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A methodological framework using MCDA and GIS applied to Barcelona

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ABSTRACT

In the move towards sustainable urban mobility through seamless intermodality, European cities are faced with the possibility of implementing shared mobility systems. They constitute an opportunity to create new urban hubs, considered as nodes of intermodality and places of urban intensity. In order to effectively plan the future locations of shared mobility hubs, this paper outlines the methodological framework that sustains the design of a new decision-support tool, the so-called *Mcda2MobilityHub (M2MHub)*,[1] using Multi-Criteria Decision Analysis (MCDA) and Geographic Information Systems (GIS). For this purpose, the analysis of existing literature and interviews with local authorities and transport operators, led to the identification of six main location criteria (mobility, compactness, diversity of uses, profile of potential users, spatial configuration and environment). The criteria weights were calculated using the Analytic Hierarchy Process (AHP) and the framework was applied to the case study of the city of Barcelona. The results obtained are presented in the form of heat maps, highlighting the flexibility of the decision-support tool to transform open data into appropriate indicators and detailed maps. This output can be used to support future policies for planning shared mobility hubs as places for convenient multimodal transfers, which also enable social activities and improve the quality of life in European cities.

1. Introduction: mobility nodes as urban places

Mobility has been an integral part of urban culture since the dawn of humanity. The first civilisations were nomadic in order to gather natural resources and satisfy the need to exchange goods and ideas (Careri, 2002). Even as humanity moved towards sedentary settlements, mobility remained a critical factor in economic development throughout history. The traditional European city embodied the benefits of urban living through the proximity of housing, economic activities, and services. These advantages were seen as a symbol of civilisation, offering collective access to a wide range of benefits compared to the rural environment, where life and work were more separated and isolated (Hall, 1990). Since the 20th century, urbanisation has rapidly transformed many cities from continuous agglomerations into non-continuous developments that are part of a metropolis. Improved transport has made daily travel times similar for a large share of citizens, even if they live outside the city centre in nearby towns. The geographical extent of urban sprawl has significantly increased as a result, and land has been occupied without the continuity of the conventional agglomeration of the industrial era (Font, 2004).

The discontinuity in the occupation of land for urban uses has become present in the metropolis, and this phenomenon implies overcoming the conception of land as a map of surfaces. As André Corboz (2001) argues, the multiplicity of effects that transcend any demarcation leads us to consider territorial issues essentially as systems of networks that do not delimit surfaces, but only mark nodes. Transport infrastructures, and in particular railway stations, have become nodes with high network content, combining different modes and scales of transport (Bertolini & Spit, 1998). Their added value lies in the fact that they are elements strongly linked to their urban environment and have the capacity to relate to other centres. We consider this nodal function as a tool that contributes to the development of the contemporary city.

The use and design of infrastructure must therefore be reconsidered in order to meet today's increasingly extensive and intensive demands. Urban planning can help in achieving better outcomes in the uncertain future of urban transformation. New paradigms in the organisation and governance of cities or metropolises can be imagined, and one of the main challenges will be to provide an adequate response by means of an

[1] Link to the *M2MHub* tool, which is available as an open plugin for QGIS: https://github.com/natrouk/Mcda2MobilityHub-desicion-support-tool_QGIS-plugin.

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efficient transport system that promotes sustainable and user-friendly mobility. Giuseppe Dematteis (2006) has already called for the *governance of networks* in order to manage and understand the new territoriality of the contemporary urban phenomenon. Through the proper use of networks there is a great potential to achieve more efficient urban systems.

Therefore, it is necessary to advance the knowledge on networks in the metropolis, especially those that belong to new paradigms such as shared mobility, to design efficient systems from a functional and environmental point of view. It is relevant to deepen the conditions that make it possible to create, in these networks and their nodes, new places of contemporary urbanity, enhancing urban and social relations to become authentic public spaces of the metropolis. The capacity of urban networks to give a new structure to the metropolis depends to a large extent on the possibility of transforming their nodes into urban centres that are beyond transport links and contribute to the urbanity of places, cities and territories (Moreno et al., 2020), considered both as physical and social spaces. The present paper is based on research conducted by a team of transport engineers and urbanists in order to tackle this tight relation between mobility and territory through the study of the location of innovative nodes so-called shared mobility hubs. These hubs are places where different transport modes are integrated seamlessly and a wide range of services come together (Roukouni et al., 2023).

The article aims to propose a new methodological framework for supporting the location of shared mobility hubs, which was materialised into a practical and operational plug-in for QGIS. In the next section, we present the state of the art of MCDA applied to mobility, which is the technique we propose to frame the location of such urban infrastructure. This is followed by a section in which we conceptualise the framework to support the location of this type of hubs. Finally, we present the results of its application to the city of Barcelona, as well as our discussion and conclusion based on the applicability of the methodology.

2. State of the art in multi-criteria decision analysis (MCDA) for urban mobility

If the *governance of networks* and the design of their nodes is the key to planning a balanced, efficient and sustainable metropolis, then decisions on the location of intermodal nodes in the territory are crucial. Intermodality is a fundamental aspect of the transition to sustainable mobility in the 21st century. The alternative to the massive use of private cars in urban areas is not another mode of transport, but a comfortable, affordable and time-saving combination of modes (public transport, active mobility, shared mobility, etc.). Mobility hubs contribute to the creation of such seamless intermodality (Aydin et al., 2022). In this sense, mobility hubs are closely related to the concept of Mobility as a Service (MaaS). MaaS can be generally defined as a set of technological tools that enable the integration of planning, booking, and payment for combined transportation. Mobility hubs are the physical equivalent of MaaS solutions in the urban world. Both components are essential to any Sustainable Urban Mobility Plan (SUMP), which provides European cities with comprehensive, integrated, and long-term visions for their urban mobility transitions (Gragera et al., 2021).

The use of Multi-Criteria Decision Analysis (MCDA) methods in transport and mobility decision making has increased since the 2000s (Macharis & Bernardini, 2015; Anastasiadou & Gavanas, 2023). Compared to other decision support and analysis methods such as cost-benefit analysis, MCDA allows to combine quantitative and qualitative criteria, taking into account uncertainty and subjectivity, by linking the weights of the criteria to language expressions (Aydin et al., 2022; Macharis & Bernardini, 2015).

With regard to the main urban mobility issues addressed by MCDA over the last two decades, many of them focus on the selection or prioritisation of a location among sites – such as neighbourhoods – previously filtered for the implementation of specific mobility projects (Aydin et al., 2022; Gaglione et al., 2022; Carra et al., 2022; Psarrou et al., 2022). Another complementary approach is to select the most appropriate variant or type of action for a given location: different combinations of micro-mobility solutions for example (Psarrou et al., 2022), urban mobility investments in medium-size cities in developing countries (Silva et al., 2022), or combinations of push[2] and pull measures (Melkonyan et al., 2022).

The introduction of the idea of scenarios increases the complexity of the approaches. For example, Melkonyan et al. (2022) evaluate urban mobility policies after defining three development scenarios for the Rhine-Rhur area. Therefore, MCDA methods seem to be appropriate for urban mobility issues to select sites for intervention, to choose between investment variants for a given site and to consider alternative scenarios (Anastasiadou & Gavanas, 2023).

With regards to the methodology used for estimating the weights of the criteria, Analytic Hierarchy Process (AHP) – the one used in our paper – is very widely used. The opinion of a group of experts is decisive in assigning weights to the different parameters considered, which is not free of error since their opinions may be subjective. Sensitivity analyses are also often carried out, given the uncertainty of the weights estimation. These consist of increasing the weight of less influential criteria by 10 % for example, while reducing the weight of the most important ones, in order to verify the role of minor indicators in the calculation of indices. Decision support tools are enriched when MCDA methods are combined with other methods. For instance, Melkonyan et al. (2022) use a system dynamics model (itself based on multiscale urban modelling and multi-agent simulation modelling) to complement MCDA. The combination of other models and methods enhances the ability of MCDA to deal with complex urban decisions. Furthermore, it is quite common to complement MCDA with GIS mapping. In Gaglione et al. (2022), a walkability index calculated by MCDA enables the production of GIS maps of accessibility around public facilities.

To establish a methodology to plan the location of shared mobility hubs, our research has focused on the selection of criteria that are relevant to distinguish different areas in what regards to their potential to cater for such novel infrastructure. As with most research applying MCDA to urban mobility, the selection of indicators is based on a thorough literature review and expert opinion. Previous work has made relevant contributions to such task. Carra et al. (2022) reviewed 60 papers and conducted an international survey among a pool of experts to select 99 indicators, considering both their relevance in relation to the location of charging stations and the availability of data. Silva et al. (2022) scanned a set of reviewed papers and produced a pre-defined set of 43 criteria divided into four categories (social, environmental, economic and technical). Among the categories of indicators considered in many papers, some are related to mobility demand expectations, such as current traffic flows, proximity to attractors or accessibility to the centre (Aydin et al., 2022; Carra et al., 2022). Another category concerns the socio-demographic characteristics of potential users of mobility solutions (income, education, age, etc.). As noted by Carra et al. (2022), to take into consideration such criteria it is crucial to tackle and prevent inequalities.

A few other papers also point at the physical characteristics of public space, in terms of structural suitability (Aydin et al., 2022; Carra et al., 2022). Increasingly, the selected indicators integrate the relationships between transport and land use and the impact of the built environment to make a place attractive for different modes of transport, especially walking and cycling (Gaglione et al., 2022). This is one of the main objectives of our paper, to balance indicators related to transport and mobility with those related to *urbanism* (urban planning, urban design, social profiles and environmental conditions). The criteria chosen are

[2] Mobility push measures are based on restrictions and tolls and seem to be more effective in the short term. On the contrary, pull measures create positive feelings on the users and enable changes in the long-term social behaviours (Melkonyan et al., 2022).

also an important point of discussion. Psarrou et al. (2022) define conditions that are considered appropriate for the implementation of micro-mobility solutions, and the criteria are used not only for site selection, but also for identifying the most appropriate form of micro-mobility for each location.

All these recent papers highlight the relevance of urban planning aspects (land use and accessibility to services), while transport planning appears as an overlapping criterion between the indicators considered (Carra et al., 2022) and digitalisation and networking as drivers of the current urban mobility transition (Melkonyan et al., 2022). Based on these findings our paper explores the conceptualisation of a decision support tool, so-called *Mcda2MobilityHub (M2MHub)*, for the location of shared mobility hubs in metropolitan areas. Our main contribution is the combination of Analytic Hierarchy Process (AHP), Multi-Criteria Analysis (MCDA) and Geographical Information System (GIS) in a by-design flexible tool that combines data and geolocation for producing quick scans of the most promising areas for installing such hubs. The proposed tool aims to assist local public administrations, such as municipalities and metropolitan areas, as well as transport operators in planning the location of new shared mobility hubs. This can contribute to achieving Sustainable Mobility as a Service (Vitetta, 2022) through a Decision Support System (DSS) that supports MaaS public administrations and companies in designing services, evaluating policies, and smart planning.

3. Conceptualization of a framework to support the location of shared mobility hubs in urban areas

The framework for planning new shared mobility hubs aims to combine the potential of building urban places with the implementation of mobility nodes. Therefore, it aims to identify locations for mobility nodes while taking into account the fact that future mobility networks are determined by urban characteristics. The methodology to conceptualise the tool followed four steps: Identification of a long list of indicators [1]; Selection of specific indicators [2]; Translation of the indicators into applicable and measurable criteria [3]; Application of Spatial Multi-Criteria Decision Analysis [4]. The main aim was the selection and identification of the appropriate indicators and the evaluation of their role and weight in the location of future shared mobility hubs. Selecting appropriate criteria to match urban characteristics and mobility needs was the basis for the *M2MHub tool*, which was programmed as a QGIS plug-in based on MCDA.

3.1. Identification of indicators

The approach to support the location desirability of new shared mobility hubs aimed to juxtapose a set of indicators on a single map that provide sufficient insights to evaluate possible locations (Blad, 2021; Blad et al., 2022). According to previous research, the most important dimension for the classification of shared mobility hubs is their urban context, which can be divided into: *City centre* [1], *Suburban* [2], *Emerging urban growth centre* [3], *Historic centre* [4] and *Key (standalone) destination* [5] (Roukouni et al., 2023). Considering the relevance of the urban context, the search for indicators was conceived in a double path: nodes and places (Bertolini & Spit, 1998; Bertolini, 1999; Bertolini & Dijst, 2003; García & Carpio, 2014; Moreno, 2014; Groenendijk et al., 2018). As a node, a hub is a key element to improve intermodality in urban mobility systems and shared mobility hubs increase the needs of urbanity to achieve seamless intermodality, a key aspect for the transition towards sustainable mobility (Groenendijk et al., 2018). However, a hub is not only a transfer between modes of transport, but also a place where people may want to stop, stay and interact (Roukouni et al., 2023). If the activities of the hub are related to its urban surroundings, it will be integrated and become a place, a useful facility for the local community. Therefore, indicators had to be defined both in terms of mobility/transport and urbanism/urban design.

One of the first approaches was to assess the diversity and adaptability of possible sites in order to generate places of urban vitality. To address this need, we selected the *City Prosperity Initiative* (CPI) and the *Emerging and Sustainable Cities Initiative* (ESCI) indices, which allow city authorities to identify opportunities and potential areas of intervention for their cities to become more prosperous (UN-Habitat, 2016; Inter-American Development Bank, 2013). To complement the evaluation of these indices, we revised a third manuscript to improve information on urban diversity. The *Certificación del Urbanismo Ecológico* proposes a tool to evaluate urban interventions in cities with more than 50,000 inhabitants according to an ecological approach. This guide establishes a set of indicators, the information requirements, the way to calculate them and their benchmarks to assess the incorporation of a sustainable approach in urban planning (Rueda, 2012). To define the urban structure and its fabric, we revised the theory constructed in *Spacematrix: space, density and urban form*, which explores the potential of urban density as a tool for urban planning and design (Berghauser & Haupt, 2021) and the work of Hillier (2009) in *Spatial sustainability in cities: organic patterns and sustainable forms*, which proposes a concept of spatial sustainability focused on the street network, the primary spatial structure of the city, which is highly related to mobility patterns.

Additionally, we have drawn on research that has taken a thoughtful approach to the relationship between urbanity and mobility. The NODES project has developed a set of tools for assessing, benchmarking and improving urban transport interchanges (García & Carpio Pinedo, 2014). We have also included in the discussion a perspective related to the notion of the *vitality* of space, linked to everyday mobility, developed by Delclòs-Alió and Miralles-Guasch (2021). To reinforce the relevance of how walkable an urban fabric can be, we have revised the principles of the *Pedestrians First – Tool for Walkable Cities*, developed by the Institute of Transportation and Development Policies that aims to facilitate the measurement of the characteristics that promote walkability, addressing urban planning, building regulations, street and urban design (ITDP, 2018). To complement the approach to walkability that includes green spaces as a foundation, the research *Green streetscape and walking: exploring active mobility patterns in dense and compact cities* (Vich et al., 2019) was consulted to explore the correlation between urban green spaces and daily walking levels of residents.

Based on this extensive review, two outputs were produced: a conceptual diagram and a comprehensive list of indicators. The conceptual diagram aimed at organising the indicators into different categories that correspond to the guiding principles to achieve sustainable mobility in liveable cities (see Fig. 1). According to the diagram, a hub is both a mobility node and a place of encounter, as referred to already. As a node its main criteria is mobility and as a place it has two basic components: a social one and a formal/physical one (Bertolini & Spit, 1998; Bertolini, 1999; Bertolini & Dijst, 2003; García & Carpio, 2014; Moreno, 2014; Groenendijk et al., 2018). As a social space, the aim is to promote its vitality so that they can contribute to the liveability of the city. The indicators to consider social dimensions are grouped into three categories: compactness (related to the intensity of the built environment and the potential activities taking place in it), diversity (related to the degree of mixing of different uses around the hub) and user profile (of people living around the hub). As a physical space, the aim is to create nodes that are well integrated into the layout of the city (spatial configuration). Finally, the last category considers some general environmental and ecological indicators in order to identify places where the implementation of sustainable mobility solutions is more urgent.

For the criteria in Fig. 1, a set of 56 indicators were selected. Each indicator has been analysed in terms of benchmarks, units, scales, description, method of calculation, data requirements and references. It is important to stress the need for defining the method to be used for producing each indicator and the data that needs to be collected to support such calculation. This usability requirement is related to the applicability of the proposed methodology. The list of indicators responds to the research question: *What would be the optimal indicators to*

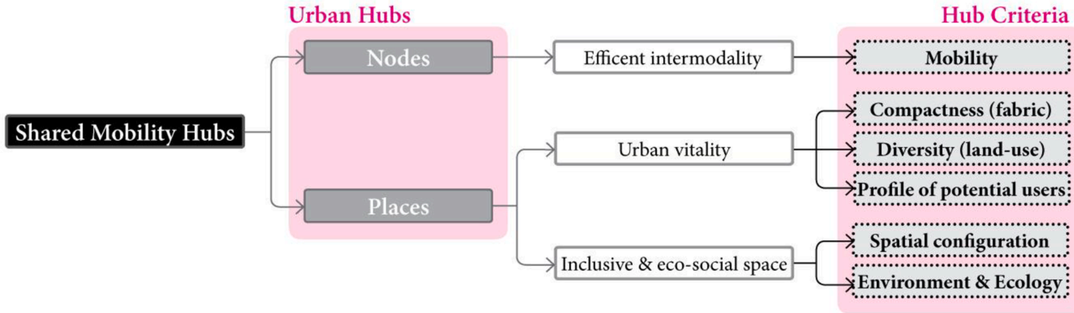

Fig. 1. Diagram of shared mobility hubs to derive key criteria.

assess the convenience of locating a shared mobility hub in an urban area? If some indicators are difficult to apply, they have not been discarded, but this may lead to recommendations for cities to collect new data or to improve the collection of existing data.

Another important piece of information about the indicators is their *scale*. It can be metropolitan, local or place-based and requires different amounts and types of data. The metropolitan scale indicators require statistical data that can be collected for an entire metropolitan area. The local scale indicators require information about the area surrounding the potential location, which can be collected statistically and aggregated for a whole metropolitan area. Sometimes, however, the local indicators use some information that requires fieldwork. Finally, place-based indicators refer to specific physical conditions, such as public space, which may influence the architectural or urban design of centres.

We remind that the methodological approach put forward in this paper is supported on the possibility of producing desirability maps through GIS. The tool is meant to produce heat maps for a metropolitan area that can be easily understood. Therefore, only the indicators that can be aggregated at these scales were selected. The third group of indicators was discarded and will be addressed later during the implementation of the hub, when indicators such as universal accessibility will be considered.

3.2. Selection of indicators

The next step was to select a reduced number of indicators from the aforementioned large pool of indicators, to make the tool operational. The selected indicators were representative of the different categories, and in order to prioritise them, a series of interviews were organised with European cities and operators currently implementing the concept of shared mobility hubs, to discuss the indicators and get their feedback. The different participating institutions (municipalities, NGOs and operators) were located in the cities of Amsterdam and Helmond (NL), Barcelona (ES), Lisbon and Setúbal (PT), and Warsaw (PL). The interest of the respondents in the set of indicators varied, but their overview was specific in how they could implement the *M2MHub* tool. We collected the overview through online semi-structured interviews, including questions on relevance, interest, applicability and data collection, following a prior review by the interviewees of the list of 56 indicators and their specifications.

The *city of Amsterdam* was interested in the indicators related to trip purpose, accessibility of the transport network, proximity to parking and proximity to facilities. Their approach was mainly focused on mobility patterns. The *city of Helmond* showed interest in the indicators related to mobility, compactness, diversity and vulnerability. They stated that not only the application of current indicators is of utmost importance, but also the existing plans for the area and future standards. In this sense, the planning approach took on a specific dimension and the temporal framework of application was broadened. The *Metropolitan Area of Barcelona* (AMB) not only highlighted the relevance of the mobility indicators, but also considered the compactness and diversity indicators to be fundamental. Barcelona was also in favour of indicators measuring spatial configuration and street comfort, in particular street hierarchy and air quality. The *Metropolitan Transport of Lisbon* (TML), which was implementing a hub in the city of Setúbal, was mainly interested in the mobility indicators, while the bike-sharing system of the Municipality of Lisbon, operated by the *Empresa de Mobilidade e Estacionamiento de Lisboa* (EMEL), introduced the need to measure walkability and bikeability, especially for those hubs focused on active modes. Finally, *Mobilne Miasto* from Warsaw pointed out that the relevance of indicators is also based on the presence of cars and their parking norms, they were also interested in diversity, social vulnerability and environmental characteristics such as air quality and noise pollution.

A key conclusion from the interviews was that there is interest in a flexible tool. This flexibility could take several forms. For example, regarding the data to be introduced for a particular indicator, cities would like to introduce not only data on the existing situation, but also data on different planned scenarios. Public administrations and operators would like to choose to use a given indicator in different ways and, most importantly, they would like to choose the weights they give to each category of indicators when using the tool, depending on the specificities of their urban environment or policy priorities. Based on the six interviews with the cities, we selected a final set of 23 indicators as sub-criteria, which were linked to the main criteria (see Fig. 2).

3.3. Application criteria

For the selected indicators, a reflection was made on how to apply them, i.e. what conclusions can be drawn from each heat map generated in order to prioritise areas for the location of shared mobility hubs. The discussion on how to apply each indicator (see Fig. 2) followed previous research on each theme, although such discussion is open-ended depending greatly on the objectives of the cities (Perdue & Gustke, 1985; Bertolini, 1999; Krizek, 2003; Landex & Hansen, 2006; Albalate & Bel, 2010; Schneider, 2013; Cohen & Shaheen, 2018; Santos, 2018; Machado et al., 2018; Bell, 2019; Tavassoli & Tamannaei, 2019; Vich et al., 2019; Claasen, 2020; Roukouni & Correia, 2020; Berghauser & Haupt, 2021; Delclòs-Alió & Miralles-Guasch, 2021; Arnold, 2022; Blad et al., 2022; Horjus et al., 2022). For instance, if shared mobility hubs are to be located where alternative modes of transport are currently most used instead of private cars, the city's decisions would be driven by the demand factor. Conversely, if shared mobility hubs are to be located where private car use is still dominant to encourage a shift in demand, the city's actions would be driven by the principle of desirability.

A second observation is that the criteria for applying certain indicators may be specific to a particular type of hub. For instance, medium to large hubs situated in city centres and connected to public transport access should be given priority in areas with less usage diversity and less balance between activity and residence, where commuting is unavoidable. On the other hand, hubs in suburban areas should always be promoted next to streets that are considered primary roads in the network hierarchy.

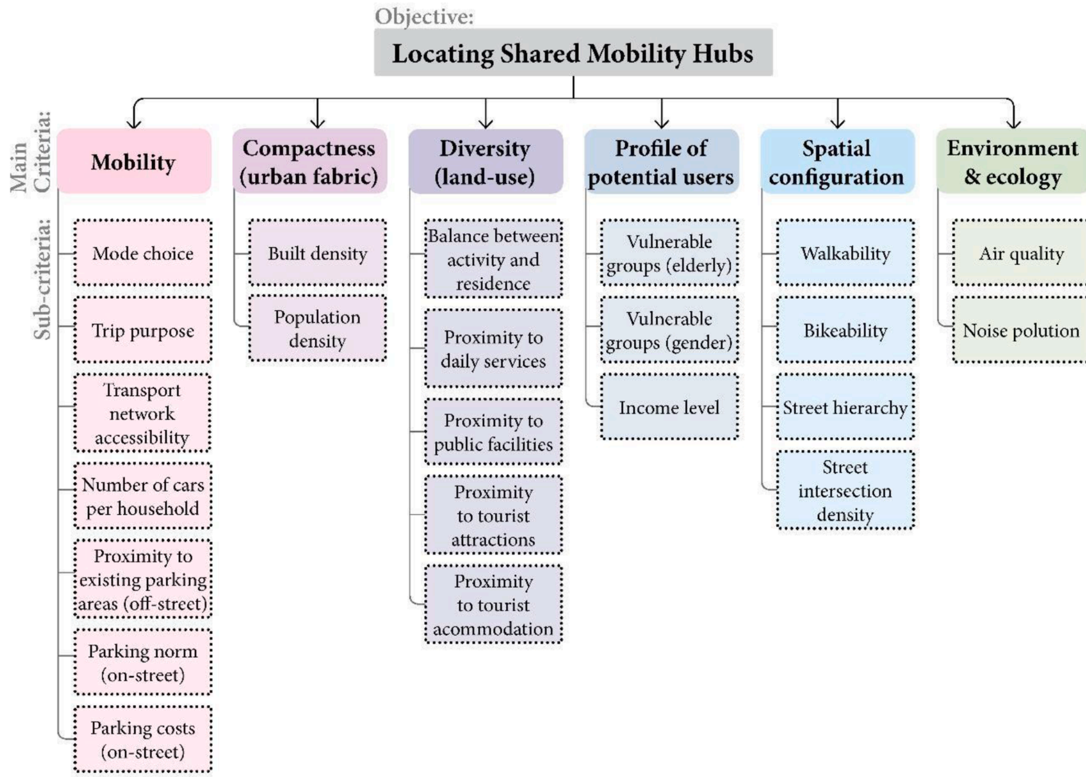

Fig. 2. The MCDA criteria – hierarchy tree with the three levels of analysis.

3.4. Weight assignment using the Analytic Hierarchy Process (AHP)

An essential part of any MCDA is the assignment of weights to the criteria. In our case, the Analytic Hierarchy Process (AHP) introduced by Saaty (1977) was used. AHP is a scaling method for eliciting weights for a set of criteria according to their importance. Since its publication, the method has been widely used, including in transport research, due to its user-friendliness, which makes it easier to understand and implement (for more information, see, for example, Vargas (1990), Lepetu (2012), Macharis and Bernandini (2015), Mosadeghi et al. (2015), Vaidya and Kumar (2006), Nosal and Solecka (2014), Shiau (2013), Roukouni et al. (2018)).

AHP uses pairwise comparisons to estimate relative preferences between the different weights. For these comparisons, a 9-point intensity scale is used, known as the basic scale of preferences or Saaty's scale. A very useful feature of AHP is that, in addition to calculating the weights, it also calculates a consistency index because, as with all issues where people make judgements, it is natural not to have absolute consistency in real life problems. But with this index it is possible to check the consistency and decide whether it is within acceptable limits or whether some of the judgments may be irrational and therefore it would be better to exclude them from the analysis. For the full mathematical approach supporting AHP, see Nalmpantis et al. (2019).

In order to assign weights to the criteria using AHP, pairwise comparison tables were created and then distributed online to the different experts that comprise our team. Each table included one group of criteria, so that in total the experts had to decide the relative preferences in six different tables using Saaty's 9-point scale. For the table of the main criteria, they were asked to make the pairwise comparisons, bearing in mind that the comparison is made in relation to the overall objective of the MCDA. As for each table of the sub-criteria, the pairwise comparisons had to be made with respect to the main criterion of the group.

A total of seven experts participated and completed the pairwise comparison tables. It is worth noting that the team was multidisciplinary, so the views of experts in transport and mobility (2 experts), urban planning and sustainable urban design (3 experts), as well as the private sector (automotive industry) (2 experts) were gathered, which promises a diverse result. The representation of the three different fields is considered balanced so no weights were used per number of participants per field. In case of over or/and under representation of one of the fields, weights would have been introduced to limit any potential associated bias.

It should be highlighted that, eliciting weights for a multicriteria analysis assumes that the goal of pacing hubs in a city is well defined. For that to happen the type of hub is an important element; a key criterion for a hub located in the city centre, for example, can be less important for another type of hub like a main regional one located at the outskirts. For this application of the AHP, we asked the experts who participated to perform the comparisons for all the criteria for the type "city centre hub" (high population density, multiple activities, multimodal environment, mixed uses, and limited room for further land development) (Roukouni et al., 2023).

The weights that were calculated through the process described above, are not meant to be restrictive in any way for the tool, as flexibility lies at the core of our conceptual model. The users of the tool are given the freedom to intervene in the weights' table and allocate them according to their wishes, policies and strategies. However, they will be allowed to also run the spatial MCDA with these weights that were derived from experts through a robust scientific process but always having in mind the disclaimer that these weights have a particular context.

4. Results of the application of the methodology to the city of Barcelona

In order to verify how complete the model proposed in Fig. 2 could be, we applied it to the city of Barcelona. The purpose of this phase was to validate the methodological framework and to discuss our approach from an in-depth planning perspective in a real case. The results presented aim to understand the extent to which the methods are valid when applied to cities with their available data. To do this, we choose the type of *city centre* hub according to the classification of Roukouni et al. (2023) and we run the AHP considering how relevant each sub-criterion could be for the planning of this type of hub in European metropolitan areas (see Section 3.4), obtaining the weights shown in Table 1. These percentages are those we used to validate the tool, giving each sub-criterion a weight within each criterion, and the criteria a weight in the overall framework. The process was designed to be reproduced by the promoters of shared mobility hubs in different cities across Europe (municipalities, public administrations, mobility operators, etc.), so the weights could change according to public and private interests.

From the results obtained after applying the AHP, there are two sub-criteria that prevail over the others: *mobility* and *spatial configuration*. Considering the relevance of the experts' position in the process, these results distinguish between *nodes* and *places*. Once we obtained the weights in Table 1, we applied these weights to the city of Barcelona (see Fig. 3), using the GIS decision support tool *M2MHub* we created.

The challenge here was to find all the data needed to calculate such a diverse set of indicators. This realistic application of the model shows that some European cities, such as Barcelona, have enough open data to calculate almost all sub-criteria, but in some other cities the availability was scarce and made it difficult to calculate even some of the generic criteria. In Barcelona, as shown in Table 1, all indicators were calculated (in grey), with the exception of two: *mode choice* and *trip purpose*. All the data used were obtained from Open Data BCN (de Barcelona, 2023) and the Spanish Land Registry (de Hacienda, 2023). In this particular case, one of the main problems in overlapping the calculation of weights to obtain desirability maps was that the available data was in different formats. In some cases, the data referred to polygons representing neighbourhoods, in other cases to points representing locations and in other cases to lines representing streets. To achieve a single type of base unit, we translated the surface of the city into a regular grid of hexagons (12,430 cells * 0.867Ha), which collected the different data sub-criteria by sub-criteria, obtaining twenty-one indicators, as shown in Fig. 4. Depending on the type of indicator, some data were first converted into density of points per area and others into proximity. The range of diversity that can be observed in Fig. 4 is the complexity we face in mapping the desirability of locating a new shared mobility hub using twenty-one indicators.

Table 1
Table of selected indicators and the application of the criteria. Indicators used in the Barcelona case study due to available data are shown in grey.

C.1. Mobility	26.64 %	C.1.1. Mode choice	16.11 %
		C.1.2. Trip purpose	9.11 %
		C.1.3. Transport network accessibility	24.37 %
		C.1.4. Number of cars per household	8.89 %
		C.1.5. Proximity to existing parking facilities (off-street)	19.61 %
		C.1.6. Parking norm (on-street)	11.41 %
		C.1.7. Parking costs (on-street)	10.49 %
C.2. Compactness	12.90 %	C.2.1. Built density	50.00 %
		C.2.2. Population density	50.00 %
C.3. Diversity of uses	13.87 %	C.3.1. Balance between activity and residence	22.43 %
		C.3.2. Proximity to daily services	20.63 %
		C.3.3. Proximity to public facilities	26.03 %
		C.3.4. Proximity to tourist attractions	14.50 %
		C.3.5. Proximity to tourist accommodation	16.43 %
C.4. Profile of potential users	12.73 %	C.4.1. Vulnerable groups (elderly)	28.36 %
		C.4.2. Vulnerable groups (gender)	22.46 %
		C.4.3. Income level	49.19 %
C.5. Spatial configuration	22.49 %	C.5.1. Walkability	36.71 %
		C.5.2. Bikeability	32.60 %
		C.5.3. Street hierarchy	20.07 %
		C.5.4. Street intersection density	10.61 %
C.6. Environment	11.34 %	C.6.1. Air quality	59.82 %
		C.6.2. Noise pollution	40.18 %

Once we had the twenty-one maps in Fig. 4, we combined them according to the weights calculated by the AHP process (see Table 1). We merged the twenty-one sub-criteria into the six main criteria and we obtained six heat maps (see Fig. 5). All the heat maps were produced using the decision support planning tool that we developed specifically for this purpose. The normalisation process allowed us to merge the different indicators. In Figs. 5 and 6, the areas highlighted in *green* are more suitable for implementing a hub within a main criterion, and the values decrease to *red* on a normalised scale from 1 to 0.

If we look at the heat maps in Fig. 5, which show the results of the tool application for the six main criteria (combining their corresponding sub-criteria), we can relate them to the urban and social reality of Barcelona. Displaying these criteria maps in the same image allowed us to read the city of Barcelona from different perspectives. Some maps draw a grid of nodes, some a grid of pixels, some a grid of patches and some a grid of gradient areas. In fact, the graphical language resulting from the analysis reflects different layers of the same city.

The *Mobility* map (the criterion with the greater weight in the final result) shows that most of central Barcelona is suitable for the implementation of a *city centre* type mobility hub. Most of the municipality of Barcelona fulfils the conditions of accessibility by public transport and the existence of parking facilities. Only the mountain and hill areas (Collserola, Montjuïc, Tres Turons), the logistic zone of the Zona Franca, the industrial areas undergoing regeneration in the north-east of the city or the railway corridor of La Sagrera (also under reconstruction) appear to be less suitable for a mobility hub. The northern seafront seems less suitable for a hub. This can be explained by the fact that there is no metro or train line close to the seafront, even though the area attracts many people. Within the central zone, the heat map shows nearby areas with different levels of suitability, allowing decisions to be made at a neighbourhood level.

In the *Compactness* map, the area suitable for a city centre hub is reduced compared to the mobility criteria. Neighbourhoods with a lower than average residential density are excluded. This is the case of the 22@ district, which is undergoing regeneration; the wealthiest districts in the west, such as Pedralbes, Sarrià or Les Corts; and some parts of the Eixample, where there are more jobs than homes. The *Diversity of uses* map shows a high degree of accuracy, in the sense that the settlement as a whole appears to have a fairly good balance between residential and economic activity, but we can see very detailed differences, almost on a per block basis. The overall picture shows a core where this balance is increased (almost all the dense areas are pixelated) and then it is reduced in the peripheral ring, particularly in the north-eastern part of the city (districts like Nou Barris, which are mainly residential, or like Sant Andreu and Sant Martí de Provençals, where industrial states still exist). In the *Potential users* map, income level is the main criterion. Therefore, the resulting image shows the wealthy neighbourhoods in red (Vallvidrera, Pedralbes, Sarrià, Les Corts, Esquerra de l'Eixample, Vila Olímpica or Diagonal Mar). As mentioned above, the criteria have been applied with the aim of promoting hubs in areas that are more in need of

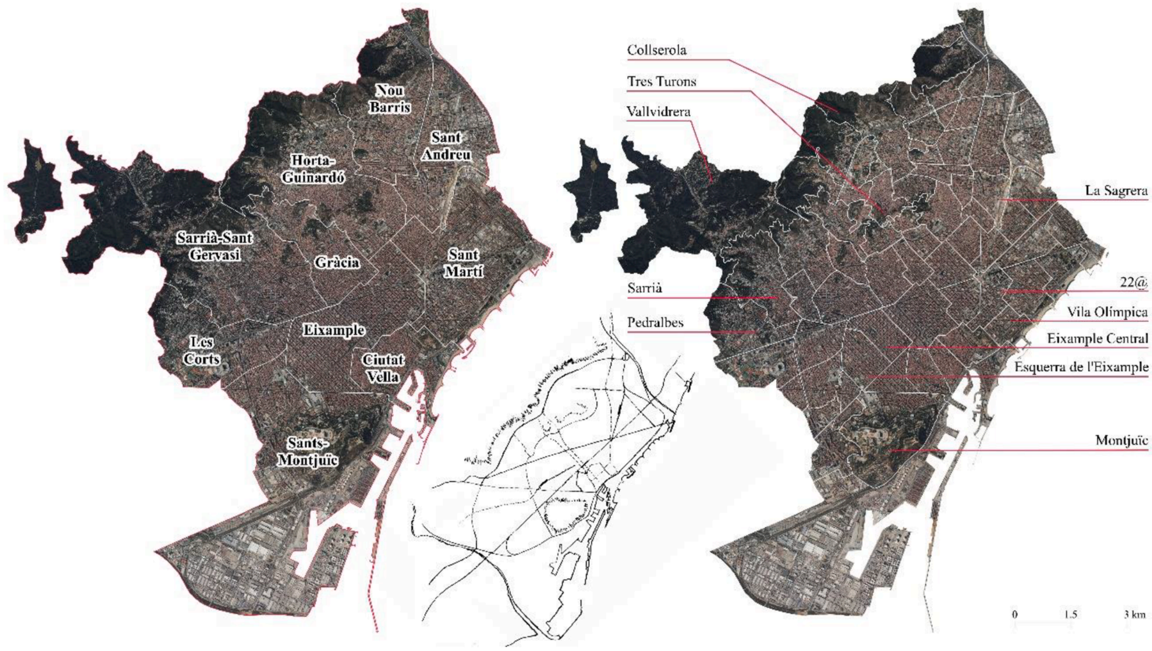

Fig. 3. Districts of Barcelona, diagram of main infrastructures and places mentioned in the text.

alternative mobility solutions, i.e. the low-income north-western sector of the city. The *Spatial configuration* map represents a different type of heat map's layout. The variables taken into account relate to street layout (walkability, bikeability, street hierarchy). It is therefore a pattern of main streets that emerges as suitable for the location of hubs. This is particularly the case in the gently sloping plain between the hills and the coast. Finally, the *Environment* map highlights the fact that the Central Eixample is clearly the area that suffers from higher levels of air and noise pollution, requiring shared mobility solutions to reduce the pressure of private cars. All the heat maps clearly show complementary and interesting readings of the spatiality of Barcelona's data.

The final *Desirability* map for the location of *shared mobility hubs* (see Fig. 6), which combines all six main criteria, is quite close to the mobility map. This is expected as the weight of the mobility criteria (26.64 %) is twice (and sometimes three times) the weight of the secondary criteria. Only the spatial configuration criterion also has a weight of more than 20 %, but it doesn't contradict the mobility criterion, rather it reinforces some axes in the map. According to the weights, the impact of the other criteria remains less visible. A sensitivity analysis could better reveal the influence of these criteria on the final result. Indeed, the fact that we have introduced indicators that are not related to mobility shows that the darker green is not placed in the main public transport node, Plaça Catalunya, a place with the greatest accessibility but with less compactness or with higher income. We can also see that the weights have been calculated in such a way as to reinforce the current conditions and the successful implementation of the hubs. If the objective had been to improve the accessibility of areas with less access to public transport, the final heat map would have been completely different.

It is important to stress that the data used refer only to the municipality of Barcelona and not to the entire metropolitan area. The area considered is therefore a compact, dense, mixed-use city with good accessibility conditions. If we had considered the metropolitan data, the resulting heat map would have pointed toward different central areas, distributed throughout the metropolis, where it would be desirable to locate city centres hubs. And at a second level, within these central cores, the tool allows the identification of certain areas that are more suitable than others, as shown in the case we present of central Barcelona. However, the collection of data in the metropolitan municipalities is inconsistent and, given the lower availability of data for the rest of the metropolitan area, the analysis would not have been as accurate.

5. Discussion

The conceptualisation of the methodological framework and the resulting decision support tool *M2MHub* is a noteworthy contribution to the application of MCDA methods in urban mobility and shared mobility hubs. It complements previous literature (Melkonyan et al., 2022; Pekdemir et al., 2024; Zhu et al., 2024) by enabling the mapping of MCDA results in GIS maps. This application is particularly useful in urban and mobility planning, especially in the new framework of SUMPs (Aydin et al., 2022; Anastasiadou & Nikolaos, 2023). The methods and the *M2MHub* tool are versatile and flexible, accommodating the demands, needs, and policies of cities and operators. This is due to the following innovations.

Firstly, the tool is designed to generate indices and heat maps for the implementation of shared mobility hubs considering an entire metropolitan area, while most of the previous research reviewed focuses on prioritising pre-selected specific locations for the implementation of mobility solutions (Aydin et al., 2022; Gaglione et al., 2022; Carra et al., 2022; Psarrou et al., 2022). This therefore increases the complexity of the approach, as it involves dealing with comprehensive data for extended urban areas.

Secondly, the paper places more emphasis on the choice of indicators than on the choice of MCDA method. The selected method is the most widely used one (AHP) combined with QGIS mapping (as in Gaglione et al., 2022). QGIS was chosen due to its competitive advantages, including being free, interoperable, and having a large number of plug-in extensions. Its rapid development was also a factor in the decision. Regarding the selection of indicators, it was based (as in other research, such as Carra et al., 2022 and Silva et al., 2022) on previous literature (pre-selection of 56 indicators) and the contribution of a panel of experts from transport authorities in different European cities (final list of 23 indicators). Our paper aimed to balance and interweave indicators relevant to transport and urbanism. In this sense, the paper is embedded in recent trends (Gaglione et al., 2022) that fully integrate land use and the influence of the built environment in transport and mobility research, going a step further thanks to the applicability of the

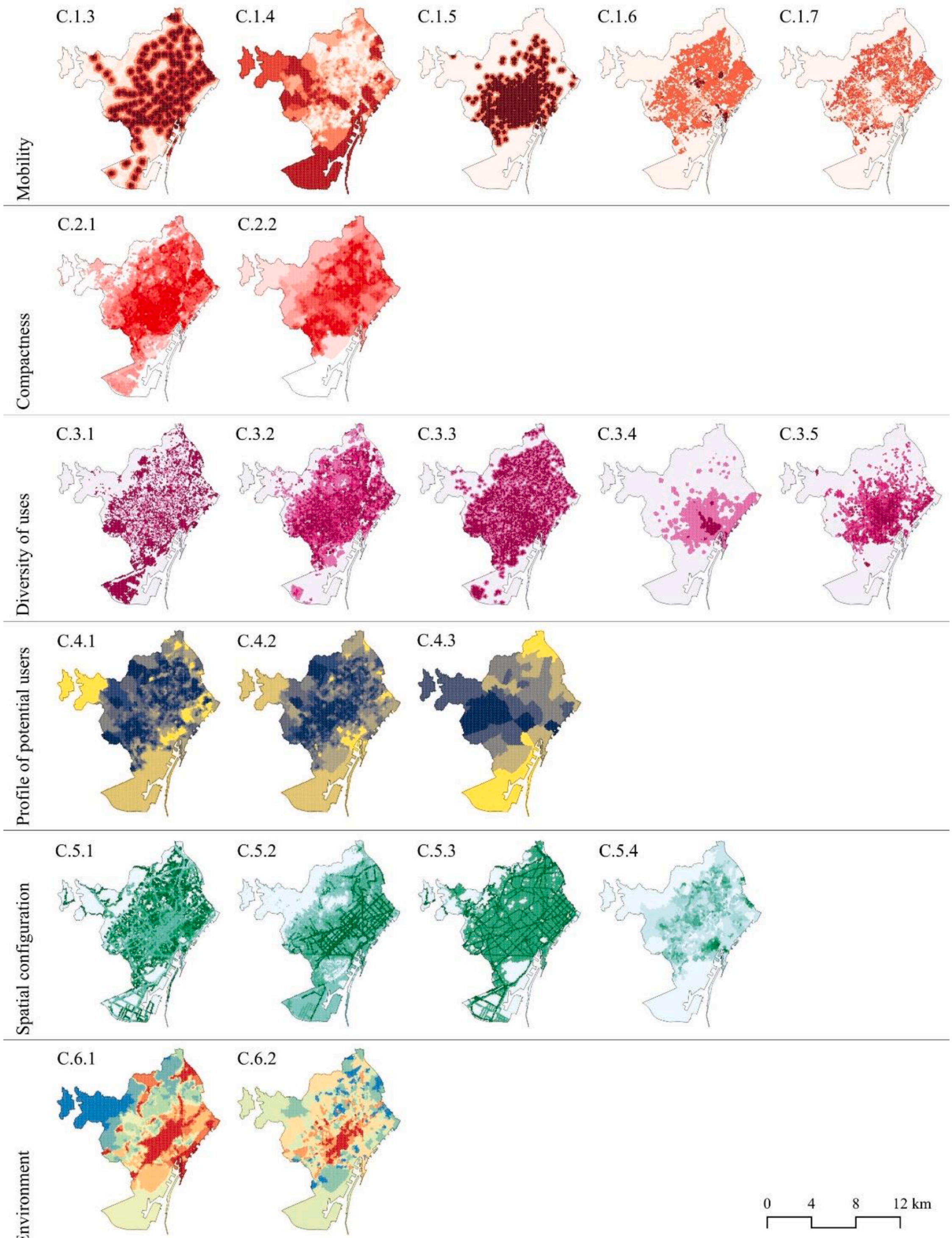

Fig. 4. The twenty-one indicators calculated using the Barcelona open source data.

M2MHub tool in any city in Europe.

Thirdly, our paper reflects deeply on the criteria for the application of the selected indicators (Psarrou et al., 2022). Besides the assignment of weights, the direction in which we apply an indicator is crucial. The answer of the *M2MHub* tool was to strive for its flexibility. Users can add indicators, they can change the preset weight for each criterion (assigned through an AHP method involving the members of the research team), and they can also choose the direction in which each criterion is applied. This flexibility has important implications whereby the tool can be adjusted to suit various mobility solutions. In the case of Barcelona, we considered a city centre hub, but if a potential user would like to consider a suburban hub, they could adjust the weights accordingly. The tool can be used with either a demand approach, which responds to and enhances current needs, or a desirability approach, which induces changes. Most importantly, the tool can consider the wishes and concerns of different stakeholders. For instance, if the administration's policy objectives change, the criteria's weights or direction of application can reflect this. Alternatively, weights can respond to various urban

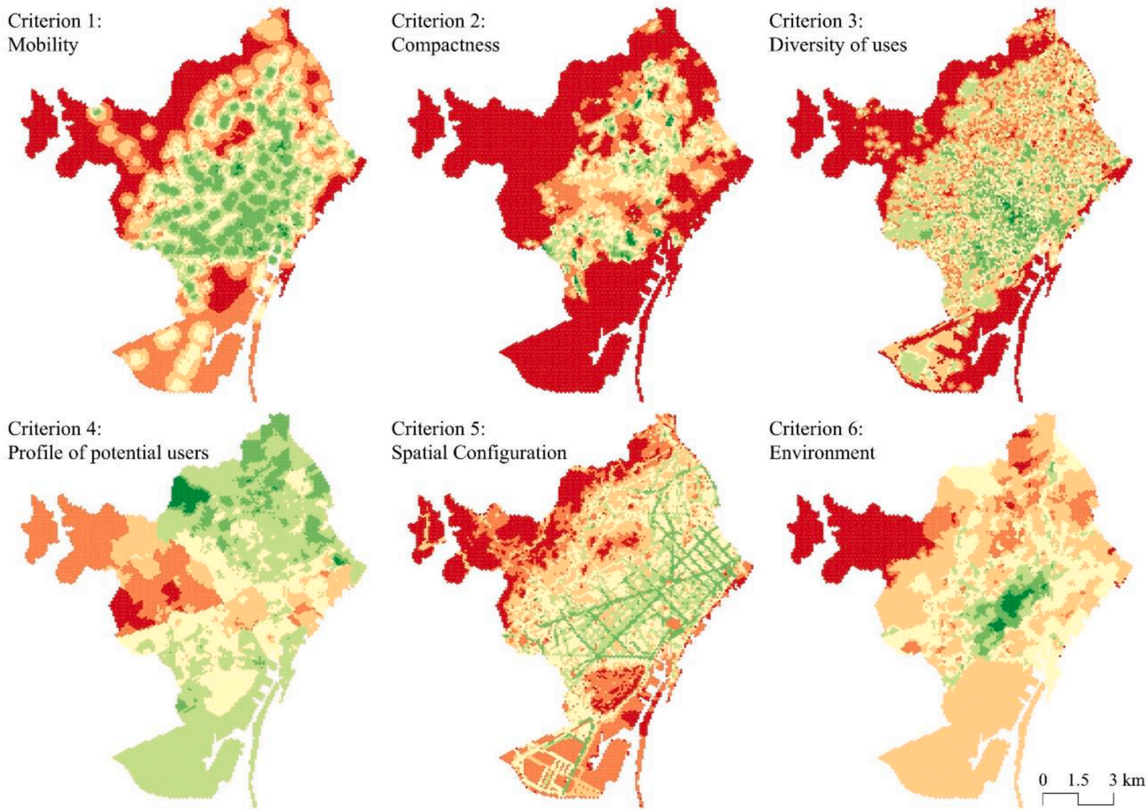

Fig. 5. Six resulting heat maps after merging the twenty-one indicators from Fig. 2 using the calculated weights from Table 1.

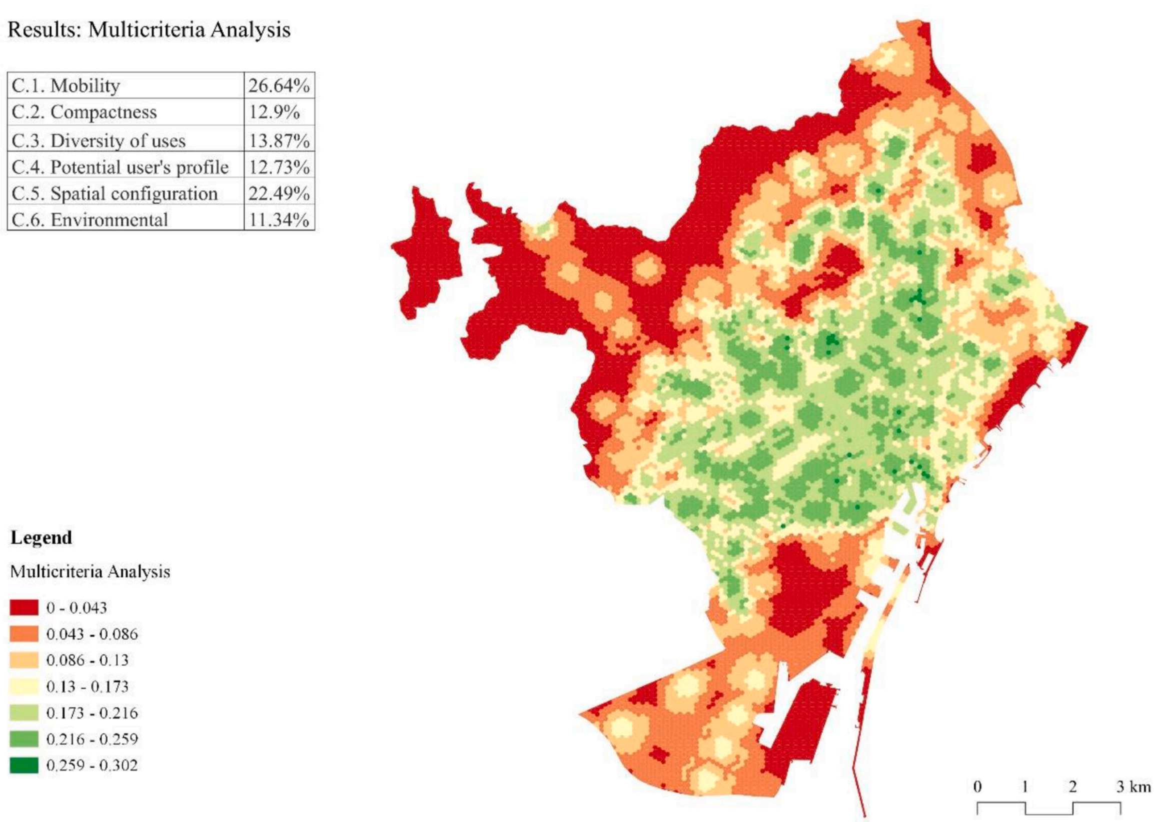

Fig. 6. Final heat map showing the desirability of a shared mobility hub location in the municipality of Barcelona according to the calculated weights.

development scenarios, as demonstrated in Melkonyan et al.'s (2022) study.

Last but not least, this paper addresses the difficulty of applying a decision support tool developed following academic research to a real case with the available open-source data. As shown in the *Results* section, it was possible to apply it to the city of Barcelona, but there were difficulties in trying to work simultaneously with more than one municipality in the metropolitan area due to the lack of data. In Barcelona, the results show the impact of the weights on the final heat map, as well as the importance of how we converted the available data into a homogeneous base map, in our case a hexagonal grid. The resulting heat maps give an idea of how differently the spatial distribution of the data defines the city. The *M2MHub* tool clearly supports the desirable location of shared mobility hubs in Barcelona.

Our research encountered several challenges, with the main one being the difficulty in obtaining the necessary data for each indicator. This type of data is generally dependent on municipalities' databases. Moreover, the units of measurement of each indicator (neighbourhoods, statistical areas, mobility areas, isochrones, etc.) must be homogenised to be combined and produce the final heat map. The process of collecting and manipulating the data to make it available for the analysis can also be challenging, as it requires both data availability and basic knowledge of QGIS. However, once the data is prepared, the *M2MHub* tool allows for convenient adjustment of criteria and sub-criteria weights.

6. Conclusions

This paper presents the conceptualisation of the *M2MHub* tool, which can promote the implementation of shared mobility hubs in European metropolitan areas as part of SUMPs and S-MaaS. The *M2MHub* tool enables the replication of presented methods in European cities through open access.[1] Shared mobility hubs are a cornerstone in the transition towards sustainable urban mobility based on seamless intermodality at a metropolitan scale (Pekdemir et al., 2024; Zhu et al., 2024). They also serve as social spaces that can enhance the livability of our cities as territorial nodes of connectivity (Roukouni et al., 2023). The 23 indicators selected based on the input of six European cities of different scale and characteristics, are a valuable contribution to the application of the new MCDA and GIS method. These maps can be used as a crucial data mapping instrument for metropolitan stakeholders and complement recent contributions (Melkonyan et al., 2022; Silva et al., 2022). The results presented for the city of Barcelona are a demonstration that the methodology and the *M2MHub* tool are appropriate elements to support the decision on the location of future shared mobility hubs as urban places and mobility nodes in Europe.

CRediT authorship contribution statement

Inés Aquilué Junyent: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Miquel Martí Casanovas:** Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Anastasia Roukouni:** Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Joan Moreno Sanz:** Writing – review & editing, Project administration, Funding acquisition. **Estanislao Roca Blanch:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition. **Gonçalo Homem de Almeida Correia:** Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Inés Aquilué Junyent reports financial support was provided by EIT Urban Mobility. Inés Aquilué Junyent reports a relationship with CARNET Barcelona - Future Mobility Research Hub that includes: employment. The research presented here is part of the SmartHubs project (2020–2022), co-funded by the EIT Urban Mobility. Grant Agreement: GA2021 EIT UM (KAVA Id 21062). We would like to thank all the municipal institutions that were interviewed and provided information and valuable data from their metropolitan and urban areas: City of Amsterdam, Metropolitan Area of Barcelona (AMB), City of Eindhoven, City of Helmond, Metropolitan Transport of Lisbon (TML), Empresa de Mobilidade e Estacionamiento de Lisboa (EMEL) and Mobilne Miasto (Warsaw). If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data can be made available on request.

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