



Beyond spatial accessibility. Redefining Access to Services Through Digital Connectivity

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Abstract

Ensuring equal opportunities for access to goods and services represents a key objective of sustainable development policies, in line with the principle of “Accessibility for all”. Perspectives and paradigms of accessibility require new updates to face the challenges resulting from multiple transitions, considering the opportunities offered by spatial proximity and recent technological digital progress.

The study develops a methodological approach to evaluate the correlations between physical accessibility levels and digital connectivity, to understand if and how the digital transition is shaping future accessibility of local communities to key services (education, mobility, socio-health). The Sardinia insular region (Italy) served as a case study to support the spatial representation of the correlation between physical accessibility and digital connectivity, enabling future sustainable regional policies, in line with the e.INS project, which aims to encourage sustainable multimodal integration in extra and intra-regional continuity, applying the concept of MaaS to the transport system.

Keywords: Accessibility; Digital transition; Triple Access Planning.

1. Introduction

Equal access to public goods and services, and equal opportunities to participate in all spheres of life is unanimously recognized as a fundamental human right and represents a key objective of public policies aimed at pursuing sustainable development goals. This principle is not merely an abstract ideal, but a tangible precondition for creating inclusive

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and equitable societies (Jian et al., 2020; Iamtrakul et al., 2024), in line with the principle of the "Design for All" (United Nations, 2015).

If mobility concerns the potential ability of moving people and goods across different locations, accessibility is the measure of such ability and represents an interaction between people/goods and localized activities (Levine, 2020; Akse et al., 2021). It is the measure of the ease or impedance for any user category to reach and utilize multiple resources, starting from a spatially separate location, using a specific transport system (Dalvi & Martin, 1976). It therefore depends on the characteristics of the individual, the spatial distribution of activities (land use), the origin and destination (distance), and the transport system used to connect the origin with the destination.

Early conceptualizations of accessibility were predominantly focused on physical mobility and spatial proximity, emphasizing the role of transport infrastructure in facilitating movement between locations (Cervero et al., 2017). Subsequent evolution reflects the most significant changes occurring in societal priorities, technological advancements, and planning paradigms. As a matter of fact, different accessibility concepts have been developed over time, emphasizing specific components such as land-use, transportation, time and human aspect, well expressed in related types of accessibility measures, which may be recognized in the following categories: Infrastructure-based accessibility measures, Location-based accessibility measures, Person-based accessibility measures, Utility-based accessibility measures (Geurs & Van Wee, 2023). Location-based also includes the potential accessibility measures or gravity-based measures, widely explored in the seminal work of Hansen (1959) (Hansen, 1959) and progressively used in urban and geographical studies up to today. In the Hansen's assumption, the accessibility of a location i in a region R characterized by n distinct locations is calculated as a function of the measure of the activities (opportunities) located in the location j belonging to R , and by an impedance function representing the generalized travel cost to connect locations i and j . The impedance (or distance decay) function is the most widely used and has a significant influence on the results of the accessibility measure as it predicts a decrease in accessibility when costs increase (Giannotti et al., 2022).

As previously mentioned, until the 1990s, accessibility was conceived as a synthetic indicator of the relationship between land use and the transport system, recognizing the latter as the primary response to local mobility demand. From the 1990s onward, web technology and, more generally, ICT systems, profoundly shaped the way people live, work, and interact. The progressive digitalization of public and private services (health, education, transport, financial, and banking services), which represents one of the most significant evolutions (Balletto et al., 2024), led to a gradual shift from the consolidated dual paradigm (spatial proximity-physical mobility) into a tripolar system (spatial proximity-physical mobility-digital connectivity). The Covid-19 pandemic recognized the role of telecommunications systems in enhancing adequate accessibility to key services and beyond (Relaño et al., 2021; Kellerman, 2022). As a matter of fact, digital connectivity played a significant role in ensuring access to key services during the pandemic. At the same time, the importance of ensuring social well-being of local communities led to promote sustainable city paradigms (Balletto et al., 2021) (smart city, healthy city, proximity city, 15-minute city), thus reducing the need for car travel and promoting active mobility (Khan, 2022).

In Italy, the origin of these paradigms can be traced back to the National Spatial Planning Law (1942) and the subsequent Ministerial Decree 2 April 1968, n.1444

introduced the proximity key services (education, community facilities, public green spaces, and parking) at the neighbourhood scale.

Perspectives and paradigms, methods and measures of accessibility always require new updates to respond to the new challenges due to the multiple ongoing transitions (ecological, digital, and demographic) (Balletto & Ladu, 2023). More recently, the conceptualization of the Triple Access Planning (TAP) approach (Lyons et al., 2024), for which sustainable urban accessibility can be achieved through the effective integration between the transport system (physical mobility), the land-use system (spatial proximity) and the telecommunications system (digital connectivity), represented one of the main achievements in the urban and transport planning discourse. The new approach recognizes all opportunities offered by technological progress that can reduce the need for travel in accessing goods and services, as well as all disciplinary acquisitions related to the opportunities of spatial proximity, well-expressed in the 15-minute city model. Accessibility to the digital network is understood as a precondition for ensuring an inclusive online environment where people can fully participate in the “information society” and access education, work, public services, and online entertainment.

In Italy, the physical accessibility levels to key services (ISTAT, 2024a) and main transport infrastructures (ISTAT, 2022) are evaluated by the Italian National Institute of Statistics and forms the basis for the development of more complex spatial analyses, including the fragility index at the municipal scale. In reference to digital connectivity, the AGCOM (AGCOM website) platform provides indices related to the number of households per municipality not served by a wired network, as well as the number of households served by networks with different speeds (0-2, 30-100, 500-1000 Mbps).

Physical accessibility and digital connectivity are at the core of the National Strategy for Inner Areas (Strategia Nazionale per le Aree Interne - SNAI) (Dezio et al., 2021; Ladu & Balletto, 2024), a national policy aimed at improving the quality of citizen services and economic opportunities in at-risk-of-marginalization areas. It was first introduced in the 2014 National Reform Program (Piano Nazionale di riforma - PNR) and defined in the 2014-2020 Partnership Agreement. The strategy has been reaffirmed in the 2021-2027 cycle, as outlined in the corresponding 2021-2027 Partnership Agreement. A set of indicators concerning the demographic, economic, and social condition, access to essential services, and the Digital Divide inform the definition, monitoring, and evaluation of the local-based strategies. The national policy classifies the inner areas as those areas characterized by a certain distance from the main urban centers/service hubs, where key services related to education, mobility, and socio-health are provided. Therefore, the level of accessibility to physical and digital mobility network infrastructure represents a significant parameter for determining those areas most exposed to multiple risks, where integrated actions are needed.

Based on a systematic analysis of the main indices proposed by the recent literature, the study develops a methodological approach to evaluate the correlations between physical accessibility and digital connectivity levels, to understand if and how the digital transition is shaping future accessibility of local communities to key services. As a matter of fact, technological innovation led to a progressive renewal of the concept of accessibility, which increasingly represents the various opportunities, for the local communities, to access physical, virtual, and hybrid services within the framework of the progressive digitalization.

The study considers the Sardinia Region (Italy) as an insular case study to apply the proposed method at the municipal scale, providing suggestions for future spatial planning

and sustainable development policies, with particular attention to inner areas. The study is part of the "e.INS - Innovation Ecosystem for Next-Generation Sardinia" project (Spoke 8), funded by the Italian Ministry of University and Research under the Next-Generation EU Programme (NRRP). The project, that is part of the broader scientific debate focused on the evolution of sustainable mobility and transport in the framework of the energy, ecological, and digital transition, aims to encourage sustainable multimodal integration in connections between Sardinia and the rest of Europe, as well as within the region, applying the concept of Mobility as a Service (MaaS) to the regional transport system, with particular attention to connections to/from airports (Ladu et al., 2024).

After a brief review of the recent literature, the contribution is organized into the following sections: Section 1.1 delves into the evolution of services towards progressive digitalization; Section 1.2 focuses on the TAP approach; Section 2 proposes a methodological approach to evaluate the correlations between the two variables of accessibility (physical and digital); Section 3 describes the case study; Section 4 is dedicated to the study's results, and Section 5 to discussions and conclusions.

1.1 Evolution of services.

The expansion of digital technologies in the 21st century has profoundly transformed the physical use of urban services, progressively moving some services to the web and reducing the use of physical spaces. A significant role has emerged from the dematerialization of Public Administration, which began in the late 1990s with complex national and European legislation and the establishment of specific governmental digital agencies (Aouici, 2025). Techno-digital innovation has therefore redefined the role of urban services, which are increasingly shifting to the digital environment to meet the needs of a complex society comprising residents and city users. Furthermore, the privatization of public services, which began in Italy in the 1990s, finds a new organizational space in the digital realm, where the SPID digital identity marks the boundary between public and private. This has profoundly changed how information and services are managed, with significant impacts on efficiency, transparency, and the relationship with citizens. Moreover, the progressive dematerialization of the public administration has generated a series of significant urban effects, profoundly changing the relationship between citizens, services and urban spaces.

The adoption of digital processes and the subsequent drastic reduction in paper use have progressively allowed for the optimization of physical archiving spaces. Another crucial effect is the increase in transparency and accessibility. Many services and much information are now available online 24/7, enabling citizens to interact with the public administration more flexibly and autonomously, regardless of office opening hours. Digital services like home banking, online grocery shopping, electronic health records, and distance learning proved particularly crucial during the SARS-CoV-2 pandemic.

The shift from physical to digital services has led to both an increase in disused building stock, creating new opportunities for functional repurposing of spaces, and a redefinition of urban areas for logistical purposes. Repurposing these spaces offers opportunities for new urban uses, such as residences, services, or green areas, helping to regenerate parts of the urban fabric. The new management of the real estate assets should address sustainable development goals, particularly those related to energy and ecological transition and the significant changes in demographic and socioeconomic structures

(Ladu, 2022). Digital services therefore influence the size and distribution of physical services, promoting the creation of more agile and even decentralized locations. A progressive reduction in the need for physical visits to public offices is shaping urban traffic and mobility, leading to decreased climate-altering emissions (Balletto et al., 2024). The new digital interaction between citizens and public administration fosters renewed inclusion, allowing access to services even for those living in peripheral areas or with mobility difficulties, contributing to greater social cohesion, effectively bringing the '15-minute city' concept to the web. Along with the recent spaces created by the dematerialization of public administration, the same happens to industrial voids, a consequence of techno-digital innovation (Balletto & Ladu, 2023). Their regeneration should go beyond mere building recovery, aiming to revitalize urban and local society and economy. However, it's essential to value human interaction, ensuring that digital technology truly serves the community, helping to strengthen the quality of life.

In this sense, the concept of "slowness," associated with the "Slow City" movement, offers a crucial and often underestimated contribution to the urban regeneration of voids, both historical industrial ones and newer spaces left empty by the dematerialization of public administration. Despite the indispensability of digital innovation in these processes, slowness acts as a catalyst for a more conscious and profound approach to renewed urban liveability. Designing pedestrian areas and bicycle paths, distinctive elements of the "Slow City" in urban contexts permeated by the digital services of the "Smart City", offers a balance between traditional social relationships and technological innovation, transforming it into an active 24/7 environment.

The digital divide is another important issue that requires the implementation of assisted access points or digital literacy policies within urban communities.

Italy is making significant strides in its digital transition. According to analyses from the European Commission, Italy records improvement in the Digital Economy and Society Index (DESI). Moving from 20th place in 2021 to 18th in 2022 among the 27 European Union (EU) member states. The DESI, introduced by the European Commission in 2014 measures the digital progress of European countries, aiming to push towards a single digital market. It's a composite index based on four key dimensions, encompassing 33 normalized indicators: Human Capital, which assesses the digital skills of the population; Connectivity, measuring the development and adoption of broadband; Integration of Digital Technology, analysing business digitalization and e-commerce; and Digital Public Services, evaluating the digitalization of Public Administration (e-Government). Further complementing the DESI, the Digital Maturity Indexes (DMI), developed in 2019 by the Osservatorio Agenda Digitale, offers a more in-depth and comprehensive evaluation of Italy's digitalization status. This system uses 117 indicators, incorporating all 33 DESI indicators. In 2023, Italy ranked 7th among EU countries and 8th overall in the open data maturity index classification, maintaining a 92% maturity level. Its DESI ranking remained at 18th among the 27 EU member states. This suggests that while Italy is progressing well in publishing open data, there are still areas where its overall digitalization can improve when compared to other European nations. Italy's NRRP provides substantial investments to digitalizing public services, accelerating the shift towards an urban model based on the smart city paradigm. This process isn't confined to large cities; it also extends to medium and small cities, as well as low density population areas. Digitalization is also transforming business models related to transport services, creating new opportunities for economic growth, exemplified by the Mobility as a Service (MaaS) concept. MaaS relies on the development of integrated digital

platforms that allow users to plan, book, and pay for various transport services—including public transport, sharing mobility (car-sharing, bike-sharing, and scooter-sharing, both electric and non-electric), taxis, and e-scooters—all managed through a single app. This simplifies the travel experience and discourages private car use. Users can locate, unlock, and pay for vehicles directly from their smartphones, reducing the need for private vehicle ownership and helping to reduce traffic congestion. However, the evolution from collective to personalized individual services is showing a decrease in direct and spontaneous social interactions. This has a significant and ambivalent impact, making it crucial to find a balance between digital efficiency and social cohesion.

The complex system of digital, hybrid, and physical services in the contemporary city represents the most evident manifestation of an "Augmented City" (Carta, 2021) an urban environment that extends beyond its purely material dimension to include a large network of immaterial interactions and services. In this context, accessibility takes on a central role, extending beyond physical accessibility and proximity to include digital connectivity, in line with the "Design for all" perspective.

1.2 The Triple Access Planning (TAP) approach.

Triple Access Planning (TAP) is a response to the growing recognition that access, not travel, should be the core concern of transport planning (Lyons et al., 2024). Travel is largely a derived demand, stemming from the need to participate in activities, access goods and services, and connect with others (Mokhtarian & Salomon, 2001). Historically, transport planning has focused on mobility, facilitating movement, particularly by car, rather than on enabling equitable and sustainable access. This has contributed to a legacy of car dependence, social exclusion, and environmental degradation.

While there is growing academic interest in prioritising accessibility over mobility (Halden, 2014; Shi et al., 2020), this shift has been slow to influence practice. Handy (2020) highlights an 'implementation gap' (Silva & Larsson, 2018), where complex accessibility measures hinder adoption. She advocates for embracing accessibility thinking, supported by simpler, more practical indicators. Accessibility planning has traditionally focused on the land-use–transport relationship: land use determines where activities occur, and transport provides physical access. However, in the digital age, access needs are increasingly met through digital connectivity (Yousefi & Dadashpoor, 2020). The idea of 'virtual mobility' is a digital alternative to physical travel. Yet this has been largely overlooked in transport planning. The COVID-19 pandemic underscored the importance of a Triple Access System (e.g., physical, digital, and land-use-based access) highlighting the need to view them together. Failing to do so increases uncertainty and limits our understanding, calling for deeper systems thinking. At its core, TAP reconceptualises access as a function of three interrelated systems: land use (spatial proximity), transport (physical mobility), and telecommunications (digital connectivity) (Lyons and Davidson, 2016). Instead of assuming mobility as the only solution to access needs, TAP acknowledges that activities can be brought to people via local development or accessed remotely via digital infrastructure. This shift is particularly critical in the context of climate targets, as reducing car use does not necessarily imply reducing access (De Vos et al., 2012). The relevance of TAP is sharpened by growing policy imperatives for decarbonisation and resilience. Local authorities in the UK, for example, have declared climate emergencies and set ambitious targets for reducing car mileage (WECA,

2023; Leeds City Council, 2021), while national projections still foresee rising road traffic in the absence of intervention (DfT, 2022). TAP provides a policy framework that aligns access needs with climate goals, allowing for supply-led, vision-driven planning under uncertainty (Lyons and Davidson, 2016).

TAP is positioned within a broader shift from the dominant predict and provide model of transport planning (focused on forecasting demand and building capacity) to a decide and provide paradigm, which is vision-led and access-focused. While implementation remains in early stages, momentum is building. TAP is being embedded in guidance documents, such as those by Transport for the North (TfN, 2020), the Scottish Government (2023), and the Swedish Transport Administration (Sandberg and Wårnhjelm, 2022). Yet, despite conceptual clarity and policy relevance, a persistent implementation gap remains (Handy, 2020; Silva & Larsson, 2018). Realising TAP in practice requires rethinking governance, integrating digital and land use planning, and strengthening the role of transport planners as facilitators of cross-sectoral change (Paddeu and Lyons, 2024). In this context, TAP offers not just a new planning tool, but a reframing of what transport planning is for: delivering equitable, sustainable, and resilient access in a rapidly changing world.

2. Method

This study proposes a methodology for the evaluation of the relationship between the level of physical accessibility and digital connectivity concerning key services to understand how the digital transition and the consequent dematerialization of public administration are shaping a novel hybrid accessibility (both physical and virtual), which also plays a significant role in identifying new peripheral or marginal areas alongside urban centres. Digital connectivity is recognized as the precondition for ensuring an inclusive online environment where all individuals can participate in the opportunities provided by the information society (access to education, employment, public services) (Stanca Act, also known as Law 4/2004; Legislative Decree 82/2022; European Accessibility Act (EAA), 2021-2030). This is consistent with several policies, such as European policies (Next Generation EU) dedicated to sustainable growth and social cohesion, the Italy's NRRP, which includes measures to reduce the digital divide and improve connectivity across the country, and the National Strategic Plan for Internal Areas 2021–2027 (PSNAI) (Dipartimento delle politiche di coesione e per il Sud, 2025), which identifies those areas where strategic priorities in the sectors of education, transport infrastructure, mobility, local public transport, and socio-healthcare services are required.

The proposed method consists in three main phases.

Phase 1 collect and systematize the main indices proposed by the literature, specifically those developed for the Italian context, to assess accessibility to both physical mobility and digital connection network infrastructure. For evaluating physical accessibility, several indices developed by ISTAT (Italian National Institute of Statistics) are considered, among which the following are the more relevant for the objective of the manuscript:

- Municipal key Services Accessibility index (MKSA index), which is selected from the Composite Municipal Fragility index (CMF index) (ISTAT, 2024a).
- Municipal Accessibility to Transport Infrastructure index (MATI index) (ISTAT, 2022). This index considers transport infrastructure, the railway stations, motorway access points, airports, and ports with passenger services.

The MKSA index measures the level of peripherality of each municipality, that is correlated to the average travel time (minutes) required to reach the nearest urban centre recognized as strategic service hubs (education, health, and mobility), thereby providing an indication of urban accessibility level. More precisely, according to the National Strategy for Inner Area (2021-2027), key services refer to hospitals with emergency and admission departments, at least one high school, and a passenger railway station. Higher index values correspond to greater levels of fragility.

The MATI index measures the distances of municipalities from the main transport infrastructure, expressed in travel times, employing a gravitational model that considers not only the spatial dimension (OD matrix), but also the services provided by each infrastructure. This model defines accessibility as the potential for opportunities, integrating the travel choices behavioural aspects into the analysis. In this sense, given equal distances, the model prioritizes the infrastructure offering the greatest number of services, considering a decay function (Gaussian function), which penalizes areas further from the infrastructure, thus reflecting the distance discouragement effect.

As regards the accessibility to the digital infrastructure, the study considers a set of indicators proposed by the National Strategy for Inner Areas concerning demographic, economic, and social aspects, as well as access to key services and the Digital Divide (Tab. 1), which collectively express the peripherality of the Italian inner areas, and a set of indices proposed by the Communications Regulatory Authority platform (Autorità per le garanzie nelle telecomunicazioni - AGCOM) (AGCOM website).

Table 1: Fixed and mobile network indicators proposed by the National Strategy for Inner Areas.

<i>Fixed / mobile network data</i>	<i>Digital Divide Indicators (SNAI)</i>	<i>Description: Percentage of population covered by telecommunication networks capable of providing connections with different speeds</i>
F1	FWA PASSED - NGA (at least 30 Mbit/s)	Speed of at least 30 Mbit/s
F2	FWA PASSED - NGA_VHCN (at least 100 Mbit/s)	Speeds of at least 100 Mbit/s
F3	FWA PASSED -NGA (1 Giga)	Speeds of at least 1 Giga
M	Mobile data - Not covered	Percentage of population not covered by mobile networks
M	Mobile network data with speed < 30 Mbit/s	Speeds up to 30 Mbit/s
M	Mobile network data with speed >= 30 Mbit/s	Speeds above 30 Mbit/s

Source: Dipartimento delle politiche di coesione e per il sud, Presidenza del Consiglio dei ministri, OpenKit Metadati, website: <https://politichecoesione.governo.it/it/search/?cerca=metadati>.

In addition to the fixed and mobile network indicators proposed by the National Strategy for Inner Areas (F1, F2, F3), the AGCOM fixed network indices concern the number of households per municipality with the following characteristics:

- Not served by a wired network. These are households that do not benefit from a stable, high-speed wired internet connection, representing a significant aspect of the national digital divide.
- Served by a network with 0-2 Mbps speed. This speed range, while formally guaranteed, represents an extremely slow connection, generally insufficient for main daily digital activities such as video streaming, distance learning, video conferencing, or remote work.

- Served by a network with 30-100 Mbps speed. This speed range is considered technically adequate to guarantee functional and complete use of the main digital services of daily life, allowing stable enjoyment of activities such as high-definition video streaming, online gaming, remote work, distance learning, and participation in public and private digital services.
- Served by a network with 500-1000 Mbps speed. This speed range is suitable for activities that require extremely high bandwidth, such as 8K video streaming, high-definition online gaming, virtual reality, and very fast downloading of large files.

In this sense, the AGCOM indices allow for a more detailed comprehension of the level of digital connectivity in the related contexts. Moreover, the proposed method consists also in a normalization of the above-described indices to the total resident households in each municipality (%) to better represent the relevant demographic-social aspects.

Phase 2 concern the categorization of the most representative indices into five classes (Tab. 2) highlights the relationship between physical accessibility and digital connectivity, and how the latter contributes to defining overall levels of access to services in the era of digital transition. Specifically, the five classes of the key services accessibility index correspond to the average travel time required to reach the nearest urban service hub, assuming 30-minute intervals as the reference for classification. Similarly, the digital connectivity indices were classified into five classes, corresponding to the connection speed of households.

Table 2: Categorization into five classes of physical accessibility and digital connectivity indices per municipality.

<i>Physical accessibility Index</i>	<i>Range [min]</i>	<i>Class</i>
Accessibility to key services	0 - 29	I
	30 - 59	II
	60 - 89	III
	90 - 119	IV
	>120	V
<i>Digital connectivity Index</i>	<i>Range [min]</i>	<i>Class</i>
Percentage of resident households served by a network with different speed	500 - 1000	I
	100 - 500	II
	30 - 100	III
	2 - 30	IV
	0 - 2	V

Author's elaboration.

Phase 3 consists in the application of linear regression, a fundamental statistical technique for examining the positive, negative, or neutral relationship between the values of two quantitative variables (physical accessibility and digital connectivity). It allows for the evaluation of the trend of the regression line through a scatter plot, obtaining different correlations (Schopenhauer, 2008): positive, when, as the values of one variable increase, the other also tends to increase; negative, if an increase in the values of one variable corresponds to a decrease in the other; and neutral, if the correlation is not significant. The results of the linear regression allow to develop a correlation matrix between physical accessibility and digital connectivity, which describes the joint distribution of the two variables in the analysed contexts.

However, the precondition for an effective application of the proposed method is the availability of constantly updated data, at different geographical scales (local, metropolitan, regional), in order to monitor the phenomenon and support its governance.

3. Case study: Sardinia Region

The Sardinia region, the second-largest island in the Mediterranean with 1.5 million inhabitants, represents a valuable case study for the present research. The region faces a continuous demographic decline and an aging population, with an average age of 48.4 years and a population density of 66 residents/km² (Ladu & Balletto, 2024). According to the ISTAT census population, the island's settlement structure is characterized by a strong dependence of smaller centres on the main urbanized areas. In 2022, 84% of municipalities had fewer than 5,000 inhabitants, with only seven exceeding 30,000 residents, concentrating 63.4% of the population in these main urbanized areas. The island's inner areas record significant population decline and rapid aging, with 25% of residents over 65 and a high elder-to-child ratio. This geographical distribution significantly impacts Sardinia's transport infrastructure and services, leading to a deficiency in terms of the supply and competitiveness. The island experiences weak transport continuity at both intra and extra-regional levels, exacerbated by policy gaps and limited public transport outside main urban centers (Ladu et al., 2024; Ladu & Balletto, 2024). In 2021, only 18.9% of Sardinian residents could reach a passenger port within 15 minutes, while for airports, this percentage was just 17.3% (ISTAT, 2022). Fig. 1 highlights a clear variation in physical accessibility to key services among Sardinian municipalities. Strategic urban services hubs (white) represent places where the key services are directly available. Urban areas closest to these hubs (light pink), show reduced average travel times compared to more peripheral/inner areas (red), which are characterized by significantly higher travel times (dark red).

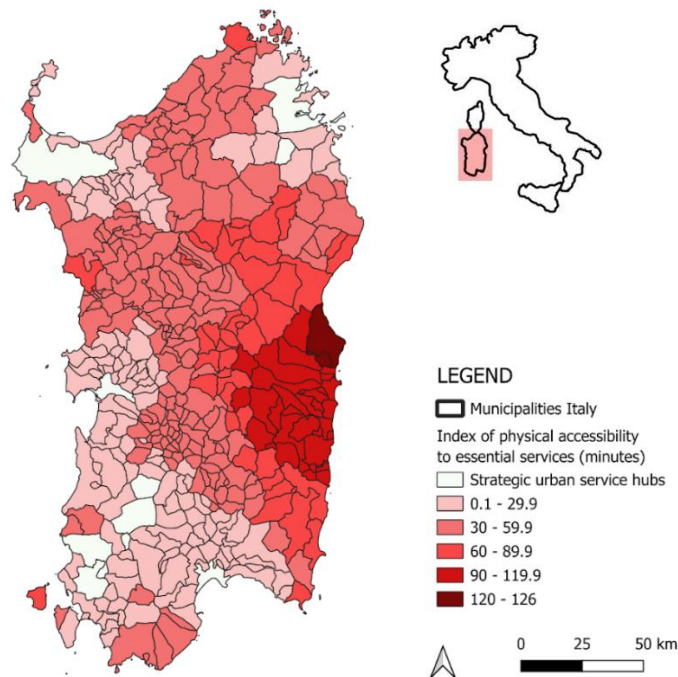


Fig. 1: Index of physical accessibility to key services in the municipalities of Sardinia. Author's elaboration. Source: ISTAT, 2021.

In general, coastal areas, except for those on the central-eastern coast, record higher levels of physical accessibility to key services compared to the rest of the Island. Key services are reachable within 0-29 minutes predominantly from municipalities located near the main urban hubs and along the major road network infrastructure. Municipalities with intermediate accessibility levels (30-59; 60-89; 90-119 min) mainly coincide with those located in inner and low-density areas. Conversely, in the central-eastern part of the island, average travel times to access key services reach high values between 120 and 126 minutes.

Along with these aspects, the study also analyses the phenomenon of the digital divide in Sardinia. In 2018, approximately 50% of Sardinian households had broadband coverage with speeds exceeding 30 Mbps, highlighting a significant gap in access to digital infrastructure. Around 184,000 housing, out of a total of 1,034,609 residential homes, were connected to fibre optics by 2020, providing a snapshot of the spread of latest-generation infrastructure on the island. The 2021 data for average monthly mobile data traffic, at 12.8 GB, exceeded the Italian national average by 17.4%. A higher reliance on mobile connectivity, possibly due to limited high-speed fixed connections, highlights a significant digital divide that mainly impacts the elderly population (digital grey divide) in inner areas. As discussed in previous sections, measure of the digital connectivity level is provided by the AGCOM indices (AGCOM website), which relate to the number of households without a wired network (Fig. 2) and the number of households with connections at speeds of 0–2; 2–30; 30–100; 100–500; 500–1000 Mbps.

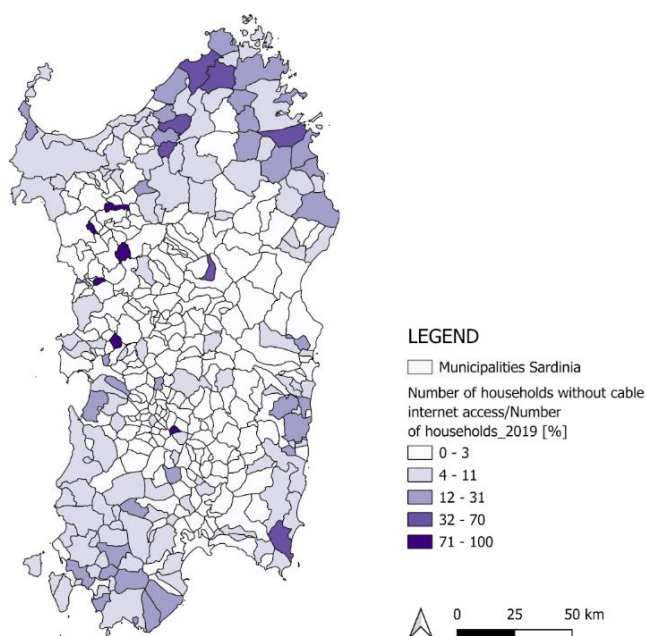


Fig. 2: Percentage of families that do not have access to stable wired internet connection in Sardinia. Author's elaboration. Source: AGCOM, 2018.

The percentage of households per municipality that do not have access to a stable high-speed wired internet connection is divided into 5 ranges (from 0-3 to 71-100%) (Fig. 2).

The colour intensity of the municipalities varies from white (minimum percentage of households without connection) to dark red (maximum percentage). Some municipalities in coastal areas show a higher percentage of households excluded from wired internet

connection (range: 12-31, 32-70, 71-100%), presumably indicating the presence of tourists and, more generally, city users who rely on mobile digital connections.

The main urban centres show a low percentage of households excluded from wired internet connection, demonstrating the presence of more performing network infrastructure to ensure digital coverage. However, the normalization of the AGCOM indices referring to the number of households per Sardinia municipality, which is an important phase of the proposed methodology to associate the analytical data (number of households per municipality) to the geographical context (total households per municipality), results in a graphical representation that tends to homogenize larger urban centres with smaller ones (white). This is attributable to the modest number of households per municipality that characterizes most Sardinia's small municipalities.

4. Results

The proposed method, structured in three phases (see Section 2), aimed at evaluating the relationships between the level of physical accessibility and digital connectivity to key services per municipality, is applied to the Sardinia Region.

Phase 1 considered the physical accessibility index to key services (ISTAT, 2021), expressed in average travel time to reach the nearest service hub (minutes) from each municipality, and the digital connectivity index, expressed as the percentage of households served by networks with different connection speeds out of the total households per municipality (AGCOM, 2018). Phase 2 classifies the physical accessibility and digital connectivity indices into five classes (Fig. 3) to facilitate comparison and enable the development of Phase 3, which is dedicated to applying the linear regression technique and subsequently developing the correlation matrix. Regarding physical accessibility, Class I includes the main municipalities/service hubs which are part of three macro-areas identifiable by the colour white in Fig. 3, located in the northeast, northwest, and central-southeast, forming extensive clusters consisting in 131 municipalities. In contrast, Class V comprises only two municipalities identifiable by the dark red colour, located on the central-eastern coast.

Municipalities classified in Class IV, identifiable by the vivid red colour, form a large cluster located south of Class V. Classes II and III characterize areas with intermediate levels of transport infrastructure. Class III forms a cluster adjacent to Class IV, with an oriental distribution extending from north to south. Class III also includes two municipalities located in the north, northwest, and southwest, respectively. Municipalities in Class II show a distribution bordering the eastern Class III, reaching the north and west coasts. Additionally, there are some micro-clusters of Class II municipalities in the southwestern part. The pattern of Classes III, IV, and V just described indicates that transport infrastructure provision is more performant on the northeast side compared to the southeast, unlike the Sardinia west side, where infrastructures are more performant in the south than in the north, although a well-performing, medium-sized cluster exists in the north. Furthermore, the central-northern part of Sardinia does not include municipalities in Class IV, while the southern part shows a gradient of classes. This demonstrates that the central-eastern area of Sardinia records low values of physical accessibility (Class IV and V). Regarding digital connectivity, Class I, representing the most performant speed range, includes only the municipality of Cagliari, which is the most important regional service hub. Classes II and III mainly comprise the main urban centres, while most Sardinian municipalities are included in Class IV: 319 municipalities, distributed throughout the region, have the highest percentage of households with access

to a low-speed connection network (2-30 Mbps). Finally, Class V includes 8 municipalities located in inner areas, characterized by low population density and a low level of digital infrastructure (high percentages of households using connection speeds of 0-20 Mbps).

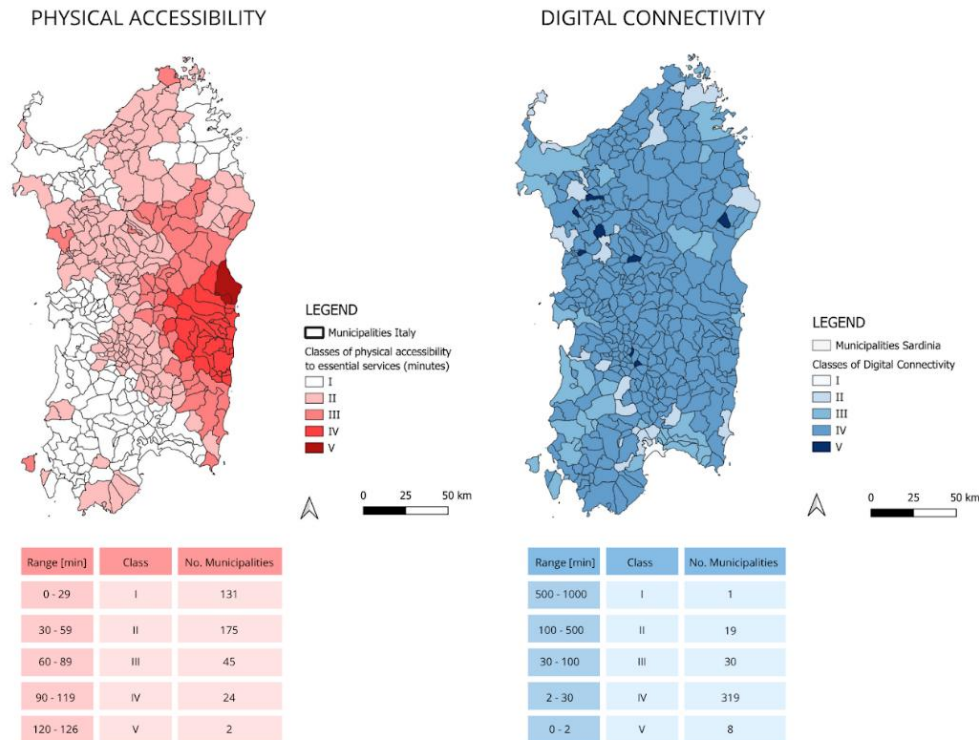


Fig. 3: Physical accessibility and digital connectivity classes of the municipalities of Sardinia. Author's elaboration. Source: ISTAT, 2021; AGCOM, 2018.

The linear regression line between the physical accessibility and digital connectivity classes in Sardinian municipalities (Fig. 4a) shows that the two variables of accessibility (physical and digital) increase with a positive correlation. The correlation matrix between the two variables classified in five classes (Fig. 4b) shows the joint distribution in the 377 municipalities of Sardinia. The rows of the matrix correspond to digital connectivity classes, while the columns indicate physical accessibility classes.

The values within the cells correspond to the number of municipalities that fit into each combination obtained. The row totals, on the right, show the distribution of municipalities by digital connectivity class, while the column totals, at the top, highlight the distribution by physical accessibility class. As the intensity of the red colour of the cells increases, the number of municipalities involved increases. The results highlight the heterogeneity of Sardinian municipalities. Municipalities with low physical accessibility (classes IV and V), often attributable to orographic or infrastructural factors, also have low levels of digital connectivity (classes III and IV), further accentuating phenomena of marginalization and vulnerability, further compromising opportunities for economic and social development. The most performant digital connectivity (classes I and II) is recorded in municipalities with high levels of physical accessibility (classes I, II, III), coinciding with the main urban centres/service hubs of the island. Furthermore, the matrix shows that the combination between class IV of digital connectivity (connection speed of 2 – 30 Mbps) and class II of physical accessibility (30 – 60 minutes) is the one that

includes 161 municipalities (43% of Sardinian municipalities). This is followed by the combination between class IV of digital connectivity (connection speed of 2 – 30 Mbps) and class I of physical accessibility (0 – 29 minutes), which includes 94 municipalities (25% of Sardinian municipalities).

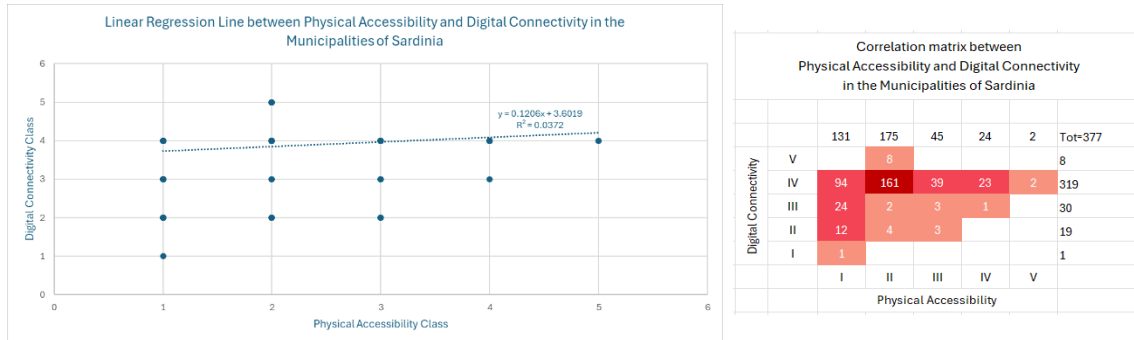


Fig. 4a, 4b: 4a) Linear regression line: the x-axis shows the classes of the index of accessibility to key services; the y-axis represents the classes of families based on the speed of network connection. Source: ISTAT, 2021; AGCOM, 2018. 4b) Correlation matrix. Author’s elaboration.

5. Discussions and conclusions

Ensuring accessibility to goods and services is a crucial challenge, moving beyond mere technical issues to encompass digital connectivity's role in shaping inclusive living environments. This evolving concept drives urban transformations, integrating spatial proximity, physical mobility, and digital connectivity under the Triple Access Planning (TAP) paradigm. This holistic approach highlights how digital connectivity significantly influences physical access to essential services.

Within this framework, the manuscript highlighted the importance of jointly considering physical accessibility and digital connectivity to evaluate how the latter is shaping the triple accessibility of local communities to key services. As a matter of fact, accessibility is crucial in defining an area's peripherality and fragility, encompassing environmental, economic, and social aspects. Based on this consideration, the study proposed a three-phase method (data collection, classification, and regression analysis) for representing the phenomenon in quantitative and qualitative terms, by geospatial analysis. In line with the objectives of the e.INS project, the manuscript assumed the Sardinia Region as a relevant case study due to its insular and low-density characteristics, the disparities in transport infrastructure and services to ensure an intra-regional connectivity, and its strong seasonal tourist characterization, with peaks in demand for physical mobility and digital connectivity. The results highlighted the relationship between the two variables, with linear regression results confirming a positive correlation between physical accessibility and digital connectivity across Sardinian municipalities. Moreover, the correlation matrix confirms a context of inequalities in access to physical and digital services.

The results suggest the importance of adopting an integrated approach in planning interventions aimed at strengthening physical accessibility and digital connectivity

infrastructures as they are no longer to be understood as independent variables but increasingly correlated.

In conclusion, in methodological terms, the development of the correlation matrix proved useful for monitoring the evolution of the two variables over time and proposing a profound change in the vision of public policies in the governance of key services.

The establishment of a permanent institutional committee between regional governmental bodies and agencies involved in different sectors (education, health, transport, digitalization) represents the first step to address a new shared provision of key services in transition (from physical to digital). In particular, this suggestion can significantly contribute to orienting the provision and spatial organization of key services when drafting or updating the local plan. Physical services always maintain their fundamental role as hubs for aggregation and social interaction. Digital services provide speed and accessibility by overcoming geographical and temporal limitations. Hybrid services represent the points of contact and synergies between the physical and digital trend. In this sense, the study and the proposed methodology will focus on a critical revision of spatial planning, providing support for defining urban regeneration policies, especially those related to marginal and peripheral areas. Moreover, in future applications, the research will consider the opportunity of applying more geographical regression techniques that consider specific weights to better estimate the levels of accessibility in different geographical contexts, in line with the place-based approach.

Author Contributions

M.L. wrote Section 1; G.B. wrote Section 1.1; D.P. wrote Section 1.2; G.B. and M.L. wrote Section 2 and 5; G.B., M.L. and L.C. wrote Section 3 and 4. All authors have read and agreed to the published version of the manuscript.

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