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The determinant conditions and causal mechanisms that explain the use of micromobility services

Las condiciones determinantes y mecanismos causales que explican el uso de los servicios de micromovilidad

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ABSTRACT

Mobility as a Service (MaaS) is presented as a possible solution to the sustainability challenges posed by the concentration of population in cities. Despite the wide range of services that it incorporates and the fact that its adoption is associated with numerous benefits, its rate of use remains low. Therefore, the aim of our research is to identify the factors which explain the use of micromobility services. Since the adoption of mobility is a complex phenomenon whose explanation involves conditions at different levels, a model based on a multilevel perspective is applied to a sample of 48 cities in different parts of the world. The application of Qualitative Comparative Analysis and Necessary Conditions Analysis shows that there are no necessary conditions in kind for the use of micromobility services, although there are necessary conditions in degree. Likewise, the different combinations of conditions that explain the use, and denial, of the micromobility services are identified. The role played by satisfaction with public transport and the perception that traffic congestion is not a problem stand out in explaining the use, or denial, of micromobility services. There is a causal mechanism that shows how certain conditions trigger the use of micromobility services. MaaS operators should take advantage of existing synergies with different services in the mobility regime to try to encourage the adoption of their applications.

Keywords: Micromobility, MaaS, QCA, NCA, SMMR.

RESUMEN

Mobility as a Service (MaaS) se presenta como una posible solución a los retos que supone la concentración de la población en las ciudades para la sostenibilidad. Pese al amplio abanico de servicios que incorpora y a que a su adopción se le vincula numerosos beneficios, su tasa de uso se mantiene baja. Por ello, el presente trabajo responde al objetivo de identificar los factores que explican el uso de los servicios de micromovilidad. Puesto que la adopción de la movilidad es un fenómeno complejo en cuya explicación intervienen condiciones a diferente nivel se aplica un modelo basado en la perspectiva multinivel a una muestra compuesta por 48 ciudades de diferentes zonas del mundo. La aplicación de *Qualitative Comparative Analysis* y de *Necessary Conditions Analysis* constata la inexistencia de condiciones necesarias *in kind* para el uso de los servicios de movilidad, si bien existen condiciones necesarias *in degree*. Asimismo, se identifican las diferentes combinaciones de condiciones que explican el uso, y negación, de los servicios de micromovilidad. El papel jugado por la satisfacción con el transporte público y la percepción de que la congestión del tráfico no sea un problema destacan en la explicación del uso, o negación, de la micromovilidad. Existe un mecanismo causal que muestra cómo determinadas condiciones disparan el uso de los servicios de micromovilidad. Los operadores de MaaS deben aprovechar las sinergias existentes con diferentes servicios existentes en el regime de movilidad para tratar de favorecer la adopción de sus aplicaciones.

Palabras clave: Micromovilidad, MaaS, QCA, NCA, SMMR.

1. INTRODUCTION

The process of population concentration in cities that we are witnessing implies an increase in the flow of mobility which leads to greater pollution and traffic congestion (Gonzalez *et al.*, 2021; Lee *et al.*, 2022; Matyas & Kamargianni, 2021). Simultaneously, however, accelerating digitization offers opportunities to change mobility from both the supply and demand sides (Lopez-Carreiro *et al.*, 2021b), shaping the future of urban mobility and creating new business models around it (Kajikci & Kabadurmus, 2022). First, they reshape transportation supply with the introduction of new mobility solutions and services (Alisoltani *et al.*, 2021; Matyas & Kamargianni, 2021). Second, the ubiquitous availability of digital technologies enables individuals to acquire real-time information about the mobility system to decide when, where or how to travel (Jang *et al.*, 2022). This causes mobility —a complex urban system with multiple interactions— to play a critical role within the response of cities to the challenges that they face by betting on sustainable mobility (Göddeke *et al.*, 2022; Medina-Molina *et al.*, 2022b; Medina-Molina & Rey-Tienda, 2022). The key to the success of this sustainable mobility will be the optimization of new urban mobility services by combining them with traditional modes (Ding *et al.*, 2023; Erhardt *et al.*, 2022; Matyas & Kamargianni, 2021; Ogata *et al.*, 2022; Van den Berg *et al.*, 2022).

MaaS integrates different mobility options into an on-demand service accessible through a single digital interface that enables seamless, door-to-door, personalized mobility (Alyavina *et al.*, 2020; Jang *et al.*, 2022; Kim *et al.*, 2021; Van den Berg *et al.*, 2022). There are multiple advantages associated with the implementation of MaaS (Erhardt *et al.*, 2019; Hensher *et al.*, 2021; López-Carreiro *et al.*, 2021ab): promoting sustainable mobility; reducing traffic congestion; decreasing private vehicle ownership and use; and, facilitating the adoption of mobility alternatives that complement traditional systems and maximize their advantages. However, contrary to the opinion of those who affirm that MaaS can contribute to the social, environmental and economic improvement of the communities it serves (López-Carreiro *et al.*, 2020), the facts show that MaaS solutions are still underdeveloped and there is uncertainty regarding its social implications (Mladenović & Haavisto, 2021). In this way, there are doubts regarding such an optimistic view of MaaS since citizens may be attached to having private vehicles and the use of MaaS could replace public transport trips (Alyavina *et al.*, 2020; López-Carreiro *et al.*, 2021b), mainly because private vehicle owners are reluctant to change their mobility habits (Kajikci & Kabadurmus, 2022). Thus, MaaS penetration could lead to unsustainable commuting and increased vehicle crowding on public roads (Alyavina *et al.*, 2020; Jang *et al.*, 2022), as well as adding traffic that otherwise would not have occurred since it replaces walking or cycling (Erhardt *et al.*, 2019).

Although it is assumed that MaaS will significantly change mobility patterns, it is not clear how the use of the mobility services that make up its offer will affect its adoption, and analyses are needed to explain this (Elmashhara *et al.*, 2022; López-Carreiro *et al.*, 2021a). In fact, it has been raised how the development of MaaS can only take place in cities with a solid public transport system and a growing and diverse offer of shared mobility (Arias-Molinares & García-Palomares, 2020). Added to this is the relevance that the characteristics of the cities themselves have in explaining this phenomenon, since the economic, social, environmental and local characteristics of a city are linked to its desire to integrate sustainable perspectives and practices that help it evolve toward a sustainable approach (García de Leaniz & Castro-González, 2023), calling for a holistic approach in studies linked to sustainability (Lunde, 2018). Therefore, the research question answered by the present work is, what factors explain the use of micromobility services integrated in MaaS platforms? One of the key aspects in the MaaS implementation strategy is the mode mix involved, as it could either improve or deteriorate sustainability (Jang *et al.*, 2022; Lee *et al.*, 2022; López-Carreiro *et al.*, 2021b). Since the introduction of MaaS is assumed to reduce private vehicle use (Gonzalez *et al.*, 2021; Smith *et al.*, 2022), a key question is whether the implementation of MaaS will succeed in replacing the private vehicle and support active modes of travel and public transport (Alyavina *et al.*, 2020; Ogata *et al.*, 2022; Ye *et al.*, 2022) that it integrates into its offer. Therefore, the research gap to which the first objective of this paper responds is to identify the way in which the perception of the different operators of the mobility regime explains the use of the micromobility services. It is necessary to implement transformational actions at the local level, reconciling economic, environmental and social needs and expectations to embrace a sustainable perspective (Carrizo-Moreira *et al.*, 2023). While the diffusion and adoption of innovations has been widely studied, the explanation of the mechanisms that determine their success has hardly received attention (Medina-Molina & Pérez-Macías, 2022; Tiberius *et al.*, 2021), resulting necessary to develop research that considers the diffusion of innovations as a process in which the underlying mechanisms play a determining role (Bui, 2015; Lee *et al.*, 2020; Van Oorschot *et al.*, 2018). Especially those mechanisms linked to sustainable urban transport, since they allow learning from past experiences and adapting to the environment can be determinant for the achievement of sustainability (Hizam *et al.*, 2021; Villegas Pinuer *et al.*, 2022). Thus, the research gap to which the second objective response is to identify the causal mechanisms that explain the use of micromobility services.

In order to answer the above research gaps, this paper is based on a sample of 48 cities included in both the Smart City Index 2021 (Institute for Management Development, 2022) and the Global Public Transport Index 2020 (Moovit, 2022). In this sample, a model is applied that, through the Multi-Level Perspective (MLP), analyzes the way in which the conditions located in its different levels (landscape and regime) explain the emergence of a niche innovation (the use of micromobility services). Since the use of qualitative methods is recommended to study the use of shared micromobility services (Elmashhara *et al.*, 2022), Qualitative Comparative Analysis (QCA) will be employed, supported by Necessary Conditions Analysis (NCA) (Fainshmidt *et al.*, 2020; Richter *et al.*, 2020).

2. THE ADOPTION OF INNOVATIONS FROM A MULTI-LEVEL PERSPECTIVE

Classical models explaining the development of innovations are criticized in two major ways. The first is that they hardly pay attention to the relevance of the interaction and interdependence between the resources that intervene and determine their outcome (Bui, 2015; Gruber, 2020; Tiberius *et al.*, 2021). Innovation is not an isolated process but the result of complex relationships between actors and entities that work together to enable the development of socio-economic and technological innovations; the innovative ecosystem is at the core of the evolution of innovation by involving multiple actors and entities that need to interrelate (Carrizo-Moreira, 2021). The second idea is not to keep in mind the alteration of the social structure, context or regime in which it occurs without attending to its potential to contribute to the transition of the socio-technical system in which it operates (Bui, 2015; Lee *et al.*, 2020). This means that the classical models explaining the diffusion of innovations are not applicable to increasingly dynamic, nonlinear, systematic and unpredictable environments (Nenonen & Storbacka, 2021).

Therefore, a shift is proposed from the view of innovation as a noun (in which the idea is developed and implemented through a diffusion process), to seeing an innovation as a verb (a journey during which actors react to the need in different ways, influencing the outcome) (Nenonen & Storbacka, 2021). Conceiving the diffusion of innovations as a process of co-construction of the market and its environment allows overcoming three underdeveloped dimensions in adoption models: diffusion includes more actors than users/adopters; the characteristics of users and environments are articulated during the diffusion process; and, it claims the need to focus on human and technical interactions that shape socio-technical systems (Avila-Robinson *et al.*, 2022; Lee *et al.*, 2020; Werner *et al.*, 2022). Thus, the implementation of an innovation requires the establishment of a socio-technical system, which involves social and technological changes (Gruber, 2020).

The socio-technical approach to transitions conceptualizes transportation systems as configurations of multiple elements called socio-technical systems, and the main changes in them are known as socio-technical transitions (STT). Such transitions are considered co-evolutionary processes that require decades to unfold and involve numerous actors and social groups (Geels, 2012). Consequently, tools are required to provide an understanding of such processes as STT`s, a systematic co-evolutionary process based on the interrelationships between social, economic and technical fields that arise when changing from one system to another, considering the context as a dynamic force that exerts pressure (Geels, 2018). Sustainable transitions are a growing field of analysis which allows a quick answer to the wicked problems facing in today's societies (Keller *et al.*, 2022).

To understand innovative processes, such as transitions within socio-technical systems, the MLP is applied (Nenonen & Storbacka, 2021). Understanding large-scale transitions to new transportation systems requires analytical frameworks that encompass multiple approaches to cover the interactions between them, such as MLP (Geels, 2012). MLP is a heuristic tool or middle-range theory used to conceptualize the dynamic patterns that take place during socio-technical transitions. These processes generate fundamental changes in socio-technical systems consisting of different elements (such as markets, infrastructures, technologies, regulations and user practices) that interact and cover social needs such as transport (Keller *et al.*, 2022).

This MLP analyzes transitions through three analytical levels (macro level/landscape, meso level/regime and micro level/niche) which accommodate either radical changes (through the niche), dynamic stability (through regimes), or broader influences (through the landscape) (Geels, 2020). The MLP conceptualizes sustainable transitions as a shift from a dominant socio-technical regime to a new one (Svennevik, 2022). The basic tenet of the MLP is that transitions to sustainable systems (innovations) are nonlinear processes whose success is not based on their intrinsic robustness but on the interaction of their three analytical levels (Geels, 2012; Keller *et al.*, 2022; Medina-Molina *et al.*, 2022b). Such levels refer to configurations of increasing stability that can be seen as a nested hierarchy with regimes embedded in landscapes and niches existing within or outside of regimes (Geels, 2012).

3. METHODOLOGY

3.1. Theoretical model to be verified

According to the MLP, urban mobility is composed of multiple regimes among which the automobile has a dominant position, doubting whether new types of vehicles acting as a niche will manage to destabilize this system and threaten its position. While niche-level developments may be the beginning of a transition, the inertia and stability of the existing regime —such as the preeminence of the automobile regime— may cause such developments to remain niche or even disappear (Hensher *et al.*, 2021; Hirschhorn *et al.*, 2019; Lyons *et al.*, 2020). Stimulating a shift toward collective modes of transport is often in conflict with the private vehicle model, which is protected by a dominant regime within the prevailing socio-technical system that has shaped consumer preferences (Sareen *et al.*, 2021). MaaS is seen as having the potential to promote a transition from the current private car regime to a more sustainable post-car system (López-Carreiro *et al.*, 2020). Nevertheless, it is not clear whether micromobility will be sufficient to generate a transition toward sustainable mobility from a regime dominated by private vehicles. It must interact with other actors in the regime and seek synergies with classical mobility alternatives (Hirschhorn *et al.*, 2019).

The theoretical model under investigation is based on the MLP to explain the use of micromobility services integrated in MaaS through its three analytical levels. At the landscape level, it is analyzed that traffic congestion in the city is not considered a problem. At the regime level, we analyze the satisfaction with public transport, the positive perception of car sharing and bike rental apps to reduce congestion, and the information provision apps, both those that direct to available parking spaces and the information provided by the authorities on traffic congestion. At the niche level, the use of micromobility services integrated in MaaS is considered. MLP has been widely used to analyze the behavior of MaaS operators at a niche level (Arias-Molinares & García-Palomares, 2020; Medina-Molina *et al.*, 2022a; Mladenović & Haavisto, 2021). Therefore, we analyze how landscape (traffic congestion) and regime characteristics (perceptions of public transport, car sharing, bike rental and information apps) explain the use of micromobility services.

3.2. Justification of the propositions

Traffic congestion is one of the main problems for many cities due to its adverse impact on the environment and quality of life (Rahman *et al.*, 2022), becoming one of the main challenges for urban mobility systems (Hong *et al.*, 2023). Traffic congestion particularly affects urban public transport systems because of its effect on travel time, service regularity and costs (Garrido-Valenzuela *et al.*, 2022; Romero *et al.*, 2022). However, there is controversy regarding the impact of the implementation of MaaS solutions on traffic congestion in cities, claiming both that MaaS companies are major contributors to traffic congestion (Erhardt *et al.*, 2019) and that they can reduce traffic congestion in the face of high demand (Alisoltani *et al.*, 2021).

Urban public transport travel is critical for sustainable mobility by alleviating congestion and emissions (Romero *et al.*, 2022; Rong *et al.*, 2022). It requires increasing user satisfaction and attracting users from other modes (Rong *et al.*, 2022). In this sense, micromobility systems feed the use of public transport by solving the first and last mile problem (Chicco & Diana, 2022; Hong *et al.*, 2023; Liu *et al.*, 2022); reducing travel time as a result of their integrated use (Kim *et al.*, 2021); or increasing their coverage (Liu *et al.*, 2022; Zuniga-Garcia *et al.*, 2022). Yet, on other occasions it is established that micromobility services are not related to the number of public transport users since their trips have an intrazonal character rather than for the first and last mile (Zuniga-Garcia *et al.*, 2022), or that they alleviate the overcrowding of public transport (Chicco & Diana, 2022).

There is no agreement on the relationship between new modes of urban shared mobility and the mobility ecosystem. Thus, it is argued that when shared mobility enters a market, public transport will be the mode of transport replaced to a greater extent (Erhardt *et al.*, 2022; Ye *et al.*, 2022). From an opposing argumentation, it is claimed that carpoolers walk, cycle or use public transport to a greater extent (Göddeke *et al.*, 2022). Several papers propose a positive relationship with public transport, indicating that the introduction of car sharing discourages private car ownership and solves the first and last mile problem (Li *et al.*, 2022; Ogata *et al.*, 2022; Ziedan *et al.*, 2021). Public transport users show positive attitudes toward the adoption of MaaS, considering on-demand services as complementary to public transport (Lopez-Carreiro *et al.*, 2021a). Therefore, car sharing will support the development of sustainable mobility systems if introduced together with a good public transport system (Li *et al.*, 2022; Ogata *et al.*, 2022).

For users with private vehicles, the difficulty of finding parking is among the explanations for the use of micromobility services (Li *et al.*, 2022; Medina-Molina *et al.*, 2022a; Smith *et al.*, 2022). Urban policies linked to parking development are effective in reducing traffic congestion and supporting sustainable mobility (Gonzalez *et al.*, 2021). Among the solutions to avoid traffic congestion are apps with parking information from which to use micromobility services to travel to the destination. However, parking app operators should ensure the accuracy of the information and incorporate features that increase its attractiveness (Hong *et al.*, 2023).

Numerous cities implement bicycle rental programs because of the benefits that they generate (economical and healthy option, increased connectivity and flexibility, reduced emissions, consumption and congestion) (Castiglioni *et al.*, 2022; Godavarthy *et al.*, 2022; Zhang *et al.*, 2022). While convenience is the main motivator for bike sharing, the distance from bike parking to the final destination is its main deterrent (Hong *et al.*, 2023). Despite the fact that bike sharing replaces other modes of transportation (Erhardt *et al.*, 2022; Sareen *et al.*, 2021; Zhang *et al.*, 2022), it can extend the reach of public transport services by improving their accessibility and reducing problems linked to the first and last mile (Godavarthy *et al.*, 2022; Zhang *et al.*, 2022).

Persuasive actions via apps are a strategy to achieve the abandonment of traditional motorized vehicles and stimulate the use of more sustainable modes of transport (Das Reis *et al.*, 2022). MaaS would benefit from offering information on mass transport, pollution levels, route options and urban safety (López-Carreiro *et al.*, 2020). Since citizens who opt for multimodal transport consult various apps, the integration of public transport and micromobility is crucial (Romero *et al.*, 2022; Ye *et al.*, 2021; Zuniga-Garcia *et al.*, 2022). The integration of different transport modes in an app will reduce traffic congestion and the need for parking. Ubiquitous real-time information enables public transport users to make better choices before and during the route (Romero *et al.*, 2022; Rong *et al.*, 2022).

MaaS uptake has complementarities with public transport and shared mobility services (Alyavina *et al.*, 2020; López-Carreiro *et al.*, 2021a) as MaaS adopters are often public transport users (Jang *et al.*, 2022). MaaS can reinforce the passenger experience and strengthen a shift from private vehicles to sustainable public transport systems (Kim *et al.*, 2021). Having ascertained the doubts regarding the way in which both landscape pressures and the different agents operating in the mobility regime are interrelated and can determine the use of MaaS-integrated services, the following propositions are put forward.

— Proposition 1a. The landscape and regime conditions are related to explain the use of micromobility services.
— Proposition 1b. The landscape and regime conditions are related to explain the denial of the use of micromobility services.
— Proposition 2a. The landscape and regime conditions are related to cause the use of micromobility services.
— Proposition 2b. The landscape and regime conditions are related to cause the denial of the use of micromobility services.

3.3. Set Theoretic Multi-Method Research.

QCA has been used to analyze the use of micromobility services according to the MLP because of its ability to explain causal complexity based on asymmetry, equifinality and conjunctural causation. According to asymmetry the presence or denial of an outcome requires different explanations. Equifinality implies that different combinations of conditions can explain the presence of a phenomenon. Conjunctural causation reflects the relevance of the combination of conditions, rather than their isolated effect. Likewise, QCA shows the necessary and sufficient conditions for the presence of an outcome, or its negation.

QCA is an asymmetric modeling with high explanatory and predictive power for the analysis of relationships between different conditions and outcomes (Kumar *et al.*, 2022; Van Nguyen *et al.*, 2023). QCA combines elements of qualitative and quantitative analysis techniques, and allows relationships to be identified through a process of logical minimization that describe several combinations of conditions to explain a specific result (Pappas & Woodside, 2021). QCA shows great benefits compared to variance-based methods. While the latter examine variables under a competitive approach that aims to isolate the net effect between the variables included in a model, QCA focuses on the combinations of conditions which explain the presence of an interesting outcome (Van Nguyen *et al.*, 2023). Likewise, QCA allows working with small samples (less than 50 cases), which makes it possible to return to the cases once the analysis has been carried out (Pappas & Woodside, 2021). Among the limitations of QCA stands out the complexity of the interpretation on the results, especially when it involves a large number of causal conditions, as well as the sensitivity of the data calibration process (Van Nguyen *et al.*, 2023).

NCA complements QCA by identifying the degree of a necessary condition that must be satisfied to reach a certain level of an outcome (Bergh *et al.*, 2022; Richter *et al.*, 2020; Sukhiv *et al.*, 2022). Finally, for the identification of causal mechanisms, Set Theoretic Multi-Method Research (SMMR) will be applied in which QCA cross-case analysis is complemented by within-case analysis via process-tracing (Medina-Molina & Pérez-Macías, 2022; Oana & Schneider, 2018). Process-tracing studies are based on in-depth qualitative studies that seek to identify and explain potential causal patterns (Hedström & Wennberg, 2017).

3.4. Data

Initially, 48 cities were selected from the Smart City Index 2021 (Institute for Management Development, 2022), which includes different areas of the smart city, among which those presented in Table 1 were selected. Since this index does not present the use of micromobility services offered by MaaS, data from the Global Public Transport Index 2020 (Moovit, 2022) were used. The Smart City Index evaluates the smartness of cities around the planet. The values of the 100 cities are not used since the outcome under analysis is taken from the Moovit Global Public Transport Index. For this reason, a sample of the 48 cities included in both indices was selected. Among these 48 cities are 23 of the 60 largest ones in the world, cities which differ in their response to the great challenges of mobility (Oliver Wyman Forum, 2022). The 48 cases exceed the minimum of 36 that Mello (2021) suggest for a QCA model with 6 conditions.

Table 1
Conditions and source

Acronym	Description	Source
USE	Frequent use of micromobility	Global Public Transportation Index 2020
STCON	Traffic congestion is not an issue	Smart City Index 2021
STSAT	Public transportation is satisfactory	
TECON	Car-sharing apps have reduced congestion	
TEJOU	Apps that direct you to an available parking space have reduced commute times	
TEBIK	Bicycle rental has reduced congestion	
TEINF	The city provides information on traffic congestion through cell phones	

Source: Own elaboration.

4. ANALYSIS

4.1. Analysis of the necessary conditions

Prior to the analysis, the data were calibrated, using the 90th and 10th percentiles for total inclusion or exclusion and the mean for the point of maximum ambiguity.

As a first step in the QCA analysis, the necessary conditions for USE and its negation (~USE) were analyzed, not reaching the required levels to be able to affirm the existence of necessary conditions in mode.

Table 2
Analysis of the necessary conditions (QCA)

	USE			~USE		
	Cons.Nec	**Cov.Nec**	**RoN**	**Cons.Nec**	**Cov.Nec**	**RoN**
STCON	0.498	0.504	0.723	0.611	0.784	0.857
STSAT	0.584	0.458	0.591	0.742	0.739	0.750
TECON	0.556	0.572	0.758	0.518	0.677	0.805
TEJOU	0.588	0.572	0.738	0.565	0.697	0.799
TEBIK	0.672	0.547	0.651	0.638	0.658	0.712
TEINF	0.621	0.603	0.751	0.530	0.653	0.775
~STCON	0.787	0.615	0.667	0.613	0.608	0.663
~STSAT	0.668	0.672	0.796	0.456	0.581	0.754
~TECON	0.687	0.529	0.614	0.673	0.658	0.686
~TEJOU	0.689	0.555	0.651	0.653	0.667	0.714
~TEBIK	0.580	0.558	0.728	0.561	0.685	0.789
~TEINF	0.642	0.519	0.634	0.677	0.694	0.731

Cons.Nec = Consistency for necessity
Cov.Nec = Coverage for necessity
RoN = Relevance of necessity
Source: Own elaboration.

To verify the existence of necessary conditions in degree, NCA (Dul, 2016) was applied. Thus, if the relationship is established according to "a high level of X is necessary for a high level of Y" (corner 1), TECON is necessary. In the case of the relationship "a low level of X is necessary for a high level of Y" (corner 2), STCON and STSAT are necessary.

Table 3
Analysis of the necessary conditions (NCA)

	d	p	c-accuracy	Abs. ineff.	Rel. ineff.
Corner 1					
TECON	0.182	0.046	77.3%	0.624	63.625
Corner 2					
STCON	0.168	0.049	97.7%	0.643	66.319
STSAT	0.127	0.020	90.9%	0.723	74.516

d = effect size
p = probability
Source: Own elaboration.

As can be seen in the table above (Table 3), based on effect size (d) in all cases it is a medium effect (0.1 ≤ d < 0.3). Since they exceed the minimum effect size of 0.1 and present a $p < 0.05$, we consider TECON, STCON and STSAT to be necessary conditions in degree for USE. However, TECON is far from the 95% threshold recommended for c-accuracy (Dul, 2016; Lee & Dul, 2023).

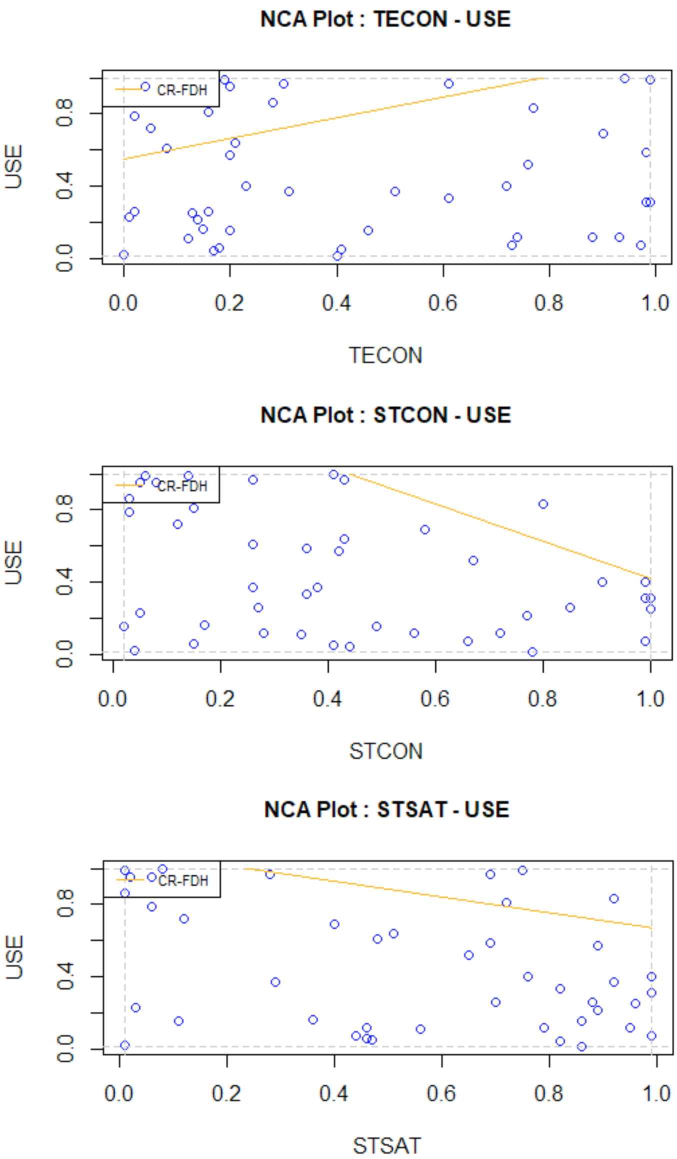

Figure 1
Ceiling lines
Source: Own elaboration.

In the figure above, we can see the ceiling line of the conditions that are necessary in degree. The first one, TECON in corner 1, and STCON and STSAT in corner 2. Since the conditions are measured through metric scales, ceiling regression–free disposal hull (cr_fdh) was chosen to obtain the ceiling line.

Table 4 shows that if we want to achieve high values of USE, TECON must also show high values. On the other hand, the values that STCON and STSAT must reach to prevent USE from doing so are very high. Thus, the necessary conditions in degree are only necessary in case we want to obtain high USE results.

Table 4
Analysis of the bottlenecks (NCA)

Y	TECON	STCON	STSAT
0	NN	NN	NN
10	NN	NN	NN
20	NN	NN	NN
30	NN	NN	NN
40	NN	NN	NN
50	NN	91.4	NN
60	9.7	81.7	NN
70	27.2	71.9	93.0
80	44.8	62.2	69.6
90	62.4	52.5	46.2
100	79.9	42.8	22.7

Source: Own elaboration.

4.2. Analysis of the sufficient conditions

To identify the sufficient conditions, the truth table was created requiring a consistency of 0.8 and with a number of required cases (n.cut) of 1. Four cases were eliminated for which any calibrated condition had a membership of 0.5 (the point of maximum ambiguity). The parsimonious solution was chosen.

In the case of USE, the solution is: ~STSAT*TEINF + ~STCON*~STSAT*TEJOU + ~STCON*TEBIK*~TEINF + ~STCON*TEJOU*~TEBIK*TEINF -> USE

Table 5
Sufficient conditions for USE

	inclS	PRI	covS	covU	cases
~STSAT*TEINF	0.754	0.554	0.370	0.048	Istanbul; Bangkok, Buenos Aires; Los Angeles; New York
~STCON* ~STSAT*TEJOU	0.766	0.539	0.331	0.020	Sao Paulo; Istanbul; San Francisco; Bangkok, Buenos Aires
~STCON*TEBIK* ~TEINF	0.779	0.530	0.396	0.139	Santiago; Montreal, Lyon; Lille
~STCON*TEJOU* ~TEBIK*TEINF	0.911	0.728	0.263	0.027	Hong Kong; Kuala Lumpur
Model	0.722	0.534	0.593		

inclS=consistency for sufficiency.
PRI=proportional reduction of inconsistency.
covS=coverage for sufficiency
covU=unique coverage
Source: Own elaboration.

As can be seen (Table 5), USE is explained by 4 conjunctions. The first two are simplified as ~STSAT (TEINF +~STCON*TEJOU). In them, ~STSAT is joined in the first case with TEINF (inclS = 0.754; PRI = 0.554; covS = 0.370) and in the second with ~STCON*TEJOU (inclS = 0.766; PRI = 0.539; covS = 0.331).

The third and fourth conjunctions can be presented as ~STCON (TEBIK*~TEINF+TEJOU*~TEBIK*TEINF). In the first case ~STCON is joined with TEBIK*~TEINF (inclS = 0.779; PRI = 0.530; covS = 0.396), in the second with TEJOU*~TEBIK*TEINF (inclS = 0.911; PRI = 0.728; covS = 0.263). Except for the third conjunction, which has a covU = 0.139, the remaining conjunctions have low covU due to the overlaps between them.

In the explanation of ~USE, there is ambiguity in the model, and model 1 is chosen. Thus, the solution is STCON + STSAT + ~TECON*TEJOU + TECON*~TEBIK -> ~USE

In the first term, we find two formulas composed of a single conjunct STCON (inclS = 0.784; PRI = 0.648; covS = 0.611) and STSAT (inclS = 0.739; PRI = 0.621; covS = 0.742). The third and fourth conjunctions present ~TECON*TEJOU (inclS = 0.818; PRI = 0.582; covS = 0.303) and TECON*~TEBIK (inclS = 0.789; PRI = 0.532; covS = 0.275). Again, the conjunctions display overlaps reflected in the covU (Table 6).

Table 6
Sufficient conditions for ~USE

	inclS	**PRI**	**covS**	**covU**	**cases**
STCON	0.784	0.648	0.611	0.014	Chicago; Los Angeles; New York; Berlin, Munich; Bologna, Zaragoza, Bilbao; Ankara; Moscow; Washington DC, Medellin, Singapore, Dubai, Abu Dhabi
STSAT	0.739	0.621	0.742	0.078	Sydney; Montreal, Lyon; Barcelona, Paris, London, Bordeaux; St Petersburg; Hong Kong; Lille; Kuala Lumpur; Madrid, Jakarta; Berlin, Munich; Bologna, Zaragoza, Bilbao; Ankara; Moscow; Washington DC, Medellin, Singapore, Dubai, Abu Dhabi
~TECON*TEJOU	0.818	0.582	0.303	0.000	Sao Paulo; Istanbul; St Petersburg; Hong Kong
TECON*~TEBIK	0.789	0.532	0.275	0.000	San Francisco; Kuala Lumpur; Chicago; Los Angeles; Ankara
Model (sol 1)	0.799	0.585	0.704		

Source: Own elaboration.

4.3. Analysis of the existence of mechanisms

The identification of the mechanisms was performed by applying SMMR, which involves using QCA cross-case analysis followed by within-case analysis with process-tracing. The use of the Set Methods package of R allows a systematic selection of the cases to be used (for an explanation of the mechanisms and their selection see Medina-Molina and Pérez-Macías (2022)).

Table 7
Identification of typical cases

	FocalConj	**Outcome**	**CompConj**	**Term**	**UniqCov**	**Best**	**MostTypFC**	**Rank**
Term 3								
FC ~STCON								
Santiago	0.92	0.95	0.62	0.62	TRUE	0.44	FALSE	2
Montreal	0.85	0.81	0.71	0.71	TRUE	0.37	TRUE	2
FC TEBIK								
Montreal	0.71	0.81	0.83	0.71	TRUE	0.49	TRUE	1
Santiago	0.62	0.95	0.79	0.62	TRUE	1.04	FALSE	1
FC ~TEINF								
Santiago	0.79	0.95	0.62	0.62	TRUE	0.70	FALSE	2
Montreal	0.83	0.81	0.71	0.71	TRUE	0.33	TRUE	2
Term 4								
FC ~STCON								
Hong Kong	0.57	0.97	0.66	0.57	TRUE	1.23	FALSE	1
Kuala Lumpur	0.64	0.59	0.58	0.58	TRUE	0.52	TRUE	2

	FocalConj	Outcome	CompConj	Term	UniqCov	Best	MostTypFC	Rank
Term 4								
FC TEJOU								
Kuala Lumpur	0.58	0.59	0.64	0.58	TRUE	0.44	TRUE	1
Hong Kong	0.66	0.97	0.57	0.57	TRUE	1.05	FALSE	2
FC ~TEBIK								
Hong Kong	0.97	0.97	0.57	0.57	TRUE	0.43	TRUE	2
Kuala Lumpur	0.78	0.59	0.58	0.58	TRUE	0.80	FALSE	2
FC TEINF								
Hong Kong	0.85	0.97	0.57	0.57	TRUE	0.67	TRUE	2
Kuala Lumpur	0.78	0.59	0.58	0.58	TRUE	0.80	FALSE	2

Source: Own elaboration.

SMMR starts with the analysis of individual cases to identify typical cases. While for USE they exist in terms 3 and 4, they do not exist for ~USE. Therefore, the rest of the analysis focused on those terms. In Table 7, the typical cases existing for each Focal Conjunct (FC) of terms 3 and 4 of the USE solution are shown. For term 3 Santiago and Montreal; for term 4 Hong Kong and Kuala Lumpur. Although in some cases the attribution principle is not satisfied, all typical cases are uniquely covered.

Next, deviant consistency cases were identified that allow us to identify missing conjuncts, namely: ~STCON*~STSAT*TEJOU Istanbul (term membership = 0.66, outcome = 0.15), ~STCON*TEBIK*~TEINF Lille (term membership = 0.64, outcome = 0.33) and ~STSAT*TEINF Istanbul (term membership = 0.89, outcome = 0.15), all three cases being MostDevCons. Also, deviant coverage cases were identified, which allow determining missing conjunctions. The best ones are identified for the corresponding lines of the truth table: Bogota, Rio de Janeiro, Barcelona, and Medellin.

The SMMR comparative analysis was then performed, which enables verifying the properties of the mechanism.

As can be seen (Table 8), pairs of cases are identified that meet the required criteria for all CFs of terms 3 and 4 in the explanation of USE. Thus, it is possible to affirm the existence of a causal mechanism in such terms, which are indicated below. In term 3 FC ~STCON (Santiago-Zaragoza), FC TEBIK (Montreal-Rome) and FC ~TEINF (Santiago-Madrid). In term 4 are the following FC ~STCON (Hong Kong-Ankara), FC TEJOU (Kuala Lumpur-Sydney), FC ~TEBIK (Hong Kong-Madrid) and FC TEINF (Hong Kong-St Petersburg).

The comparison of two typical cases indicates whether the generalization of the mechanism to all typical cases is possible.

Again, pairs of cases are identified that meet the criteria that allow the mechanism to be generalized to all typical cases. In term 3, Montreal-Santiago is the pair for all the FC (~STCON, TEBIK, and ~TEINF). For term 4, the pair is Kuala Lumpur-Hong Kong for all the FC (~STCON, TEJOU, ~TEBIK, and TEINF).

The comparison of the typical and deviant consistency cases allows identifying omitted conjuncts. Resulting for the terms ~STSAT*TEINF and ~STCON*~STSAT*TEJOU Bangkok-Istanbul, and for the term, ~STCON*TEBIK*~TEINF Santiago-Lille. Finally, adjustments between deviant coverage-IIR cases were identified, corresponding to Bogota-Rome; Paris-London; Jakarta-Madrid; Medellin-Singapore. From this comparison, omitted conjunctions can be identified.

Table 8
Comparison typical cases-IIR

Typical	IIR	UniqCov	GlobUncov	Best	PairRank
Term 3					
FC~STCON					
Santiago	Zaragoza	TRUE	TRUE	1.02	2
FC TEBIK					
Montreal	Rome	TRUE	TRUE	0.85	1
FC ~TEINF					
Santiago	Madrid	TRUE	TRUE	1.04	2
Term 4					
FC ~STCON					
Hong Kong	Ankara	TRUE	TRUE	2.09	1
FC TEJOU					
Kuala Lumpur	Sydney	TRUE	TRUE	1.13	1
FC ~TEBIK					
Hong Kong	Madrid	TRUE	TRUE	0.45	2
FC TEINF					
Hong Kong	St Petersburg	TRUE	TRUE	0.51	2

Source: Own elaboration.

Table 9
Comparison of typical-typical cases

Typical1	Typical2	UniqCov1	UniqCov2	Best	PairRank
Term 3					
FC ~STCON					
Montreal	Santiago	TRUE	TRUE	1.44	4
FC TEBIK					
Montreal	Santiago	TRUE	TRUE	1.95	1
FC ~TEINF					
Montreal	Santiago	TRUE	TRUE	1.55	4
Term 4					
FC ~STCON					
Kuala Lumpur	Hong Kong	TRUE	TRUE	2.29	3
FC TEJOU					
Kuala Lumpur	Hong Kong	TRUE	TRUE	2.17	2
FC ~TEBIK					
Kuala Lumpur	Hong Kong	TRUE	TRUE	1.96	4
FC TEINF					
Kuala Lumpur	Hong Kong	TRUE	TRUE	2.08	4

Source: Own elaboration.

5. DISCUSSION OF THE RESULTS

The first research gap to which the work responds has been to identify the way in which the different operators in the mobility regime explain the use of micromobility services. First, the paper identifies three necessary conditions in degree that condition the use of micro-mobility services. The positive perception of the effect of car sharing apps, confirms how users' perception of them influences the use of MaaS (Lesteven & Godillon, 2020) and the driving role that car sharing can play in the adoption of MaaS. It is also verified that not considering traffic congestion as a problem is necessary for low levels of USE. This situation is replicated for satisfaction with the use of public transport. Such results show how satisfaction with public transport can become a deterrent to the use of micromobility services offered by MaaS (Rong *et al.*, 2022), with the relationship between MaaS and public transport being approached more as competition than as cooperation (Ye *et al.*, 2022).

This finding is relevant since previous works indicate that the development of MaaS could only happen in cities with a strong public transport system (Arias-Molinares & García-Palomares, 2020). The explanation for this situation can be found in the relationship between traffic congestion and public transport. In three of the recipes that explain USE, ~STCON appears a condition that suggests that traffic congestion is a problem for the cities under analysis. This situation, in line with previous works (Garrido-Valenzuela *et al.*, 2022; Romero *et al.*, 2022), particularly affects public transport. To finish with the relationship between the use of public transport and the use of MaaS services, it should be noted that it acts as a bottleneck only when faced with high values of the conditions and to avoid highs results.

When analyzing sufficient conditions for the use of micromobility services, the first two formulas agree that there is no satisfaction with public transport (~STSAT). Thus, it is reiterated that rather than cooperating with public transport, it seems that MaaS services come to replace them (Ye *et al.*, 2022; Zuniga-Garcia *et al.*, 2022). Such a condition must be presented together with the provision of information regarding the city's traffic congestion (TEINF), being the case of Istambul, Los Angeles or New York. Or else together with the denial of the perception that congestion is not a problem (~STCON) and that apps that direct to available parking spaces have reduced travel time (TEJOU). This situation is observed in cities like Sao Paulo, Istanbul or San Francisco. The overlaps between the solutions mean that Bangkok and Buenos Aires are explained by both conjunctions. In the first case, users value positively that the city provides information about traffic congestion (Das Reis *et al.*, 2022), a situation in which MaaS may provide a solution to congestion (Alisoltani *et al.*, 2021). Also, the explanation can be found in the fact that users of mobility services use them to travel from the parking lot to the destination (Hong *et al.*, 2023). Thus, these are ideal cities to implement urban policies linked to parking development (Gonzalez *et al.*, 2021). In the remaining two explanatory configurations of USE, denial that traffic congestion is not a problem (~STCON) in one of the cases is coupled with the perception that bicycle rental services have reduced congestion (TEBIK) and denial that the city provides information on traffic congestion via cell phone (~TEINF), explaining Santiago, Montreal, Lyon and Lille. In these cases, bike sharing may solve the first and last mile problems, possibly supported by the popularity achieved in recent years (Godavarthy *et al.*, 2022; Zhang *et al.*, 2022). In the last conjunction these two terms are reversed (~TEBIK*TEINF) along with the idea that apps directing to a parking lot have reduced travel times, explaining Hong-Kong and Kuala Lumpur. That the solution is not linked to satisfaction with public transportation reflects again a competitive relationship with MaaS. Since landscape and regime conditions are interrelated to explain the use of micromobility services we can accept *proposition 1a*.

To explain ~USE it is sufficient, firstly, that traffic congestion is not considered to be a problem (STCON) or that there is satisfaction with public transport (STSAT), explaining 15 and 25 cities respectively. Thus, it seems that these are cities where the use of public transport is not complemented by MaaS (Zuniga-Garcia *et al.*, 2022). These are joined by the denial that car sharing apps have reduced traffic congestion (~TECON) along with the perception that apps that direct to parking lots reduce travel time (TEJOU). This conjunction explains the situation of Sao Paulo, Istanbul, St Petersburg and Hong-Kong. In this case we find a negative user opinion of car sharing services, which may evolve as advances in mobility do (Lesteven & Godillon, 2020). Or else car sharing is considered to reduce traffic congestion (TECON) along with the denial that bicycle rental does so, explaining San Francisco, Kuala Lumpur, Chicago, Los Angeles or Ankara. Since landscape and regime conditions interrelate to explain the denial of the use of micromobility services we accept *proposition 1b*.

In the second research gap, the explanatory causal mechanisms of the use of micromobility services are analyzed. The existence of causal mechanisms linking the combinations of conditions with the outcome was then studied, so that the combinations of sufficient conditions exposed not only explain the presence of an outcome or its negation, but also trigger —cause— the presence of the outcome. It is possible to differentiate those conditions that act as a scope condition from those ones which help the existence of a causal relationship between the conditions and the result. To identify the mechanisms, process-tracing is helped by an in-depth analysis of the cases through the construction of a narrative under such constructions. For this reason, we will present in detail the different pairs of cases identified.

We start with the analysis of conjunction 3 (~STCON*TEBIK*~TEINF), analyzing each of the FCs. The first FC is ~STCON, for which the typical case is Santiago, a city that despite the extensive development of urban infrastructure and public transport, witnesses an increase in congestion (Garreton, 2017). The IIR case is Zaragoza, where the use of multimodal transport supported by information dissemination was proposed (Belanche *et al.*, 2016). The second FC is TEBIK. In Montreal walking and public transport are the main modes of transportation, and it was the starting point of a bike sharing service subsequently extended across Canada, presenting a high density of rental stations (Verma & Awasthi, 2020; Wu & Kim, 2020). Rome (IIR case) opted for a zero-impact strategy on individual travel through solutions favoring micromobility, contemplating actions aimed at the use of bicycles by supporting infrastructure for its fragmented network (Cerasoli *et al.*, 2022). Rome reinforced bike lanes as a response to the Covid-19 pandemic; there is a project for a bike lane around the city center (Castiglioni *et al.*, 2022). The last FC is ~TEINF. From the choice of Santiago, we can extract the low valuation it presents in that condition, much lower than that of the IIR case, Madrid, which has a multimodal offer of mobility modes integrated in apps (Gonzalez *et al.*, 2021).

The pairs of cases identified for term 4 (~STCON*TEJOU*~TEBIK*TEINF) are presented below. For the ~STCON conjunct, the typical case is Hong Kong a city where despite having an extensive urban subway network and connections between different transport modes (Li & Love, 2022), traffic congestion is considered a problem as reflected by its rating in the Smart City Index. The IIR is Ankara, a city that presents a better rating in the index despite having a bus-based public transport system, causing a decrease in its use and an increase in private and shared vehicles. In Ankara, the difficulties of the mobility system are concentrated in the city center, counting on green corridor initiatives (Kulińska & Dendera-Gruszka, 2019; Özkazanc & Sönmez, 2017). The second FC is TEJOU, the typical case of which is Kuala Lumpur, where private vehicles cover most of the trips generating concerns about traffic congestion (Hizam *et al.*, 2021; Zailani *et al.*, 2016). It has a good public transport infrastructure and integrated mobility system (Hizam *et al.*, 2021; Zailani *et al.*, 2016), which can be linked to TEJOU. Sydney, the IIR case, has a MaaS initiative that shows how an appropriate level of incentives would achieve a critical mass at which to change mobility behavior (Hensher *et al.*, 2021). In the FC ~TEBIK the typical case is Hong Kong, while Madrid is the IIR case. In recent years, Madrid has implemented mobility policies to reduce the use of private vehicles in the city center. Thus, shared mobility emerges strongly in Madrid, supported by parking policies (Ampudia-Renuncio *et al.*, 2020; Gonzalez *et al.*, 2021). The fourth FC is TEINF, whose typical case is Hong Kong and IIR St Petersburg. St Petersburg suffers from an underdeveloped transport infrastructure and a high concentration of commuting in the city center, proposing a multimodal transport system that integrates the elements used within its smart city strategy (Tokunova & Rajczyk, 2020).

In the comparative analysis, pairs of cases appear in all conjuncts of terms 3 and 4. Therefore, we confirm the existence of a causal mechanism in terms 3 (~STCON*TEBIK*~TEINF) and 4 (~STCON*TEJOU*~TEBIK*TEINF) in the explanation of USE. Through the comparative analysis, the possibility of extrapolating to all typical cases of terms 3 and 4 the existence of a causal mechanism is established. In contrast, there are no mechanisms that cause ~USE. Thus, for ~USE we can only explain the combinations of conditions that must be present for the outcome to occur, but not that such conditions cause the outcome. Thus, *proposition 2a* is accepted and *proposition 2b* cannot be accepted.

6. CONCLUSIONS AND CONTRIBUTIONS

6.1. Conclusions

This work has been developed to identify the factors that explain the use of micromobility services. For this purpose, a model has been established using the MLP through its different levels. According to the results, landscape and regime level characteristics are linked to explain the emergence of a niche level innovation. To explain the use of micromobility services, the joint presence of landscape and regime conditions is required in three of the four existing conjunctions. This situation is reversed for the negation of use, where it is only present in one of the conjunctions. In this way, while the study of use requires models that consider all the dimensions of LTM, in the denial of use the role played by the landscape is relativized and the role of conditions at the regime level is highlighted. This fact stand out the role played by the innovative ecosystem.

Since landscape and regime conditions condition the emergence of innovations, we have further analyzed how they are interrelated to explain USE and ~USE. First, some of these agents act as constraints on USE (the use of apps that provide information and satisfaction with public transport). Also, the fact that the agents of the analyzed regime (information apps and perception of the impact of shared vehicles) interrelate with the landscape highlights the suitability of MaaS operators to interact and seek synergies with such agents (Hirschhorn *et al.*, 2019).

Finally, we note the existence of two mechanisms that show how the contemplated conditions trigger USE. In contrast, there are no such mechanisms in the ~USE explanation. However, satisfaction with public transport does not appear among the causes that explain the use of micromobility services. In the first of the mechanisms, there appears a positive perception linked to bicycle rental services, while the second is the provision of information by the city or apps. Because of that, it seems that the approaches of Arias-Molinero & García-Palomares (2020) reinforce the role of a growing and diverse offer of services as an explanation of the use of micromobility.

6.2. Contribution and limitations

On a theoretical level, this paper shows the suitability of QCA to explain the adoption of innovations through the MLP because of its ability to respond to causal complexity. The relevance of the asymmetry is confirmed when USE and ~USE are explained by different combinations of conditions. Equifinality is appropriate because there are four possible combinations of conditions that explain the results under analysis. Conjunctural causation is derived from the analysis of the effect of the combination of conditions and is found when there are conditions and their negation whose effect differs according to the conditions that combine (see the way in which TEBIK and TEINF are combined in conjunctions 3 and 4 of the explanation of USE). Also, the relevance of NCA for refining the necessary conditions analysis is confirmed by presenting the necessary conditions in degree. Finally, the analysis of causal mechanisms confirms the difference between the existence of conditions that make possible the presence of an outcome and those that trigger the presence of the outcome.

It also shows the suitability of completing the classical models of innovation adoption by considering the relevance of the interaction between elements, since the landscape and regime levels interact; and not taking into account the alteration of the context, as the actions of the regime elements determine the outcome. Especially relevant is the role played by the agents that make up the innovative ecosystem related to the regime, and which largely determines the adoption or not of innovations. In any case, the complexity of modifying the mobility habits of consumers through the development of innovations is confirmed.

From an applied point of view, the inertia and stability of the automotive regime may be causing MaaS to fail to overcome its niche innovation status (Hirschhorn *et al.*, 2019; Lyons *et al.*, 2020). But not only the automotive regime, even the applications that provide information about the transport situation or regarding parking could explain the denial of the use of the micromobility services offered by MaaS. MaaS operators should therefore try to establish themselves in cities before citizens become accustomed to using some of the services that the MaaS platforms themselves eventually integrate. Likewise, in addition to working on the incorporation of those emerging micromobility models in line with user demands, MaaS operators could focus on increasing the information they offer their users online, as suggested by López Carreiro *et al.* (2020).

It is also enriching to analyze the impact of the individual use of some of the services that can be integrated into MaaS. Firstly, from the role played by satisfaction with public transport it can be inferred that citizens do not view MaaS from a complementary perspective. However, the relationship observed in the performance of satisfaction with public transport and the use of MaaS services shows the opportunity that these applications have concerning citizens who are not satisfied with public transport. In a similar vein, MaaS applications have an opportunity to be employed both in those cities where there is a perception that traffic congestion is a problem and where there are applications that provide information regarding available parking spaces. In this way, MaaS service operators must work on finding synergies with those agents that interact in the mobility regime if they want to overcome the bubble of the niche in which they present themselves due to their innovative nature.

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