inequalities in transport supply and reduced accessibility can lead to social exclusion, limited participation of citizens, and deprivation among disadvantaged groups [5]–[8]. From a sustainable economic perspective, the focus of this research refers to the profits and gains of the service providers, hereafter referred to as demand efficiency.

Mobility hubs are a relatively new mobility strategy that can be simply defined as convergence points for multimodal services. Their purpose is to enhance seamless multi-and-inter modal trips. Mobility hubs, which are emerging especially in Europe [1], are currently of particular interest to developers and planners. However, as far as the consulted literature showed, the scientific research on this field is not broad yet. There is even a more significant gap about the allocation process, with only a few publications on methodologies or guidelines. Some of the findings relate to the placement of mobility hubs in various neighborhoods to ensure that social equity objectives are met [1], [9]–[12]. Furthermore, in the field of transportation and urban planning, the most common driver when defining the location of mobility hubs, or other transportation services, is the potential demand that it represents, i.e., the economic benefits. A recent study identified the most important factors for the allocation of mobility through a systematic literature review regarding multiple alternative modes hubs (i.e., bike, scooter, and car sharing, as well as ride hailing, taxi services, and charging stations) [13]. The principal factors can be associated with the purpose of having a high demand and not necessarily related to a fairer distribution of resources. For instance, the list of main factors includes employment density, population density, points of interest, education level, proximity to educational institutions, residential and mixed land-use, among others. Moreover, little research has been done on multicriteria analysis [9], a strategy commonly used -and much relevant- on transportation topics, specifically, during decision-making processes where more than one factor is relevant.

This research aims to contribute to the existing literature by developing a methodology that considers multicriteria for the identification of potential locations for mobility hubs. To achieve this goal, a preliminary identification of the criteria was done considering the three pillars of sustainability: social (equity), environment, and economic (demand efficiency). The most important criteria found in the literature are filtered by considering those available for spatial analysis. The Analytical Hierarchy Process (AHP) is then applied to determine the significance of each determined criterion based on the experts' knowledge. The experts' inputs are gathered together to have the final weights to prioritize each criterion. The results from the AHP are then implemented considering the city of Munich as a case study. A GIS software (QGIS) was used for the suitability analysis to identify potential locations of a mobility hub. The focus of this research was defined at the macro-level. This means larger areas rather than specific street-level locations.

This study seeks to fill the gap on literature regarding the allocation of mobility hubs, specifically from a sustainable perspective. The proposed method based on an AHP-GIS approach can be straightforwardly reproduced in other local contexts. The method provides a reference list for the selection of the final sustainability criteria, which depends on the specific local context. The results obtained from this method are visually represented through maps where the territory is ranked according to its suitability, and the existing train and subway stations are presented. This representation is aimed to provide the decision-makers more flexibility in terms of the scale and typology of future mobility hubs based on the suitability levels and the coverage of areas well served by railway services.

2. Literature review

2.1. Mobility hubs.

Mobility hubs Mobility hubs can be understood as nodes where various sustainable modes converge to provide seamless and higher connectivity to the users [9]. Commuting modes may include cycling, public transport, shared services (e.g., bicycle, car sharing, e-scooters, etc.), private car, and certainly, walking. Particularly, a fundamental goal of mobility hubs is to support the first and last-mile trips for more convenient travels [14]. Mobility hubs aim to connect workplaces, residential areas, and other points of interest (POIs). POIs cover multiple activities and places that attract people, including services, recreational, and entertainment avenues. According to Aono[9], the catchment area of a mobility hub is everything one can reach within a five-minute walk, cycle, and/or drive.

Based on the previously addressed characteristics, other transport stations concepts can be mistakenly confused as mobility hubs. As Miramontes points out, mobility stations and mobility points, although similar, are limited to the integration of different modes of transport, while mobility hubs have a stronger link to land use and user experience [15]. In addition, the purpose of the latter goes beyond transportation alone. For instance, through placemaking strategies, mobility hubs can enhance the sense of identification and can support the transport-and-land-use link characteristic of these types of stations [9], [14]. Mobility hubs can become both destinations and interchange points by improving the public realm and providing supplementary services and retail [16][9].

2.1.1. Mobility hubs typologies

The availability of specific services and activities may vary according to the type of mobility hub. Even though there is not concrete consensus on the classification levels, different authors have identified categories of mobility hubs based on their location, the context of the place, and their function within the local transport system. An initial example is the four levels pointed out by Bell [17], explained as follows:

- Urban central hub: provides various transport modes to connect at a local and a supra-regional extent. For these urban hubs, pedestrian accessibility, cycling, e-mobility options, and more diverse sharing opportunities (e.g., kiss and ride, bike and ride) are especially relevant. Supplementary services are abundant and diverse.
- Suburban hubs: connects peripheral regions with more dense areas like city centers. Users are typically commuters, therefore, the provision of sufficient parking spaces and, particularly park and ride, play a major role. Provided services are similar to those in the first category.
- Regional central hubs: its principal function is to connect public transport with more rural areas to reduce car usage, accordingly to the general goal of mobility hubs. Similarly, to the previous case, parking facilities are key components, while the provision and variety of services are not the main focus.
- Gateway hubs: are simpler forms of mobility hubs and can be found in both urban and rural contexts; being particularly important for wider users' groups than in the latest case. Mobility services are more focused on active modes and public transport and less on private vehicles and car-sharing.

Monzón et al. [18] identified two ways of categorizing a mobility hub. The first one is a classification based on "functions and logistics" (1) focusing aspects of demand, modes of transport, and provided services and facilities. Regarding the users' demand (1.1), the authors recognized 3 levels: 30 000 passengers per day or less, between 30 000 and 120 000 passengers/day, and more than 120000 passengers/day. Another sub-category is the main transport mode that is offered (1.2); namely: bus, rail, and the cases where there are two or more public transport combinations as main transport modes. Lastly, the provision of services and facilities (1.3) which can also be grouped into 3 groups. The first, and most basic one, corresponds to small kiosks or vending machines, the second includes the provision of retail shops and different eating possibilities, while the last one corresponds to the placement of complementary larger shopping opportunities into the hub (e.g., shopping mall).

The second form of classification relates to the characteristics of the local context (2) where the hub is located. The first related sub-categories match those addressed by Bell, in relation to the specific location and function (2.1). The second sub-category refers to the surrounding activities (2.2) and whether they support or not the operation of the hub. Finally, the third aspect corresponds to the degree of integration within the region's development plan (2.3). This typically implies commercial and residential developments as well as more employment opportunities.

In addition, Aono [9] performed a literature review and summarized the different and most common classifications of mobility hubs. His findings coincide with the formerly explained concepts, however, the assigned name might differ. More precisely, he denoted the first classification as “gateway and anchor hubs” (1). These are hubs with a major part within the transport network, which implies the placement on highly dense areas. The second typology corresponds to the “urban context and the transport function” (2). The former term refers to mobility hubs located at the city center, urban or suburban nodes, developing urban centers, historic town centers, or at other particular destinations. While regarding its function (3) within the network, mobility hubs can be distinguished between those working as an access point, as a means of transfer, or as a destination. Aono [9] also mentions that mobility hubs can also be identified as neighborhood, central, or regional hubs (4).

Table 1. Summary of mobility hubs classification according different sources.

Source	Mobility hubs typologies
[19]	1. Location (including associated mobility options and services)
[18]	1. Function and logistics. 1.1. Users’ demand. 1.2. Main transport modes provided at the hub. 1.3 Complementary services and facilities. 2. Local context. 2.1. Location and function. 2.2. Activities and services. 2.3. Inclusion of the within the local development plans.
[9]	1. Gateway and anchor hubs. 2. Urban context and transport function. 3. Function. 4. Location.

Regardless of the mobility hub, the associated benefits range from the enhancement of more sustainable transport modes leading to a reduction of greenhouse gases (GHG) and pressure of private parking spaces to seamless and flexible interchanges for the users, as well as safety, pleasant and attractive environments [20]–[22]. Nonetheless, the multimodality offered by mobility hubs comes also with certain disadvantages and challenges. For example, adequate visibility from surrounding public areas, wayfinding, and informative elements are all essential to the successful implementation and operation of mobility hubs. Additionally, physical integration of the various modes might be challenging. The placement of the different modes is of particular relevance when it comes to a pleasant user experience and safety. Short distances and segregated roads for each mode are advised to reduce conflicts between different user types [15]. Moreover, mobility hubs require coordinated urban/rural planning to properly integrate transport and land-use planning and design [2].

2.2. Sustainability criteria

Table 2 shows identified criteria in the field of transportation related to social equity. After a significant number of consulted sources, some concepts were unified due to similarities of the concepts. This is the case of the accessibility and connectivity criteria, which include lack of access to public transportation, POIs, employment opportunities, and services.

Table 2. Social equity criteria identified from the literature review.

Category	Criteria	Sources																			
		[1]	[5]	[6]	[7]	[8]	[10]	[12]	[22]	[24]	[25]	[26]	[27]	[28]	[29]	[30]	[31]	[32]	[33]	[34]	[35]
Socio demographic	Low income		✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓		✓
	Elderly population		✓	✓						✓				✓	✓	✓		✓			✓
	Poverty																	✓			
	Migrant population & minority ethnic groups		✓	✓												✓		✓			
	Unemployed population			✓							✓		✓		✓	✓		✓			
	Low education level															✓		✓			
	Gender															✓		✓			
Social conditions and characteristics	Public/affordable housing						✓					✓									
	Population with disabilities			✓						✓		✓						✓			
	Population not able to drive a car									✓		✓									
	Low public transport affordability								✓	✓		✓								✓	
	Housing conditions (quality & tenure security)			✓														✓			
	Health and well-being status																	✓			
	Single parents' households			✓										✓	✓	✓		✓			
	Population dependent on public transport		✓														✓				
Spatial location related	Low accessibility	✓		✓	✓				✓		✓	✓				✓	✓	✓	✓		✓
	Low economic participation											✓	✓								
	Low political participation											✓	✓								
	Rural communities	✓																✓			
Transport related	High traffic fatalities rate								✓			✓									
	Low car ownership (zero-car households)	✓	✓			✓	✓		✓			✓			✓	✓			✓	✓	✓

Similarly, Table 3 presents aspects related to environmental sustainability most frequently mentioned in the consulted literature. In this case, the criterion of "air pollution" includes carbon dioxide and other emissions associated with climate change and its impact on human health. As well as other more general references, like emission savings as an indicator associated with sustainable mobility [36]. Correspondently, Table 4 depicts the criteria concerning the economic spectrum, specifically those related to demand efficiency, as explained in the former section. This means the identified criteria are typically associated with the potential generation of trips. In this case, the criterion "land-use and POIs" refers mainly to residential, commercial areas and, a variety of services, facilities, or attractions.

Table 3. Environmental criteria identified from the literature review.

Criteria	Sources									
	[24]	[7]	[23]	[33]	[37]	[36]	[38]	[39]	[11]	[40]
Air pollution	✓	✓	✓	✓	✓	✓	✓	✓		✓
Noise	✓	✓	✓							✓
Traffic volume/flow and congestion				✓					✓	
Vehicle traveled distance					✓	✓				
Mode share						✓				

Table 4. Demand efficiency criteria identified from the literature review.

Criteria	Sources											
	[1]	[9]	[10]	[11]	[14]	[22]	[36]	[24]	[41]	[42]	[43]	[44]
Land-use & POIs	✓		✓	✓	✓		✓		✓	✓	✓	
Employment density	✓		✓	✓			✓			✓		
Population density	✓	✓	✓	✓		✓	✓			✓	✓	✓
Public transport users/day						✓					✓	
Location of sharing services			✓									
General travel costs				✓								
Unreliable travel times				✓								
Mobility rate								✓				
Mode share								✓			✓	
Traffic volume								✓				

2.3. Analytical Hierarchy Process

The analytical hierarchy process (AHP) is a method commonly used for multicriteria analysis, created by T.L. Saaty in the 1970s, where subjective judgments are translated into a hierarchical arrangement [10]. Although the AHP has multiple applications, it is often used to create rankings of different alternatives to meet a specific objective [10], [45], [46]. According to the consulted literature, this method has been widely applied on suitability analyses to identify optimal locations for a wide range of projects with varying topics (e.g., [47]–[49]). More importantly, AHP has been broadly applied in the transport planning field [10], [40]. One example, is the application of the method to include equity and resiliency aspects in municipal processes to identify the location of mobility hubs. AHP has also been employed to recognize optimal transit alignments [50].

The basis of the method is to set a hierarchy with the primary goal on top of it and related factors on the subsequent levels. On these levels, there are different "branches" or categories, which can also hold sub-categories; see Fig. 1, [46]. The factors on each level -and under the same category- are subject to pairwise comparisons with the purpose of identifying which element is more important than the other (e.g., sub-criterion 2.1 against sub-criterion 2.2 and 2.3, and this two against each other as well). From the comparisons and through different algebraic and mathematical operations, the weights of each criterion can be determined. The steps to determine the weights is covered in the following section. Hence, with the weights there is a prioritization of the criteria or alternative scenarios [46], [51]. It is suitable for participatory processes where decision-makers and experts can be involved. Furthermore, the method considers the consistency of the answers, allowing to achieve accurate results [52].

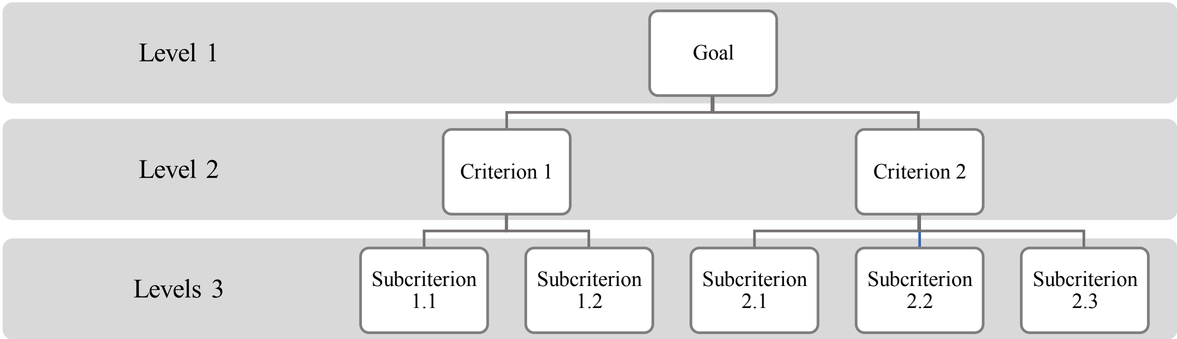

Fig 1. Analytical hierarchy process organization.

3. Methodology

Initially, general criteria for each sustainability category were determined after an extensive review of the literature from the transportation and mobility field, and not only related to mobility hubs due to the limited sources on this field. Moreover, considering that mobility hubs integrate different transport modes. The list of criteria was then narrowed down based on the spatial data available on open sources for the area under study. In this case, the method was applied to the city of Munich. The final criteria were then ranked by a group of academic researchers working on mobility hubs at various European universities and practitioners from different regions of Germany also working on the field. With the individual rankings, final weights were determined for each criterion, representing how relevant each one is for the identification of potential locations for a mobility hub. The spatial analysis was done using a GIS software, QGIS [53], to visualize the optimal areas for development. Fig. 2 summarizes the steps of this methodology. In the following sections, each step will be discussed in more detail.

3.1. Criteria selection

The most relevant criteria are summarized Table 5, those correspond to those most frequently cited in the consulted literature (Table 2, Table 3, and Table 4). The factors related to public transport (i.e., public transport accessibility, unreliable travel times, users/day) were not included. The purpose is to illustrate the existing train and metro stations on the suitability map. In this way, developers can decide whether to locate the mobility hub using existing infrastructure or create it in an area that might be underserved.

Table 5. Summary table of the sustainability criteria most frequently mentioned in the consulted literature.

Social Equity	Environment	Demand efficiency
Low income	High concentration of air pollutants and GHG	High points of interest density
Low accessibility and connectivity	High traffic noise levels	High population density
Low car ownership	Traffic congestion	Employment opportunities
Elderly population		
Minority ethnic groups and population with migration background		
High unemployment		
Single parents' households		

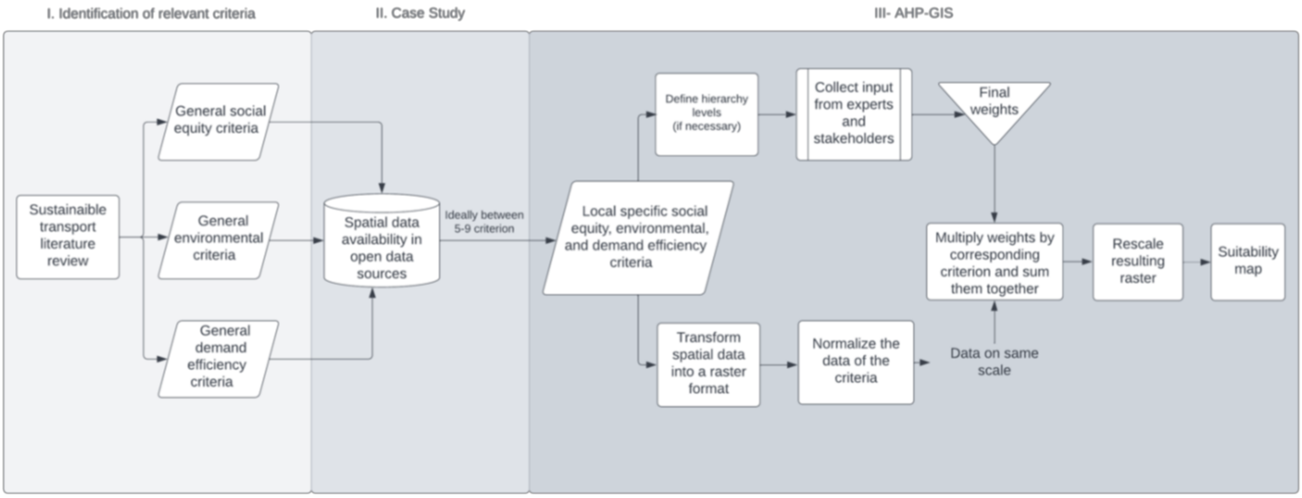

Fig. 2. Methodological workflow for the land suitability analysis to allocate mobility hubs.

3.2. Analytical Hierarchy Process – GIS

The weights for each criterion are determined through the AHP. The AHP is applied to define the weights that represent the importance of each criterion. As explained in the previous section, AHP is a systematic and hierarchical arrangement of a solution to a problem where a specific goal is placed at the top and other related factors at the subsequent levels (see Fig. 1). The number of criteria on each level is recommended to be between 5 and 9, given that the higher the higher the number of criteria, the greater the chances of having more inconsistent results. The chosen criteria are subject to pairwise comparison by one or more participants. When the participants are experts on the specific topic, the number of participants can be limited to less than 15. However, not when dealing with the general public or users [54].

AHP uses a square, reciprocal, and consistent matrix to organize the pairwise comparisons. Each criterion against all the others, a value from 1 to 9 is selected based on how important it is for the allocation of mobility hubs (see Table 6 for the prioritization scale). Given the reciprocity characteristic of the matrix, $\alpha_{ij} = 1/\alpha_{ji}$, where i are elements in a row I, j to those from column J, and α_{ij} is a value from Table 6, as explained before. Next, the normalized right eigenvector and the eigenvalue and of the matrix are determined. The eigenvector represents the prioritization values or weights. Brunner [50] represents the basic concept of the AHP with Equation 1.

$$\begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} = \lambda \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} \quad \text{or } \mathbf{A}\,\mathbf{x} = \lambda\mathbf{x} \qquad (1)$$

where:

$n =$ number of criteria;

vector x $=$ the eigenvector of the matrix **A** with eigenvalue $\boldsymbol{\lambda}$;

α_{ij} = relative value (scoring factor) of criterion i to criterion j, and

vector $\boldsymbol{w} = (w_1, \cdots, w_n)$ = the priority values (also refer to as *weights*) for criterion 1 to n.

Table 6. AHP scoring factors for pairwise comparisons. Adapted from [46], [55].

Importance	Definition	Explanation
1	Equal importance	Both criteria equally contribute to the objective
3	Moderate importance	Base criterion is moderately more important than the other criterion
5	Strong Importance	Base criterion is essentially more important than the other criterion
7	Very strong importance	Base criterion is relatively more important than the other criterion
9	Extreme importance	Base criterion is overwhelmingly more important than the other criterion
Intermediate values: 2,4,6,8 can be used to express intermediate values		

To validate the accuracy of the results, the AHP demands to determine the consistency of the results. For this, the consistency index (CI) and consistency ratio (CR) are required. Equation 2 and Equation 3, describe how to calculate those values, respectively. Typically, the CR should be less than 0.1 (10%) [51], [52], [55]. These values were calculated for individual judgments from the experts.

$$CI = \frac{\lambda_{max} - n}{n-1} \qquad (2)$$

$$CR = \frac{CI}{RI} \qquad (3)$$

where:

λ_{max} is the maximum eigenvalue, which can be obtained by multiplying each weight by the sum of the column from the initial comparison matrix; and

RI is the random consistency index, which is defined based on the number of criteria. The corresponding values are presented in Table 7.

Table 7. AHP scoring factors for pairwise comparisons

Number of criteria	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Before the final weights can be combined with the spatial data, the layers containing this spatial data need to be prepared to have the same format and numeral scale. First, all the files need to be transformed into a raster format. Besides the spatial data for the criteria, a shape layer representing the study area is also indispensable for the spatial representation. This layer should be use to define the boundaries of the newly created raster layers.

As mentioned, in order to bring together all the raster layers to obtain the suitability map, all the data must be in the same scale. Therefore, it needs to be normalized and, for this, different methods are possible. In this case the data was normalized to values ranging from 0 to 1 using a continuous method (Equation 4.1). In this approach, 1 represents the areas that are more relevant for each criterion, and 0 the least relevant. For instance, for the population density, the areas with the highest density are ranked as 1 and least dense areas with 0. However, when the areas with lower values are the most important, the equation was slightly modified as explain in Equation 4.2. During the application of the method, this was specifically used to normalized the low car ownership values.

$$\frac{\chi - min}{max - min} \tag{4.1}$$

$$1 - \frac{\chi - min}{max - min} \tag{4.2}$$

Subsequently, the raster layers are aggregated using the weights established by the experts. This can be achieved using the raster calculator tool available in a GIS software and by adding the products of the multiplication of each weight and the raster representing each criterion. The resultant raster can be normalized using Equation 4.1 to have a scale from 0 to 1, similarly as done before. The results were classified into five categories to create a suitability ranking considering five classifications based on the following ranges: 1) least suitable: 0 - 0.2, 2) moderately suitable: 0.2 - 0.4, 3) suitable; 0.4 - 0.6, 4) very suitable: 0.6 - 0.8, 4) and most suitable: 0.8 - 1.

4. Application in the city of Munich

4.1. Local context

Munich, one of Germany's major cities and capital of the state of Bavaria, holds a population of 1,563,723 [56]. In 2017, Munich's modal share was 24% private motorized transport drivers, 24% public transport users, 24% pedestrians, 18% cyclists, and 10% private motorized transport passengers [57]. By 2019, the number of registered private passenger cars per 1000 inhabitants was 337 [58].

In recent years, multimodal opportunities and sharing services have expanded. The different types of alternative mobility options currently available in Munich include bike and car-sharing (both station-based and free-floating services), cargo bikes, and e-scooters [15], [59]. The Modellstadt-2030, a strategy created in 2017, seeks to improve the quality of mobility trends in Munich. The strategy is an example of how shared services, electric vehicles, and connectivity are part of the current agenda of planners and developers to improve the transportation sector [59]. Furthermore, the implementation of mobility hubs has been a leading focus for the planning authorities in Munich [36]. Intermodal arrangements, smaller than the average stations, can be found in the city since the beginning of the past decade [15]. However, the first official mobility hub, Münchner Freiheit, was introduced as a pilot project in 2014 and is still in operation at the moment. Multiple mobility options can be found at this hub, including bike-sharing, free-floating car-sharing sites, a charging station, and a bike repair facility [15], [59]. At the station, public transport options are also available (i.e., metro, trans, and bus).

Another example of a mobility hub in Munich is Domagkpark, initially created in 2016 for private users from a residential development. Nevertheless, Domagkpark implemented another mobility spot in the same area publicly available. At the hubs, car-sharing (including electric vehicles) options are available, as well as e-cargo bikes, e-scooters, and, e-bikes [60]. Other projects, such as City2Share and Smarter-Together, have developed similar mobility hubs in the region. Between the two projects, twelve more small stations were introduced. Complementary services, such as storage facilities for deliveries, have been also introduced [59]. Fig. 3 shows the location of the formerly mentioned hubs. Public and private stakeholders, together with academia, have been involved in the planning, implementation, and operation of these stations, proving the pressing matter of providing more sustainable transport options through mobility hubs. More recently, local authorities aim to expand the number of mobility hubs by around 200 stations distributed through the region by 2026 [61].

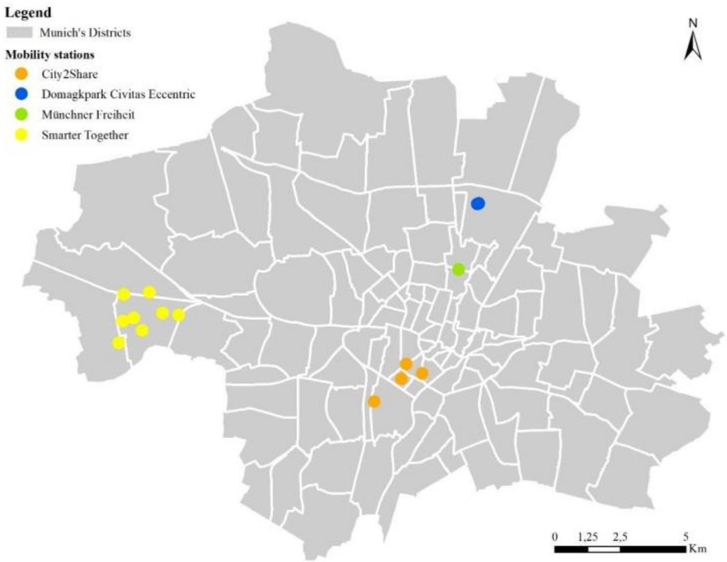

Fig. 3. Location of existing mobility hubs in the city of Munich. Source: [59]

4.2. Local context

A wide range of open data sources were consulted to find appropriate spatial data. The final list of criteria was selected by prioritizing those most cited in the literature and, at the same time, taking into account the available spatial data (Table 4). In addition, one important consideration was to keep the final number of criteria between 5 and 9. This range is defined by the typical number of criteria used in the consulted studies [40], [48]–[50], [62]. Moreover, Saaty [51] indicates that a smaller number of criteria or elements may result in fewer inconsistencies. Table 8 shows the final criteria to be used for the AHP and the corresponding source.

Table 8. List of selected sustainability criteria and associated sources for spatial data.

Sustainability category	Criteria	Description	Range of values	Source	Open data format
Social equity	Car ownership	Number of privately registered passenger cars per 1000 inhabitants per neighborhood	181.8 – 696.8	[58]	xls
	Unemployment	Percentage of unemployed population per neighborhood (%)	0.1 – 6.5		
	Elderly population	Percentage of elderly citizens from the total residents per neighborhood (%)	5.0 – 27.5		
Environment	Nitrogen dioxide (NO_2) concentration	Concentration on parts per billion (ppb) per district	10 – 52	[63]	Instant online data

Sustainability category	Criteria	Description	Range of values	Source	Open data format
Demand efficiency	Traffic noise	Noise index LDEN in main streets on dB(A)	55 – >75	[64]	wms
	Points of interest	Density of POIs per km	0 –691.96	[65]	shp
	Population density	Population density per km	0 –1,432.32	[66]	shp

The concentration of nitrogen dioxide was chosen as a representant pollutant for the "high concentration of air pollutants and greenhouse gases" given that it is one of the main transport related emissions. The spatial information of the points of interested was filtered to include only entertainment and recreation avenues (art centers, parks, museums, etc.), services (e.g., banks, hospitals, government offices, education, restaurants, etc.), and, retails.

As previously addressed, the spatial data had to be prepared before its integration with the AHP results. All information was transformed into raster layers considering a spatial resolution of 10 m. In some cases, it was a straightforward step that required only the conversion from vector layers into raster layers, as it for all the spatial data of social equity and NO_2 concentration. The noise data was exported from the "wms" format to a raster file. While for the demand efficiency, the spatial data were available as point vector layers. The points were used to obtain the heatmaps, in raster format, considering an area of 1 km radius. This distance was selected as it is considered an acceptable distance between mobility hubs and high-quality public transport (e.g., train, tram or subway) [67]. Furthermore, distances shorter than 1 km can be considered short trips [8], which are more likely to be done using an alternative transport mode. Finally, the steps described in the methodology, corresponding to the normalization and integration of the weights with their respective raster layers, were followed to obtain the suitability maps.

4.3. Analytical hierarchy process

The criteria used for this process has been specified in Table 8. For this study, the hierarchy is organized in only two levels; the goal on the first level and the different sustainability criteria in the following level. The goal is to identify potential locations for mobility hubs and the relevant criteria (Table 8) to reach the goal are all placed the level below. The decision to place all criteria at a single level, i.e., without including a first level where the sustainability pillars could be prioritized or a sub-level to categorize different POIs, was made merely to simplify the pairwise comparison process for the experts.

A published Excel tool created by Goepel [55] was used to collect the experts' judgments. The tool has already been used in previous studies [40] and was a convenient option considering the need of consulting several experts and time limitations. The spreadsheet tool is already coded to calculate all required parameters, including consistency values for both individual judgements (matrices) and aggregated arrays.

In AHP there are two main approaches for aggregating methods: the aggregation of individual judgments (AIJ) and the aggregation of individual priorities (AIP). AIJ is preferred when decision makers or stakeholders are thought to work together and make a decision [68], [69]. To calculate the consolidated matrix, Goepel's tool uses the AIJ based on the weighted geometric mean [55], [70]. The final aggregated priorities, or weights, are determined through the eigenvector method explained in section 2.2. However, the tool also provides the results of the individual weights of each participant, which are calculated using the row geometric mean method (RGMM). All accepted methods to obtain the final weights [71]. Furthermore, the tool specifies the CR values for both individual and aggregated results. At this point, it should be mentioned that for the consistency ratio calculation, Goepel [55] uses a modified linear method (Equation 5) instead of the original Equations 2 and 3.

$$CR = \frac{\lambda_{max} - n}{2.7699 \cdot n - 4.3513 - n} \quad (5)$$

The Excel tool was slightly modified to include a section for consulting experts for their more detailed opinion on the criteria taken into account. The experts contacted were carefully selected based on their experience, both in terms of their direct experience with mobility hubs and the local context in which they have worked. This decision was made to have representation from different regions and not only from Munich to have a general understanding of what experts might consider important. In total 29 experts, including academic researchers and practitioners, with experience in mobility hubs, were contacted and provided with an instructional manual to fill out the AHP tool. The participants were given the opportunity to fill out the spreadsheet on their own or to schedule an online meeting to fill out the form or clear out possible doubts. Finally, eleven answers were gathered, including those from the two requested meetings. Table 9, presented below, details the local context of the experts who contributed to this study. The individual prioritizations were combined for each of the two groups of experts to analyze possible differences and then all the answers together to obtain the final weights.

Table 9. Local context of the expert contributing to this study.

Group of experts	Number of participants	Current local context	Institution / Company
Researchers from the academia	2	Belgium, Brussels.	Vrije Universiteit Brussel.
	1	Münster, Germany.	University of Münster.
	2	Wien, Austria.	University of Natural Resources and Life Sciences. Technical University of Wien.
	1	Munich, Germany.	Technical University of Munich.
Practitioners	1	Fürstenfeldbruck, Germany.	City of Fürstenfeldbruck.
	1	Hamburg, Germany.	Hamburger Hochbahn AG.
	1	Offenburg, Germany.	City of Offenburg.
	2	Munich, Germany.	City of Munich.

4.4. Results

Fig. 4, Fig. 5, and Fig. 6 correspond to visual representation of the criterion considered to determine the suitable areas for new mobility hubs. The darker shaded areas in the maps represent those of greater importance for each thematic focus. Table 10 presents the final weights obtained by means of the criteria prioritization done by academic researchers and practitioners. All the values are presented with their respective errors and associated consistency ratio.

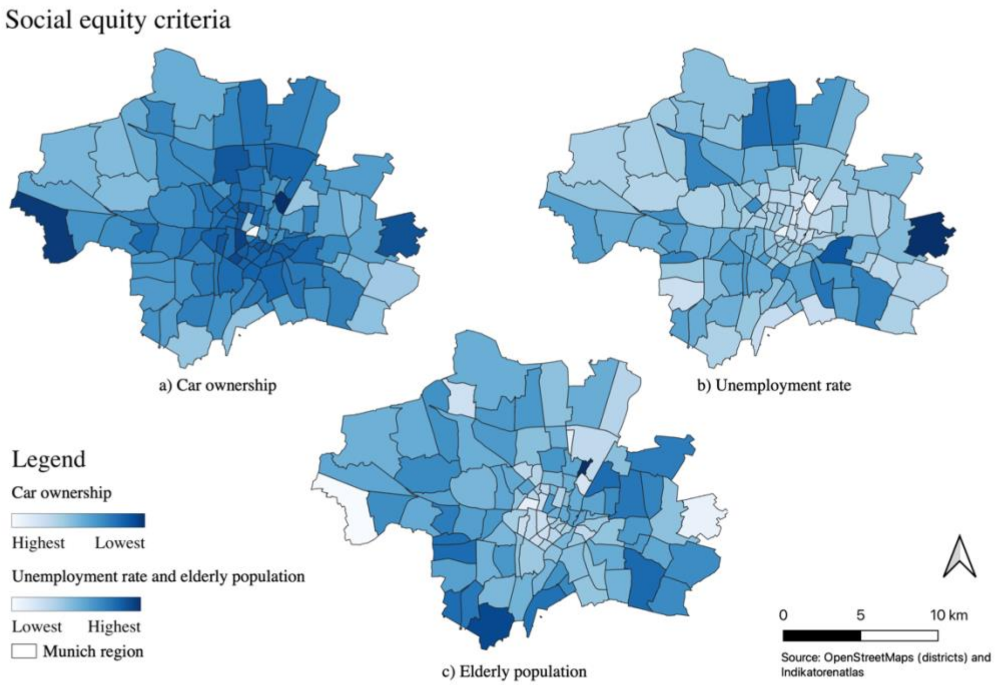

Fig. 4. Preferred areas for the social equity criteria. (a) Car ownership; (b) unemployment rate; (c) elderly population density.

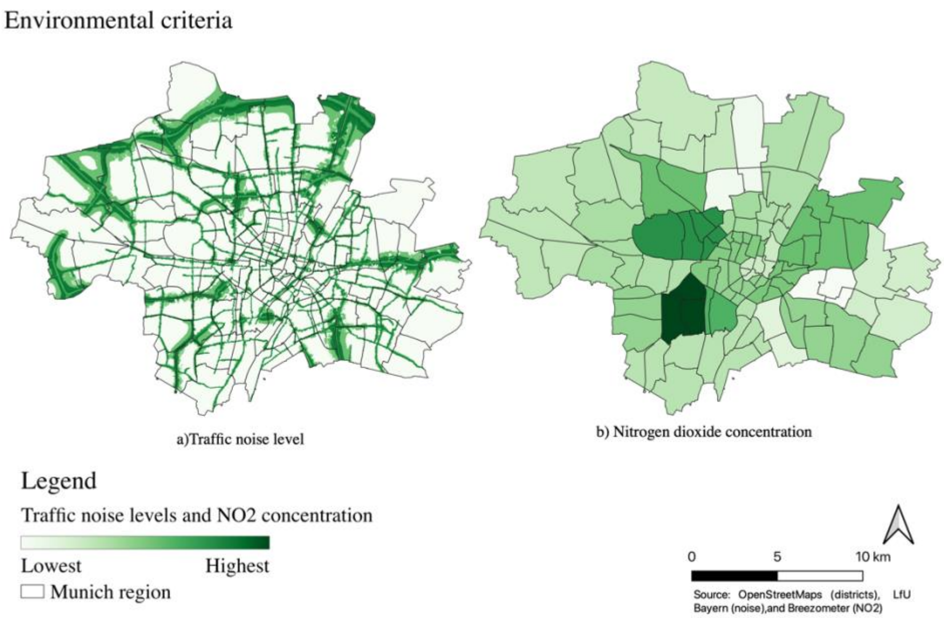

Fig. 5. Preferred areas for the environmental criteria. (a) Nitrogen dioxide concentration; (b) Traffic noise in main streets.

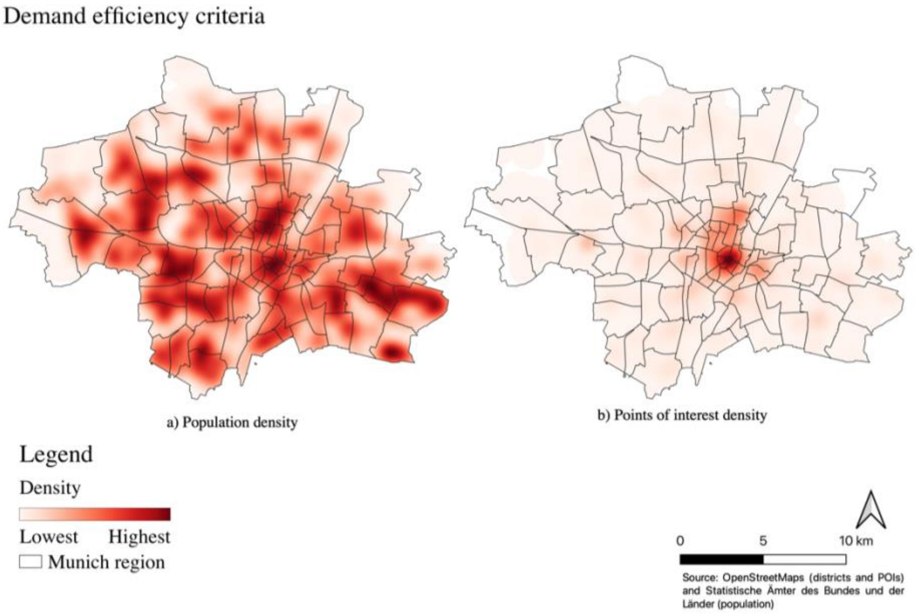

Fig. 6. Preferred areas for the demand efficiency criteria. (a) Points of interest; (b) Population density.

Table 10. AHP scoring factors for pairwise comparisons.

Sustainability category	Sustainability criteria	Weights (%) Academic researchers	Practitioners	Combined
Social equity	Low car ownership	12.36	13.26	12.94
	Unemployment rate	7.87	7.98	8.07
	Elderly population	6.77	7.73	7.32
Environment	Nitrogen dioxide (NO^2)	10.92	4.22	7.10
	Traffic noise	8.19	4.12	6.16
Demand efficiency	Points of interest	29.51	30.32	30.28
	Population density	24.39	32.36	28.13
Consistency ratio [%]		**1.7%**	**1.0%**	**0.9%**

From the previous table, it is evident, that the demand efficiency criteria are certainly the most important when deciding where to locate new mobility hubs. From the comparative graph presented in Fig. 7, it can also be noticed that the environmental aspects are less significant for the practitioners than for the researchers. Considering the social equity criteria, the weights for low car ownership do not show a significant difference. The criterion takes the third place of high priority in all cases. On the one hand, for both researches and practitioners, the unemployment rate is slightly more significant for the allocation of mobility hubs than the high density of the elderly citizens (see Table 10 for more details about the weights). On the other hand, the unemployment rate and the density of the elderly population are the least relevant factors for experts from academia, while practitioners placed them above the environmental criteria.

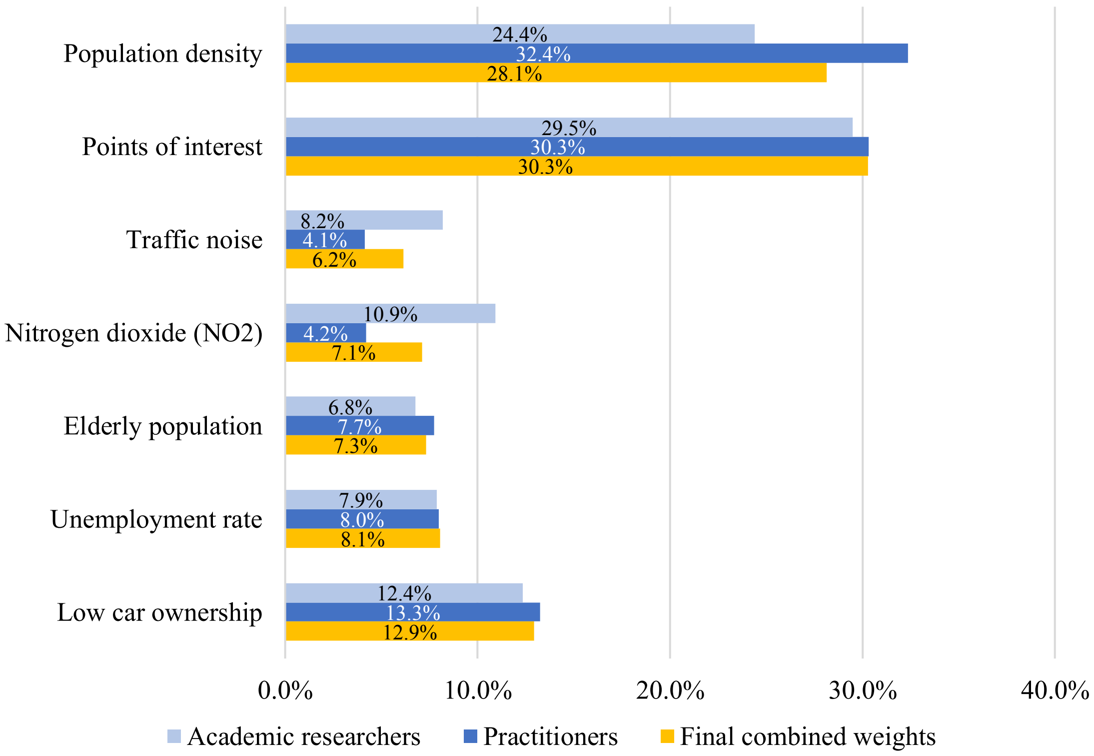

Fig 7. Comparison between the weights from researchers, practitioners, and final combined weights.

The preceding results are also supported with the findings presented in Fig. 8. This graph contains the answers to the question if the particular criterion is relevant or not for the allocation of mobility hubs and why. Since not all responses were completely straightforward by indicating yes or no, the answers were classified according to the explanatory commentary of the experts.

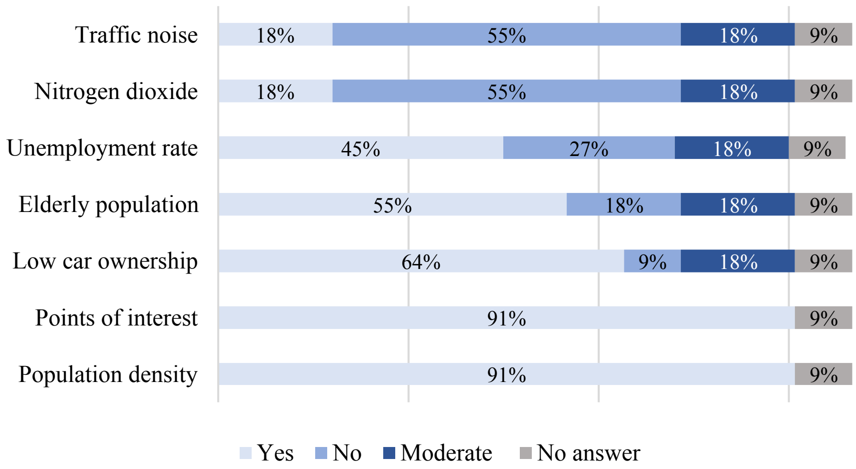

Fig. 8. Expert opinions on the importance of the criteria for the location of mobility hubs.

As formerly explained, the weights were used integrated into the GIS software to visualize the suitable zones. Fig. 9 and Fig.10 illustrate the city of Munich ranked according to its suitability for the development of new mobility hubs. In all representations, the color scale goes from red to green, corresponding to the least to most suitable areas. The maps shows that the "most suitable" areas, colored in darker green, are found in the city center. Areas classified as "very suitable" are also located in central districts, especially on the north side, while "suitable areas" are more scattered throughout the west, south, and east side. When comparing the suitability maps of researchers and practitioners (Fig. 9), in general terms, the results do not differ significantly from each other. Nevertheless, it is possible to identify a difference in the extent of the more peripheral "suitable areas" from the researchers and the practitioners' results, the latter being vaster. From the final combined suitability map (Fig. 10), it can be noticed that "suitable areas" can be found throughout all Munich city, more predominantly on the southern regions and that the north side has fewer and smaller areas under this category.

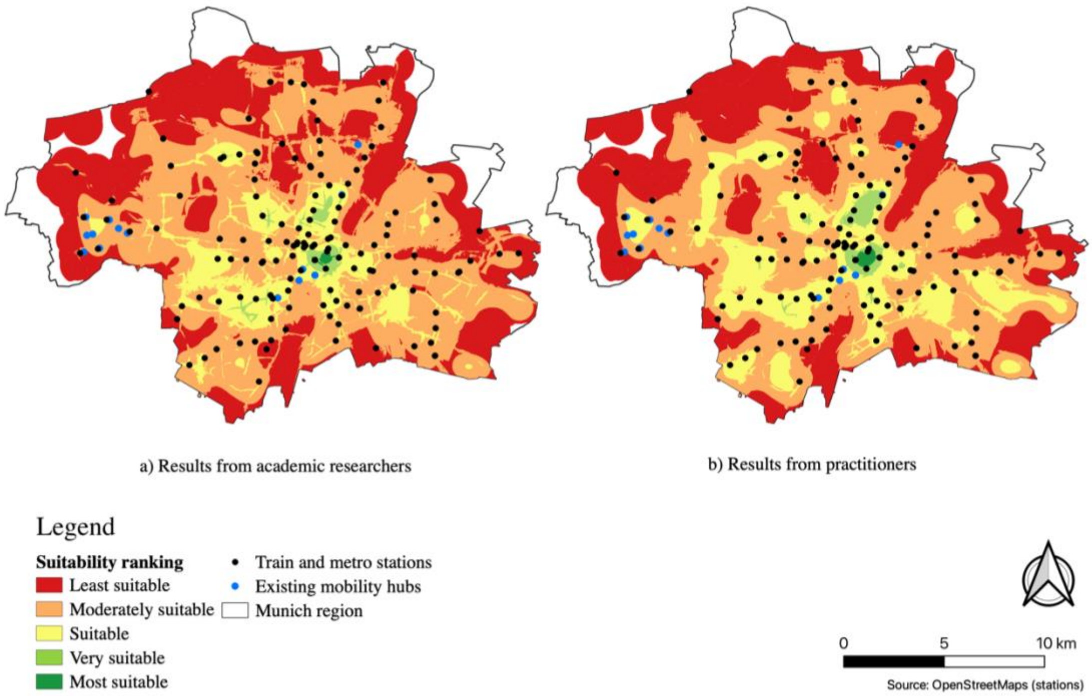

Fig. 9. (a) Suitability map based on the researchers' answers; (b) Suitability map based on practitioners' answers.

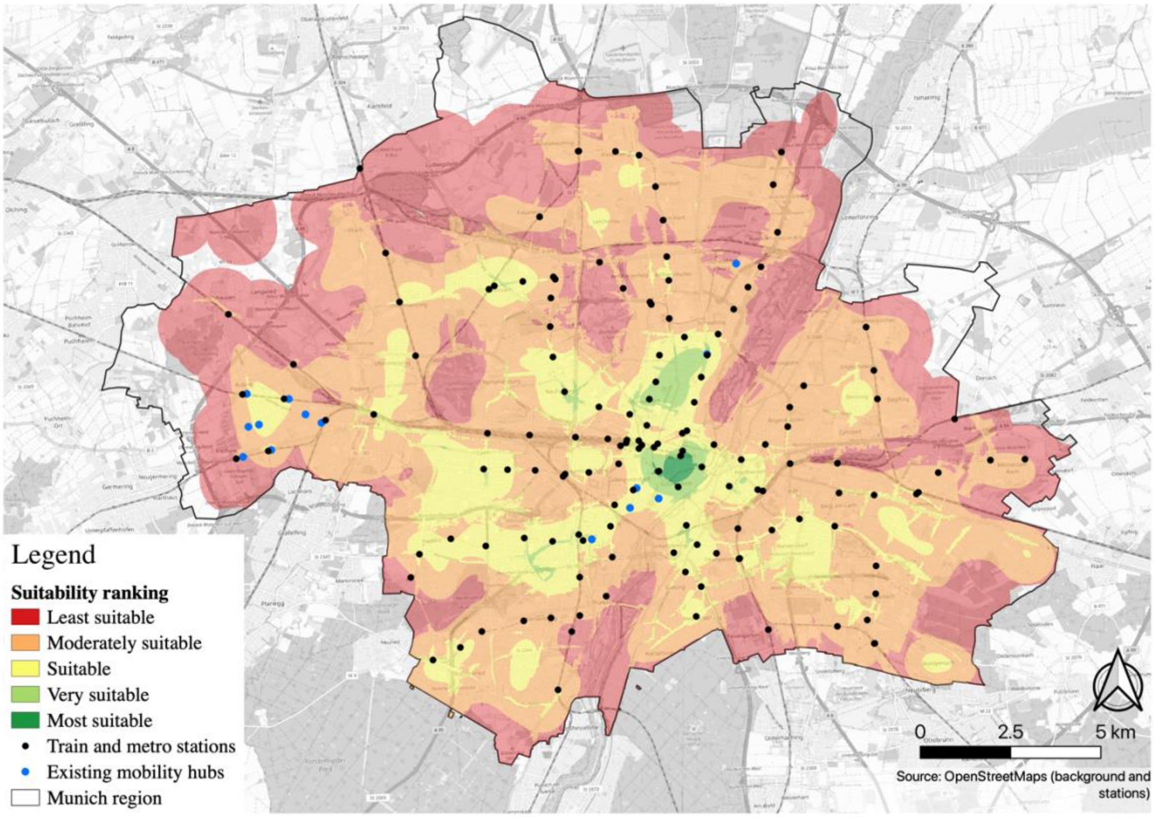

Fig. 10. Suitability map based on the final combined answers.

5. Discussion

5.1. AHP-GIS method to identify potential locations

Several studies confirm that the analytical hierarchy process has been proven to be an effective approach for decision-making and transport planning [10], [40], [50]. In this study, AHP allowed to combine the identified social equity and environmental criteria, not regularly considered in transport planning, together with economic factors related to the high demand for transport services in a comprehensive way. AHP is not only a method for multi-criteria analysis but also is suitable for the inclusion of multiple stakeholders.

The AHP Excel tool created by Goepel [55] was used with the intention of easing the process of collecting the experts inputs and verify how convenient the tool could be for future applications of the proposed methodology. Most participants filled out the questionnaire by their own, without reporting any difficulty or without the need of any support. This supports that conducting the AHP using the tool is a convenient and practical approach and could simplify the collection of the experts' inputs in further applications. Therefore, it represents an advantage for the participants and for those conducting the study. Typically, the aggregation process would have implied more complex and time-consuming calculations. However, in besides being able to obtain the results (weights) directly, the tool also has the advantage of allowing access to the individual matrices and results of intermediate calculations to determine the consolidated weights.

As referenced in previous sections, the AHP considers the CR to verify the accuracy of the results. On the one hand, using the CR is an advantage as it ensures the calculated weights are consistent and reliable. On the other hand, it can be tedious when working with a large number criteria and may require the experts to adjust their judgements to improve the CR, especially when working with Goelpel's tool. In this regard, once the participants have completed all the pairwise comparisons, Goepel's tool has the advantage of indicating the three most inconsistent results to be modified if possible; consequently, improving the CR. The CRs calculated for all cases (Table 10), are below 10%, the predefined threshold [51], [52], [55], confirming the certainty of the final weights.

To the author's knowledge, this is one of the few studies that has focused on identifying suitable areas for the location of mobility hubs, more specifically, that have used the AHP method to integrate the three pillars of sustainability in the considered criteria. One if this few studies focused on incorporating equity and resiliency criteria for mobility hubs in the municipal context and the subjective designation of weights relying on literature and discussions with experts and researchers [10]. However, the study has a different approach as it defined indexes to include social related variables and created different scenarios to address various social and resilience concerns. Moreover, it solely focused on the aforementioned aspects, while the present study is based on a comprehensive approach to sustainability. Referring to another study published by Brunner et al., the use of the AHP method can be supported [50]. It is used analogously and includes similar categories of criteria for determining the location of transit alignments.

5.2. Suitability results and criteria selection

This study presents a list of criteria to be considered as a reference when searching for mobility hubs' locations from an integrated and sustainable perspective. Furthermore, with this preliminary list as a baseline, the proposed method can be replicated to obtain analogous results in another location context, from the selection of the available spatial data to the visualization of the suitable areas. Nonetheless, finding the spatial data might represent a barrier on the application of the method, especially when considering only open data sources. The spatial data limitation is also acknowledged in similar studies [10], [11]. If the spatial data is very limited, in some cases it might be necessary to use proxy values when the data for the specific factors is not available; however, that was not needed for this study. This limitation is addressed in more detailed the following section.

By analyzing the weights from the researchers and the practitioners, it is noticeable that the prioritization of the criteria does not significantly differ between the two groups of experts. The most significant variations are with respect to the environmental factors and the population density. In the first case, the weights from the academic researchers are higher for both NO_2 and traffic noise, by almost 7% and 4%, respectively. While the combined weight of the practitioners for the population density is close to 8%. Regarding the suitability maps (Fig. 9), beyond the extension of the areas located in the southern and eastern sectors of Munich classified as "suitable", there are no significant changes on the distribution of the ranked areas. While a certain level of congruency between the groups of experts is a promising outcome, it might also imply the need to involve other associated stakeholders in future studies (e.g., shared mobility and public transport providers, planners, potential users).

As expected from the weights, the "most suitable" areas for the allocation of mobility hubs shown in the maps (Fig. 9) are located mainly in the more central regions of Munich. It is possible to notice that these areas have a very high population and density of POIs (Fig .6a and Fig. 6b). Given that these were the criteria with the highest weights assigned by the experts, it was expected to have high suitability levels in the city center. Here, there is more land-use diversity, i.e., more residential units, commercial, entertainment opportunities, working spaces, education, etc. The high prioritization of these criteria comes as no surprise. Based on the literature review, it has already been confirmed that economic and profitability aspects have been the main driver in transportation planning. Furthermore, Table 4 shows that both (POIs and population density) were found as the most frequently mentioned in the literature for the demand efficiency factors.

Moreover, central districts are also characterized by a lower car ownership, with two clear exceptions of the more central districts (see Fig. 4a). This criterion was the third factor with the highest consolidated, which also influences the concentration of the "very and most suitable" areas in the city center. Even though this factor was included as part of the social equity criteria, it also has some influence on the demand efficiency, as pointed out by various experts. They commented that where car ownership is lower, people might be already used to public transport and other alternative modes; as it was mentioned by one of the experts during an online meeting However, it is also necessary to take into account the most car-dependent areas in order to lower it, as it is also part of the mobility hubs' goals. Therefore, low car ownership stands as a relevant factor from both social equity and demand efficiency perspectives.

Nonetheless, the remaining social equity factors were assigned lower weights, although varying from expert to expert. Based on the assigned priorities and the additional comments from the experts regarding the importance of each factor, reaching the most vulnerable people was not as important as achieving a high transport demand. For example, some experts mentioned that the elderly population may already have established car use habits that are difficult to change. However, it was also explained during one of the two online meetings that there are external factors, such as the COVID pandemic, that forced many people, including the elderly, to use public transport or other alternative means for various reasons, including unemployment or limited economic resources.

It is important to recognize that travel behavior depends socio-economic characteristics, like age, employment, and income [9]. Even though the unemployment rate and elderly population were not assigned high weights, including such criteria into the planning process improve the inclusion of vulnerable populations in the planning processes and allocation of resources. Furthermore, it is crucial to understand that, commonly, car is the most used transport mode, granting the owners higher levels of accessibility. Consequently, the population with more restricted incomes, that might be related to an unemployment condition, suffer from more accessibility and connectivity limitations [34], [38]. There relies the importance of considering these aspects when placing new mobility hubs.

Although with fluctuating values between the different experts, the environmental criteria were, in general, given the lowest priority, as previously mentioned. According to some of the expert's inputs, it is mainly because a single mobility hub would not be able to reduce high levels of air pollution or noise. It was also addressed that these are not aspects that users typically consider when using the services offered in a mobility hub. Yet, a recent study conducted a survey of potential users of mobility hubs in the city of Munich, revealing that among the most important expectations for them are the reduction of car traffic, transport-related emissions and road traffic noise [72]. Thus, while is true that the selected environmental criteria do not influence whether or not people use mobility hubs, as some of the experts argued, those aspects should be considered when allocating new hubs, following the expectation of potential users in terms of improvements on the environmental quality.

Ultimately, by comparing the resulting suitability map (Fig. 9) and the location of the existing mobility hubs (Fig. 3) it is possible to notice certain congruency. It can be seen how the vast majority of the current hubs align mainly with areas classified as "suitable" or "very suitable" as shown in Fig. 9. Existing mobility hubs can even be found in regions ranked as "moderately suitable", specifically, some of the hubs belonging to the Domagkpar*k* station and the Smarter-Together project (see Fig. 3). The first of these projects is located in the northern region. More concretely, it is placed on a mainly residential area. In fact, the hub was implemented to reduce car dependence and the high demand for parking spaces in the area. This goal was proven to be reached through an evaluation study [60]. Moreover, on this northern side, close to Domagkpark, one important industrial park is located (Euro-Industriepark). Considering this, more mobility hubs could be allocated to those "moderately suitable" areas, which are even covered by three subway lines (U3, U6, and U2), potential benefit not only the residents of the areas but also the commuters working in the industries. In the second case, the *Smarter Together* hubs are also located mainly in residential areas. Furthermore, the various hubs were implemented to increase the attractiveness of the area, as Silva summarized [59]. As in the previous case, major business parks operate in the area (i.e., Triebwerk and Sirius Business Park München- Neuaubing). This can be related to the location of multiple hubs from the Smarter-Together project. In this western region of Munich,

Fig. 10 shows that even "suitable" areas are comprised. The existing hubs in Munich city cover different typologies and functions (i.e., suburban, urban, gateway). Bearing in mind that these stations are under operation at the moment, it could be inferred that the results of this are accurate and reliable.

By showing the ranked areas, the final map of this study is thought to provide flexibility to the decision-makers. More concretely, decision-makers could decide the scale or typology of the mobility hub based on the displayed suitability levels. The resultant map can also be used to plan for mobility hubs' networks through the region that would combine hubs of diverse scales and functions. Experts on the field recognized that highly dense networks are essential to meet the users' expectation in regard to the benefits of mobility hubs [72]. Another relevant remark from the final suitability map is that even the areas classified as "moderately suitable" are covered by the train and/or metro service. The existing infrastructure in those stations can determine where the new mobility hub is implemented. It should be borne in mind that mobility hubs should serve areas of varying density and not only the most populated regions, as the equity objectives dictate [9].

5.3. Limitations of the application in Munich

In this study, only open data sources were consulted which, given the limited resources of this type that are available in Munich, limited the selected to be considered for the AHP. For instance, data about income, social status, and environmental data related to transport are not easily available. Nonetheless, specifically regarding the social equity criteria, it is possible to find a close relationship between the unemployment rate, low car ownership criteria, and low income -the most frequently mentioned aspect in the literature. It can be inferred that the three criteria are closely related. Population with low income are most likely not able to purchase or maintain a car if they have it. While an unemployed person, in most cases, has no income for the time this situation prevails. Additionally, the selected criteria were both represented in the available spatial data and cited in multiple consulted sources. Still, future applications should prioritize low-income data, if available.

Regarding NO2 concentration, the data used was taken from a website that provides temporal air pollutant concentration data. For this reason, data were collected over an entire week to consider the mean values for each district. Even though the values that were used might not representative enough, the decision to use this data was made to demonstrate how the process would be if other more reliable data were available.

For similar reasons, the low accessibility criterion was not considered. One of the purposes of this study, as also addressed before, was to have a comprehensive method that could properly function with the data available and that is convenient for planners and other stakeholders. Consequently, although the low accessibility and connectivity could have been calculated and used for the AHP, the selected criteria were preferred as they were also repeatedly mentioned in the literature.

As mentioned in the previous sections, experts from both practical and research fields, were consulted. To have a broader perspective, the contacted experts represented different contexts, more concretely, the researchers represented different European universities, and practitioners, various regions of Germany. This was decided to have a general perspective on the relevance of the selected criteria. However, as the method was applied to Munich solely, the priorities of people outside the local context may not be as representative. Nonetheless, as mentioned before, the CR from both experts' groups showed that the results were consistent and there was not significant variation between their individual judgements. However, regarding the results from Fig. 8, it is important to point out that given the small number of consulted participants, to accurately define whether a criterion is important or not, more experts need to be consulted. For the AHP to determine the weights on a particular case, the number of consulted experts was appropriated, following similar cases found on the literature [50], [73].

6. Conclusions and further research

This study proposes a comprehensive method that could be applied to identify suitable areas for allocating mobility hubs. The presented method uses an AHP-GIS approach to integrate the different sustainability criteria. A preliminary list of the sustainability criteria most frequently mentioned in the literature consulted was created. The list is included as part of the proposed method to use it as a reference for the selection of the final criteria, which depends on the spatial data availability on each local context. Hence, the preliminary list is expected to ease the selection of relevant criteria, and simultaneously, provide a sustainability framework to select the location of mobility hubs.

A total of 7 final criteria were considered and given a weight to represent their importance in the allocation process. The weights assigned by the experts through the AHP showed that the factors related to a higher transport demand are perceived as more important than the social equity and environmental factors. Those weighted values were used to identify suitable areas within the city of Munich using 5 suitability levels. This selected approach follows other studies where AHP was also applied in the transportation field. Yet, no other studies were identified that use the AHP method to integrate sustainability criteria to determine suitable locations for mobility hubs. Hence, the importance of the contribution of this study. Similar studies also apply AHP but limit the application to a specific type of mobility hub [11] or focus only on social and resilience aspects [10]. While other studies used more complex methodologies than AHP to allocate mobility hubs [12].

The results of the application of the method indicate that the “most suitable” areas are located in the very city center, where the concentration of POIs and population, the two more important criteria, are higher. More extended areas classified as "very suitable" can be found in other central districts. Still, “suitable areas” are found in more peripheral areas and expand mainly in the southeast and southwest regions. These areas were compared with the location of some current mobility hubs, concluding that they are still mostly located in suitable and very suitable areas. Most of the existing mobility hubs can be found in areas classified by this study as “suitable” and some other even in regions only considered as “moderately suitable”.

The information provided in the maps is intended to grant the decision-makers enough information from a macro-level perspective to allocate mobility hubs from a sustainable perspective. Specifically, the final suitability map is presented as a straightforward visual aid to use as a framework when selecting an area where a mobility hub will be placed. The results from this approach, can be used to plan the placement of mobility hubs of different typologies and scales or whole networks. However, further on-site assessment is required to evaluate land availability, surrounding available modes consistent for each typology, as well as the conditions of the existing infrastructure (e.g., cycling and pedestrian infrastructure, railway stations, more detailed information about of the surrounding locations, such as POIs). Future research may focus on adapting the methodology to identify optimal street-level locations. Identifying potential locations on the micro-level would require more specific data that might entail on-site observations and data collection.

Some opportunities to improve the method in further application include selecting better and more representative spatial data for the environmental criteria. As previously mentioned, the NO_2 measurements were not representative over time. Additionally, the number the number of factors to be evaluated using the AHP could also be increased to include other factors that are relevant for future case studies. This means that the number of criteria should not be limited to seven factors, as in this study. However, as it has been proven in previous studies a higher number of criteria might increase the inconsistency of the results. Thus, following Goepel's recommendation, and based on the typical number of criteria considered by the consulted literature, it is suggested that no more than 9 criteria be considered.

Furthermore, further applications could use the input of other stakeholder involved with the mobility hubs allocation. The cooperation with multiple mobility services providers, potential users, and local authorities would improve the representation of the all interests at stake. By involving experts from different fields, various, and sometimes contradicting, positions and priorities are expected. Herein lies one of the advantages of the proposed method, which by having a preliminary list of baseline criteria, ensures a comprehensive sustainable approach.

In relation to local expertise of the AHP participants, although international experts were considered for this study with the purpose of having a general notion of what is considered important when allocating mobility hubs. Nevertheless, for further applications of the method it is suggested that, ideally, the experts to be consulted have a good understanding of the local context. To collect the inputs from experts, some suggestions for improvement should be pointed. Although, using the Excel tool resulted convenient and efficient, the participation of experts could be more interactive. This process could be held in sessions of small groups. During these sessions it could be explained in more detail the definitions and reasons for selecting the criteria. This could ensure all experts are on the same level of understanding of all criteria. In addition, during the sessions, a more constructive exchange of perspectives might take place.

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