Finanziato dall'Unione europea NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani
Piano Nazionale di Ripresa e Resilienza

Finanziato nell'ambito del Piano Nazionale di Ripresa e Resilienza PNRR. Missione 4, Componente 2, Investimento 1.3 Creazione di "Partenariati estesi alle università, ai centri di ricerca, alle aziende per il finanziamento di progetti di ricerca di base"

GRINS FOUNDATION

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Deliverable D2.2: Scientific Reports

Report 1: PUBLIC POLICIES, STRUCTURAL GAPS AND TERRITORIAL ECONOMIC PERFORMANCE

Report 2: MOBILITY AND ACCESSIBILITY AS KEY FACTORS FOR SUSTAINABLE AND RESILIENT CITIES AND TERRITORIES

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Spoke 7, D2.2 Scientific Reports

Report 1: PUBLIC POLICIES, STRUCTURAL GAPS AND TERRITORIAL ECONOMIC PERFORMANCE

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Executive Summary *(Report Coordinator: Raffaele Paci)*

This Scientific Report analyses the effects of public policies on structural gaps and territorial economic outcomes in Italy. The Report integrates the results of seven scientific contributions elaborated by different research groups within the GRINS Spoke 7. Therefore, the range of public policies considered is quite broad, spanning from the public capital expenditures across varying levels of institutional bodies (national, regional, local), the EU Cohesion Policy (CP) funds, the Local Expenditure Needs (LEN) of municipalities, the Special Economic Zones (SEZ) policy, the digital and green policies embedded in the European Regional Development Fund (ERDF) and the green transition policies.
Moreover, the territorial disparities examined are also heterogeneous, covering a wide range of geographical areas in Italy: regions, provinces, and municipalities. Consequently, given the high degree of heterogeneity in the policies, territorial coverage, and methodologies employed, the results in terms of territorial disparities are rather diversified. Despite these varieties, the Report provides interesting indications to policymakers and stakeholders on the suitable policies to contrast territorial inequality in Italy.
In the following pages, we will briefly outline each section's main contents and results.

Chapter 1 deals with "Public capital and institutions' quality in the Italian regions". The contribution starts from the fact that Southern local institutions will receive significant funding from the Italian PNRR in the coming years, raising concerns among policymakers and analysts about their capacity to manage these resources effectively. The study examines the economic impact of public capital in Italian regions over the past two decades, focusing on the role of local bodies in Southern Italy to assess their ability to realize public investments. The regional public capital stock series has been computed using Territorial Public Accounts (CPT) data, which allows for disaggregation by different administrative bodies. An augmented production function is estimated to assess the impact of public capital on regional value-added, using lagged capital stock and labor as instruments in a 2SLS approach to address endogeneity issues. The results show an overall positive effect of public capital, but investments by local bodies in Southern regions have a much lower impact compared to those in Northern Italy, primarily due to the lower institutional quality in the South. Enhancing institutional quality, particularly in Southern Italy, is crucial for maximizing the effectiveness of the PNRR. Short-term solutions include expert and central government support, while long-term efforts should focus on improving human capital and changing social norms.
The issue of investment in public infrastructure is resumed in **Chapter 2** which examines "Modelling Infrastructure Gaps and Expenditure Capacity in Italian Municipalities". This study develops an empirical framework to assess Local Expenditure Needs (LENs) for infrastructure across Italian municipalities from 2016 to 2022, focusing on local transport, waste management, and cultural services. Utilizing a comprehensive dataset from the Banca Dati delle Amministrazioni Pubbliche (BDAP), which includes over 1,000 variables, the study presents a robust method to quantify the existing gaps in infrastructure investment. The innovative approach leverages capital expenditure data, moving beyond traditional methodologies primarily focusing on current expenditure evaluations. This contribution

introduces a series of gap indicators—Waste Management Gap Indicator (WMGI), Local Transport and Roads Gap Indicator (TRGI), and Cultural Services Gap Indicator (CSGI)—to systematically measure discrepancies between actual and standard capital expenditures. These indicators are visualized through cartograms that highlight geographical disparities and track improvements over the study period. The findings reveal significant regional disparities, particularly between northern and southern municipalities, and underscore the urgent need for targeted investments to bridge these gaps and enhance local resilience and attractiveness. The paper concludes with policy recommendations to optimise infrastructure investments to support sustainable local development across Italy.

The role of public policies in affecting territorial performance is also the broad topic of **Chapter 3** which specifically deals with "Cohesion Policy Impact on Tourism in Italy: A Municipality-Level Assessment". This study examines the effects of the European Union's Cohesion Policy (CP) on tourism development at the municipal level in Italy, addressing a gap in the literature that predominantly focuses on broader geographic units such as regions and provinces. The CP aims to reduce inequalities and stimulate economic growth by allocating substantial financial resources to less developed areas across the EU, with a significant portion directed toward tourism—a vital sector for income generation, employment, and trade in services. Italy, a leading global tourism destination with 60 UNESCO World Heritage sites as of 2024, provides an ideal case study to evaluate the localized impacts of these investments. In the two programming periods 2007-2013 and 2014-2020, the EU allocated 11.9 billion euros to culture and tourism in Italy. This research uses data from OpenCoesione, covering over 2,000 municipalities, to offer the first large-scale analysis of CP's impact on tourism at this granular level. The study spans four programming cycles (2000-2006, 2007-2013, 2014-2020, and 2021-2027) and evaluates all tourism-related projects completed between 2014 and 2022. Key objectives include assessing the impact of CP investments on indicators such as tourist arrivals, overnight stays, and expenditures, and understanding the differential impacts across municipalities. Findings reveal how localized CP investments in tourism contribute to broader economic development, emphasizing the importance of regionally tailored interventions. The study offers valuable insights for policymakers, highlighting the need for sector-specific analyses and strategic planning to maximize the effectiveness of EU funding in fostering sustainable tourism development and reducing territorial disparities.

CHapter 4 covers the topic of "Assessing the impact of Special Economic Zones on Italian firms behaviour". The study evaluates the effectiveness of Special Economic Zones (SEZs) as policy instruments aimed at stimulating industrial activity and promoting regional economic development in Italy's underdeveloped Mezzogiorno region. Introduced through Law Decree 91/2017, SEZs offer economic, fiscal, and bureaucratic advantages to attract foreign direct investment and foster economic expansion. Key features include Free Economic Zones that allow duty-free storage and processing of goods, a 50% reduction in corporate income tax, investment tax credits, and simplified administrative procedures. Firms are required to operate within these zones for a minimum of seven years to qualify for benefits. The study employs a Matching Difference-in-Differences (DiD) model, using the annual value of total fixed assets as a proxy for investment levels, to assess firm behavior and economic performance before and after SEZ implementation. Findings indicate that SEZs have positively

impacted high-tech sectors, contributing to reduced regional economic disparities, enhanced local economies, and increased employment. However, the impact varies across regions, with some areas benefiting more than others. The study underscores the importance of refining SEZ policies to involve other significant sectors, such as the food industry, and suggests future regional analyses to explore individual regional effects. These insights are pertinent to the recently introduced Single SEZ policy in 2024, which extends SEZ benefits to the entire Mezzogiorno area, aiming to promote balanced territorial development and address Italy's persistent North-South economic divide.

In the following sections, we introduce a more specific analysis of the green policies. More specifically, **CHapter 5** deals with "Smart and Green. The spatial effects of the Twin Transition in EU regions". This study examines the integration of green and digital priorities—termed the Twin Transition (TT)—within the Smart Specialisation Strategies (S3) of European Union (EU) regions during 2014–2020. Aligning with the EU's European Green Deal and Digital Compass, the research explores how regions incorporated these priorities into their innovation strategies and assesses the economic impacts, particularly amid the COVID-19 pandemic. The analysis reveals significant variation in the adoption of green and digital priorities across regions. Utilizing a growth convergence model, the study finds that digital technologies positively influenced productivity in less developed regions pre-pandemic; however, this effect diminished post-pandemic, benefiting only low-productivity areas. Conversely, green policies generally posed short-term economic challenges, with negative effects on overall productivity, though some positive impacts were observed in lower-productivity regions. The combined effects of the twin transitions mirrored these trends, with positive outcomes for less productive regions but negative impacts overall. The findings underscore the need for a balanced approach to regional development, viewing digital and green policies as complementary. Policymakers are encouraged to tailor strategies to specific regional contexts, investing in digital infrastructure and skills for immediate economic benefits, while supporting green initiatives for long-term sustainability. Strong governance and stakeholder engagement are essential to promote sustainable and equitable regional growth amid emerging challenges.

The policies related to the green transitions are also examined in **Chapter 6**, which covers "Opportunities and Challenges for the Green Industry: Specializations of the Italian Provinces and Implications for Industrial Energy Policies". This study examines regional variations in Italy's green industry specialization and their implications for energy and industrial policies. Utilizing the Taxonomy Alignment Coefficient (TAC) and Taxonomy Exposure Coefficient (TEC), the research assesses the alignment of provincial sectors with low-carbon economies and their dependence on fossil fuels, respectively. Findings reveal significant heterogeneity across Italian provinces: regions like Aosta, Bergamo, and Brescia exhibit strong green specialization, while areas such as Turin, Rome, and Catanzaro are more reliant on vulnerable, high-emission industries. These insights inform policy recommendations tailored to regional contexts. For provinces with high green specialization, policies should enhance competitive advantages through investment in research and development, subsidies for green innovation, and support for sustainable operations. Conversely, regions with high vulnerability, particularly in Southern Italy, require strategies focused on economic diversification and a transition away from fossil

fuel-dependent industries, including investments in renewable energy projects. Provinces with dual specialization necessitate balanced approaches that manage the decline of vulnerable sectors while fostering green industry growth, such as retraining workers and supporting SMEs in innovation. The study emphasizes the necessity of a coherent national strategy to complement regional efforts, ensuring equitable resource distribution and reducing North-South disparities. Adaptive policies, responsive to technological and market evolutions, are crucial, as is collaboration between public and private sectors to drive innovation and inclusive growth. By addressing regional specificities and promoting innovation, Italy can effectively navigate the green transition and position itself as a leader in global sustainability efforts.

The analysis of the green funds within the European cohesion policies is examined in **Chapter 7**, which deals with "The contribution of green Cohesion Policy funds to carbon abatement: a heterogeneity analysis across Italian municipalities". During the programming period 2014-2020 the sustainability transition represented a key pillar of the EU Cohesion Policy. However, the bulk of extant studies still investigates the impact of such regulatory framework on socio-economic growth, neglecting its contribution to achieving environmental targets such as carbon abatement. This study aims to fill this gap, by analysing the effects of green Cohesion Policy funds in terms of PM2.5 reduction across municipalities with a heterogeneous level of territorial capital in Italy. Through the application of panel Spatial Durbin Models (SDM), the study highlights that such programs of financial support display both a significant direct and indirect effect in municipalities characterized by a high economic capital. Indeed, funds targeting carbon abatement tend to reduce PM2.5 concentration levels both in the municipalities where such projects are implemented and in the neighbouring administrative units. This contribution rather shows how these green funds are associated only with significant spillovers in the cluster of Italian municipalities exhibiting a strong presence of Tourism infrastructures. The study does not find either significant direct or indirect effects in the municipalities mainly located in the Centre-South of Italy with high levels of human capital. The study also discusses how these findings might be related to the local institutional capacity and to the capability to select and implement projects actually contributing to carbon abatement.

1. Public capital and institutions' quality in the Italian regions *(Federico Aresu, Emanuela Marrocu, Raffaele Paci - UniCA)*

1.1. Introduction

In the next years, Italy is expected to receive a vast amount of public funding (almost 280 billion euros) from the National Recovery and Resilience Plan (NRRP) for Italy and the new European Union (EU) Cohesion Framework 2021-2027. These plans aim to finance structural reforms to boost the economy by accelerating the green and digital transition and removing barriers to market

competitiveness and access to essential services, primarily healthcare and education. It is important to remark that the regional and local administrations will manage a large share of the available financial resources. Moreover, almost half of the funding will be allocated to the eight less-developed Italian Southern regions. From a back-of-the-envelope calculation, the Mezzogiorno's regions are expected to allocate and spend almost 94 billion euros from the NRRP and 30 billion euros from the EU framework in the next five years. An amount of money they have never received before.

In this context, a relevant question raised by political analysts and policymakers is about the actual capacity of the Southern administrations to deal with such an extraordinary task. Some doubts about the capability of the local public bodies in the Mezzogiorno to manage and efficiently spend these financial resources have also been advanced by economists because of the low quality of the local institutions (Albanese et al. 2020, Di Caro and Fratesi 2022).

Rodriguez-Pose (2020), in an inspiring overview of the open issues on the relationship between institutions and territories, highlights that local institutions may have a direct and an indirect effect on regional economic performances. Local institutions leverage the provision of public goods (education, innovation, infrastructures) in their regions, thus directly affecting their economic performance. Moreover, local administrations play a pervasive role in setting the normative and regulatory framework, and consequently, they influence firms' productivity (Lasagni et al. 2015). At the same time, they have indirect effects given their influence on the local effectiveness of other national or European policies (Rodríguez-Pose and Garcilazo, 2015).

This paper aims to contribute to the current debate on public capital effectiveness by distinguishing among the government levels responsible for the expenditure (central and local bodies) and explicitly considering local institutions' quality. Although institutional quality is getting more and more attention within the regional economic literature, accounting for the diversified role played by different government levels has been largely overlooked, mainly because of the limited data availability.

The empirical analysis focuses on regional economic performance in Italy over the past two decades, where a persistent divide between the northern and southern regions has shaped development patterns. The economic divide makes Italy a particularly relevant case for analyzing the relationship between public capital impact and the role played by different institutional levels. To this aim, we first set up a novel database on public capital at the regional level using the investment expenditures of the Extended Public Sector (Settore Pubblico Allargato, SPA) provided by Territorial Public Accounts (Conti Pubblici Territoriali, CPT). Following the methodology proposed in Marrocu and Paci (2010), we build the series on public capital stock for 21 NUTS2 Italian regions over the period 2000-2019, disaggregated by five levels of institutions responsible for the investments' implementation.

Our econometric specification is based on a standard Cobb-Douglas production function augmented with a measure of the institutions' quality and other intangibles and territorial factors and considering different levels of disaggregation of the public capital. We adopt an instrumental variable approach to deal with the issue of potential endogeneity of the main productive inputs.

The main results highlight the positive impact of public capital on regional product levels with an elasticity higher than the private one. Another remarkable result is that the quality of institutions exhibits the expected positive and significant elasticity, robust to all different specifications. When

we disaggregate public capital into central and local bodies, according to the administrative entities in charge of the expenditures, significant differences between Centre-Northern and Southern regions emerge. Central bodies in the Southern regions exhibit an elasticity much higher with respect to the Northern ones. The opposite happens with the local bodies, which appear much less effective in the Southern regions. This finding is mainly due to the fact that the effectiveness of local bodies is a positive function of the level of institutional quality.

Although our analysis focuses on Italy, our results are also relevant to the rest of the European regions, which feature varying levels of institutional quality. In some countries (e.g., Romania, Bulgaria, Hungary, and Greece), institutions responsible for managing and allocating public funding have a quality level very similar to the one exhibited by the Southern Italian regions.[1]

The rest of the paper is organized as follows. In section 1.2 the literature on public capital impact is briefly reviewed. Section 1.3 deals with constructing and describing the public capital stock series and the other variables. Section 1.4 presents the empirical model. The econometric results are discussed in section 1.5, and section 1.6 concludes.

1.2. Outline of literature background

The impact of public capital on the economic performance of states and regions is increasingly seizing the attention of academic researchers and policymakers alike. In addition to the traditional approach to the effects of public capital and infrastructures, a new stream of the literature has explicitly focused on the impact of public expenditures resulting from the EU structural funds.

The foundational approach to studying the impact of public capital on production emerged following Aschauer's (1989) influential work. However, initial studies (Aschauer 1989, Munnell 1990, Sturm and de Haan 1995) provided questionable estimates of the public capital elasticities because of unsolved econometric issues, such as reverse causality and spurious correlation (Romp and de Haan 2005, Holtz-Eakin 1994). In a meta-analysis based on 578 estimates from 68 studies for 1983–2008, Bom and Ligthart (2014) have found an average elasticity of 0.11, showing a major impact of infrastructures realized by the local and regional levels of government. More recently, Núñez-Serrano and Velázquez (2017), in a meta-analysis based on almost 2,000 elasticities from 145 studies, found an average elasticity of 0.13 and 0.16 for the short-term and long-term, respectively.

Over the last two decades, the literature on public capital impact has prospered through cross-countries and within-country analysis. The former studies have proven the positive effect of public capital on economic growth in developed (Kamps 2004, Fournier 2016, Han et al. 2017) and developing countries (Gupta et al. 2014, Agénor and Neandis 2015, Santiago et al. 2020).

Numerous analyses have studied the impact of public capital stock at the regional level, specifically concerning the case of Spain and Italy. In Spain, a positive effect of public capital has been estimated on economic growth by Moreno et al. (2015) and productivity levels by Gómez-

1 According to the European quality of Government index in 2021, the Italian Mezzogiorno has an index of -1.47, Bulgaria and Romania have very similar values (-1.47 and -1.48, respectively), Hungary and Greece a slightly higher one, -1.18 and -1.13. Note that the index ranges from -1.48 (Romania) to 1.68 (Finland).

Antonio and Fingleton (2012). Furthermore, Aray (2019) found a positive effect of decentralization on the allocation of public infrastructures. In Italy, several contributions have estimated a positive impact of public capital on economic performance. Marrocu and Paci (2010) remarked a higher elasticity in the Northern regions, and Daniele (2009) showed similar results studying public expenditures. The role of public investments in Southern Italy has been analyzed by Papagni et al. (2021), finding a positive impact only between 1951 and 1973. Moreover, Cosci and Mirra (2018) revealed that post-war public investments in road infrastructures had not reduced the economic divide between Northern and Southern Italy.

A second approach has focused on the impact of capital expenditure originated by the European structural funds. The EU has developed its cohesion policies to encourage and support the integration process among the country members by fostering economic growth and promoting development in the less developed regions. It is important to remark that the EU cohesion policies have gained relevance in the last years. Therefore, many researchers have analyzed the impact of EU capital expenditure on economic growth and regional integration. While some contributions highlighted the overall positive influence of such policies, others have emphasized the heterogeneity of these effects across countries (see the meta-analysis by Dall'Erba and Fang 2017). Several authors report that the regional differences depend on national and regional contextual factors, such as the quality of local institutions and human capital endowment (Albanese et al. 2021, Di Caro and Fratesi 2022). Looking at the national intervention model, Crescenzi and Giua (2020) found that EU programs are more effective in enhancing economic growth in Germany, while their impact is weak in the Southern European regions. This result is coherent with Albanese et al. (2020), who estimated an average null effect of EU structural funds on Southern Italy total factor productivity. On the other hand, Coppola et al. (2020) indicated a positive impact of EU cohesion policies in Italy.

In general, the literature highlighted the relevant role of public infrastructures financed through EU cohesion policies. More importantly, sound evidence has been provided on the fundamental role played by the quality of local institutions in favoring the impact of public capital expenditure on economic performance.

1.3. Data and descriptive statistics

1.3.1. Regional public capital stock

The data on public capital stock is not available in Italy at the regional level. The Italian National Institute of Statistics (Istat) provides data only for total capital stock at the national level without distinguishing between private or public expenditure.[2] Therefore, to obtain the series of regional public capital stock, we accomplish the following steps: (i) compute the series of total regional capital stock; (ii) compute the regional capital stock for the public component; (iii) decompose total capital in its public and private components.

2 See Table A1 in the Appendix for data definitions and sources.

The initial value of the capital stock in 1999, which represents the base for the series' reconstruction, is computed considering the annual mean value of the national total capital stock for 1996-1999. Then, we divide the national stock in the base year 1999 among the regions using the methodology in Gleed and Rees (1979), also used by Marrocu and Paci (2010). Next, the total capital series for each region has been computed for the period 2000 to 2019 by applying the perpetual inventory method, which entails that the value of the capital stock at time *t* is equal to the value at time *t-1*, augmented by investment measured at time *t* and diminished by depreciation (we assume a 10% depreciation rate). Regional data on gross fixed investment, published by Istat, are at constant prices.

The second step entails constructing the public capital series using the Extended Public Sector (SPA) investment expenditures. It is important to remark that the SPA includes public administrations and public companies, thus allowing for a more comprehensive assessment of the public investments' impact on the economy.

It is worth remarking that we consider a broad definition of public investments in this paper. In addition to the categories "real estate assets and works" and "movable property, machinery", we also include "capital transfers to households and social institutions" and "capital transfers to private undertakings". In such a way, our definition of public capital embraces the capital expenditures financed by the public sector, although the investment is realized by private entities.

The SPA dataset distinguishes five bodies responsible for the investments' implementation. The "central administration" includes the Italian State and government agencies such as the Revenue Agency, CDP (Cassa Depositi e Prestiti), and ANAS (the National Agency for Roads). The "regional administration" encompasses the regional government and the local health units. The "local administration" embraces municipalities, provinces, and other territorial entities such as municipalities' unions, universities, port authorities and national parks. The "national public companies" include firms under the direct control of the government. Often, they are former public monopolies transformed today into private companies listed on the stock exchange, but where the State still owns a relevant share.[3] Finally, the "local public companies" level comprises firms owned by the regional and local administrations, usually operating in local public services (water, transports, energy) and agrarian consortiums and cultural foundations.

This disaggregation is crucial for our analysis, which aims to investigate whether the impact of public capital depends on the level of government responsible for the expenditures. As before, the public capital stock series have been constructed using the perpetual inventory methodology with a 10% depreciation rate from 2000 to 2019. The initial value of regional public capital has been computed using the annual average share of regional public investments on regional total investments between 1996 and 1999. Following the same methodology, we have also obtained a series of public capital stock disaggregated into levels of government.

Finally, in the third step, we compute the private capital component as the difference between total and public capital.

Figure 1 displays Italy's total and public capital stock series over the years 2000-2019. The total capital stock decreased notably (-1.28% yearly) during the observed period. The decline in the capital accumulation process appears even more pronounced after the financial crisis of 2008.

[3] Notable examples are ENI (the energy company), ENEL (the electrical company), Poste Italiane (the postal service), and Ferrovie dello Stato (the railway company).

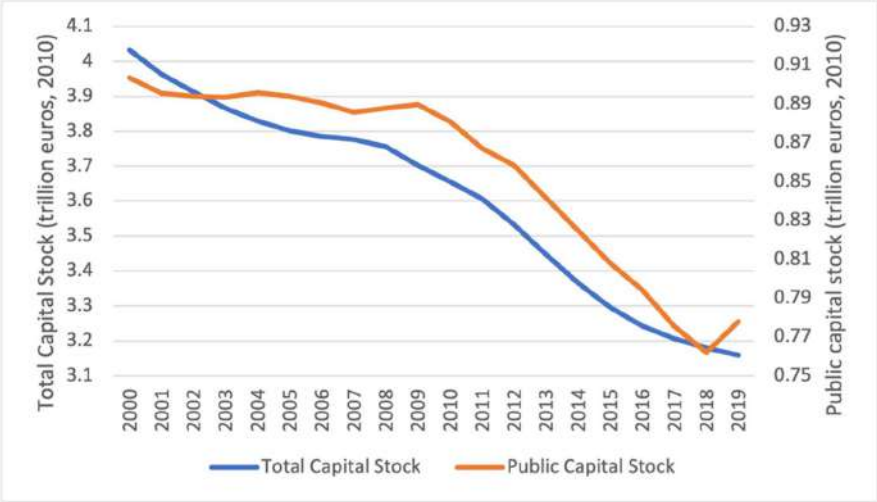
Table 1. Public capital stock by macro-areas

	North		Centre		South		Italy	
	2000	2019	2000	2019	2000	2019	2000	2019
Share on total stock (%)	17.0	19.5	22.2	26.1	33.9	36.1	22.4	24.6
Per labour unit (index)	82	88	97	99	133	124	100	100
Per capita (index)	92	98	103	107	108	99	100	100

On the other hand, the level of public capital remains almost unchanged until 2009 and starts decreasing afterward.

Table 1 reports the share of the public over total capital stock and some summary measures for the public stock of capital, namely index numbers for per capita and per unit of labor. In general,

Figure 1: Total and public capital stock in Italy, 2000-2019



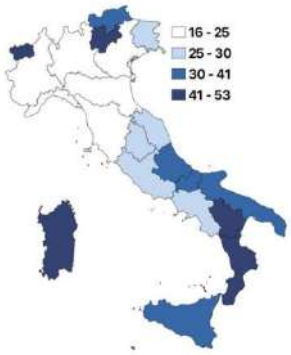
the share of public capital expenditure over the total is persistently increasing, and it reached the value of 24.6 in 2019. The public component of the capital stock is more relevant in Southern Italy (36% in 2019). Public capital per labor unit is higher in Southern Italy even if they decrease over time, while they increase in the rest of the country.

Figure 2 represents the regional shares of public capital (panel 1), the regional public capital per labor unit (panel 2), and the regional per capita public capital (panel 3) in 2019. The maps show important differences between Northern and Southern Italy in all cases. Together with the small autonomous regions in the Alpes, the Southern regions show a much higher presence of public investment.

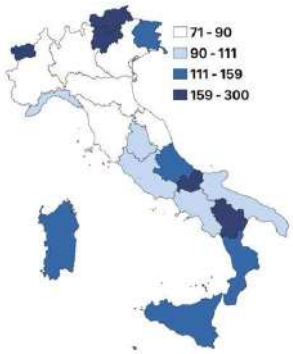
Table 2 describes, for the years 2000 and 2019, the share of public capital stock for the five levels of government responsible for the capital expenditure. Interestingly, local administrations in the North show the highest share of public capital in 2000, while in Southern and Central Italy the highest shares are exhibited by the central administration and national public companies. It is worth remarking that the role of national public companies has strongly increased over time, and in 2019 they manage 36% of national public capital expenditure. On the other hand, the role of local, regional, and central administrations decreases over time (by -7, -3, and -5 percentage points, respectively). The considerable differences in the share of local public companies

among the areas are also interesting: they play a relevant role in the North (15% in 2019), while they control a small share of public capital stock in the Southern regions (5% in 2019).

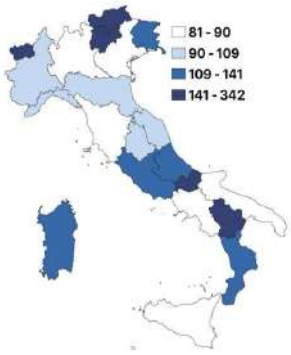
Figure 2: Regional distribution of public capital, 2019



1. Public capital shares on total capital



2. Public capital per labour unit (index, Italy=100)



3. Public capital per capita (index, Italy=100)

Overall, a highly differentiated picture among the regions emerges regarding the government levels responsible for capital expenditures and the sectoral distribution of capital expenditures. We will consider this heterogeneity in the econometric analysis.

Table 2. Public capital stock by institutions and macro-areas (% share)

Bodies	Macro-bodies	North		Centre		South		Italy	
		2000	2019	2000	2019	2000	2019	2000	2019
Central administrations	Central	16.2	15.7	25.3	23.6	34.4	24.0	25.1	20.1
National pub. companies	Central	22.0	33.0	28.2	41.7	16.4	35.5	21.0	35.7
Regional administrations	Local	16.8	12.8	7.6	5.4	15.8	12.6	14.6	11.2
Local administrations	Local	31.6	23.2	27.8	19.2	27.4	22.4	29.2	22.1
Local pub. companies	Local	13.4	15.3	11.2	10.1	6.0	5.4	10.1	10.9

1.3.2. Regional value-added and control variables

We start by providing a statistical description for the dependent variable, regional value-added, followed by institutional quality and the main contextual variables: human capital, social capital, and technological capital. Table 3 and Figure 3 report the summary statistics of all the variables, while the complete list of the variables and their sources is reported in Table A1 in the Appendix. The Italian value-added (VA) series shows a sharp decrease after the financial crisis of 2008 (-5.4% between 2008 and 2009) and after the Italian debt crisis of 2011 (-4.2% between 2011 and

2013). Looking at the per capita VA, the Southern regions are well below the national average (index 61 in 2019), while Northern Italy has an average value 13% higher than the national one, confirming the huge and even increasing economic differences between the two areas.

In the econometric analysis, as factors influencing the economic performance at the regional level, we consider the intangible assets whose effect on production has been largely documented in the empirical literature on regional economic growth. Among them, we devote specific attention to the Quality of the Institutions since administrations and public companies implement a large share of public investment at the local level. Seminal contributions have emphasized institutions' role in determining economic system performance (among others, North 1990, Acemoglu et al. 2001, Glaeser et al. 2004).

A high-quality government ensures the provision of more efficient public services, thus supporting local economic development. More recently, the growth-enhancing effect of institutions at the regional level has been remarked by Rodriguez-Pose (2013) and Rodríguez-Pose and Ganau (2022). In this paper, we use the Quality of Institutions (QI) index computed by Nifo and Vecchione (2014) as a composite index based on various measures of corruption, government effectiveness, regulatory quality, rule of law, and voice and accountability.[4]

Table 3. Descriptive statistics, indices (Italy = 100)

	North		Centre		South	
	2000	2019	2000	2019	2000	2019
Value Added (per capita)	113	113	105	102	63	61
Quality of Institutions (a)	135	132	112	118	54	55
Human capital	98	106	116	121	92	81
Social capital (b)	131	127	96	97	61	66
Technological capital	102	110	129	110	70	65

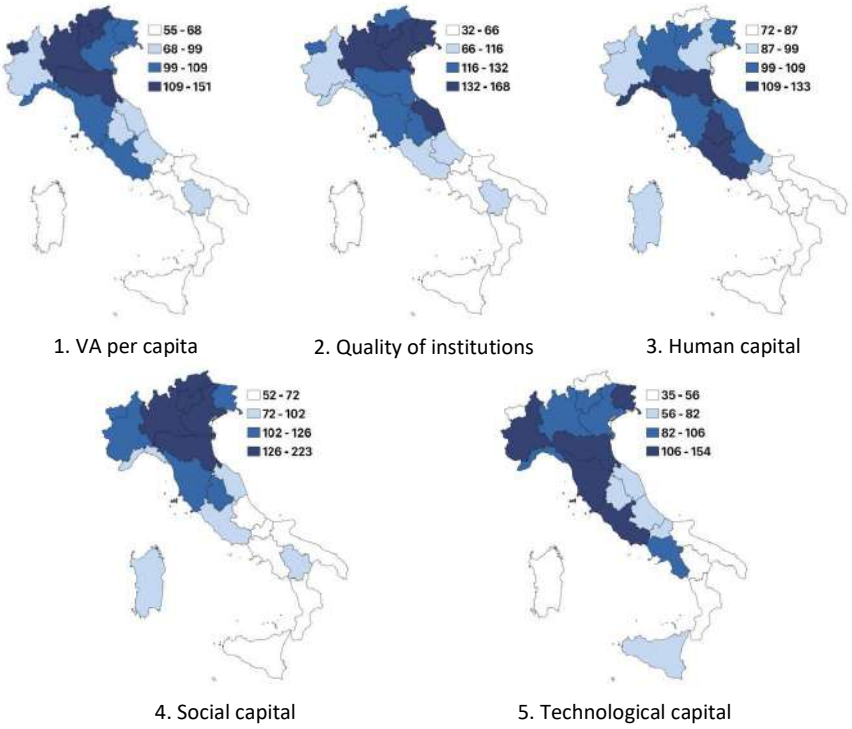
(a) initial year, 2004

(b) final year, 2018

Table 3 and Figure 3 show a clear dualistic pattern between Northern and Southern Italy for all the exogenous factors considered. In the case of Institutional Quality, the Southern average is about half of the national one, while the Northern average is 2.4 times higher than the Southern one. As expected, institutional quality is particularly low in territories characterized by the presence of criminal organizations such as Sicilia (32), Calabria (32), and Campania (42). Six out of the eight Southern regions are in the lowest quartile of the Institutional Quality index distribution, whereas Centre-Northern regions display much more variability with none of them in the lowest quartile. Social capital shows a less dramatic difference, but the gap between the South and the North is still remarkable, as the two areas are, on average, 65 percentage points apart. The regional differences are very high, with Trento showing in 2019 the highest value, which is 4.3 times higher

[4] This index is similar to the Quality of Government Index computed by Gothenburg University for the European regions (Charron et al., 2015).

Figure 3: Regional distribution of main variables, 2019



1. VA per capita
2. Quality of institutions
3. Human capital
4. Social capital
5. Technological capital

than the lowest one in Sicilia. Human capital shows a minor difference between Northern and Southern Italy. At the same time, Central regions have the highest level of graduates with an average value of 19% higher than the national one. Differences between Northern and Southern Italy have decreased over time for social capital and institutional quality, whereas they have increased for human capital (6 percentage points in 2000 vs 25 percentage points in 2019). Technological capital is similarly distributed as human capital: Central regions display the highest mean value, even if, in this case, it decreases with time (129 in 2000 vs 110 in 2019). In this case, Southern and Northern Italy show significant and growing differences (32 percentage points in 2000 vs 45 percentage points in 2019).

It is important to remark that intangible factors exhibit positive correlations. This is particularly true for the Quality of Institutions and social capital (0.78). We will consider this issue in the econometric estimations.

1.4. Methodology

The role of public capital in the Italian regions over the period 2000-2019 is assessed by estimating a Cobb-Douglas production function considering different levels of disaggregation of the total capital stock and including a set of controls for the regions' intangible factors and territorial characteristics. The general formulation of the model is:

$$Y_{it} = A_{it} L_{it}^{\alpha} K_{it}^{\beta} e^{\varepsilon_{it}}, \quad (1)$$

where the subscript *i* indicates the region, while *t* refers to the time period; *Y* is regional value added in constant prices 2010, *L* are units of labor, *K* is total capital stock; *A* represents the total efficiency level.

As argued in the previous sections, the total factor productivity is assumed to depend on the Quality of Institutions (*QI*), because it exerts a pervasive role in driving economic outcomes, especially when public bodies are directly involved in investment decisions and indirectly by setting the normative and regulatory framework. Moreover, to control for regional heterogeneity, we consider three immaterial factors: the endowments of human capital, social capital, and technological capital, which play a decisive role in enhancing the effectiveness of production inputs. Population density is also included to account for demographic trends and possible agglomeration effects. All the exogenous variables are included with a five-year lag, which allows us to consider a period long enough for the contextual variables to exert their effects on the dependent variable and guard against the potential problem of reverse causality.

As discussed in Section 1.3.1, the total capital stock can be disaggregated into private and public capital. The latter can also be split up according to the bodies in charge of carrying out the investments.

The empirical specification is obtained by log-linearizing Equation (1) and accounting for the lag structure discussed above:

$$\ln(Y_{it}) = \alpha \ln(L_{it}) + \beta \ln(K_{it}) + \delta \ln(QI_{it-5}) + \gamma South_i + \lambda_t + controls_{it-5} + \varepsilon_{it}. \quad (2)$$

To deal with the issue of potential endogeneity of the main productive inputs, we adopt an instrumental variable approach and the Two Stage Least Squares (2SLS) estimation method. Following Reed (2015) and the common practice usually adopted when it is very difficult to find valid external instrumental variables, we resort to the internal ones; hence, labor and capital stock are instrumented by their own lagged variables in all the estimated models. It is worth noting that lagged variables could not be valid instruments if they are correlated with unobserved confounders (Bellemare et al., 2017), to attenuate this problem, we have considered lags of five years. Although the choice of such a long lag comes at the cost of reducing the estimation sample size, it allows us to tackle endogeneity threats more effectively with respect to the case of shorter lags.[5] Notwithstanding such considerations, all the estimated effects must be interpreted cautiously.

In a preliminary analysis, we considered estimating Equation (2) by including regional fixed effects. However, such specification resulted in all coefficients of the explanatory variables being not significant at conventional levels. This could be due to the small-time dimension of the panel and to the fact that most explanatory variables exhibit persistent cross-region variation.

[5] We have also estimated the models with using as instruments for labor and capital stock variables their six-year lagged values. The results remain unchanged.

To take into account the time-invariant divide between the Centre-North and the Southern areas, we include a dummy variable *South* that takes the value of 1 for the eight Southern regions.[6] Finally, time dummies (λ_t) are included to account for common shocks at the macroeconomic level.

1.5. Findings – Discussion

Table 4 reports the main results. The first specification considers capital stock at the most aggregate level. The elasticity of labor is 0.6, while the total capital stock shows an elasticity of 0.38. With respect to previous studies on the Italian case covering the pre-crisis period (Marrocu and Paci, 2010) the estimated return appears higher for the capital input and lower for the labor input. The quality of institutions exhibits the expected positive and significant elasticity.

[6] In a preliminary analysis we also included a dummy variable for the 9 Northern regions, however no significant differences were found with respect to the reference group of regions, i.e. the 4 Centre ones.

On the contrary, the other intangible assets are not statistically significant; this unexpected result is reasonably due to the high collinearity among the contextual variables. We will return to this issue later. Among the territorial covariates, the population density shows a positive and significant impact signaling the relevance of agglomeration effects, while the dummy South has the expected negative sign, although it is not statistically significant.

Table 4. The effect of public capital on value added, 2000-2019

Dependent variable: value added

	(1)	(2)	(3)
Labour	0.602 ***	0.463 ***	0.461 ***
	(0.090)	(0.069)	(0.065)
Total capital	0.383 ***		
	(0.094)		
Private capital		0.233 ***	0.234 ***
		(0.042)	(0.041)
Public capital		0.362 ***	0.365 ***
		(0.049)	(0.045)
Quality of Institutions	0.039 **	0.096 ***	0.098 ***
	(0.018)	(0.018)	(0.019)
Contextual factors			
Human Capital	0.054	0.098 *	0.096 **
	(0.087)	(0.052)	(0.048)
Social capital	0.066	0.005	
	(0.047)	(0.025)	
Technological capital	0.013	-0.023	-0.023
	(0.028)	(0.023)	(0.023)
Population density	0.068 **	0.094 ***	0.094 ***
	(0.032)	(0.023)	(0.023)
South	-0.060	-0.082 ***	-0.084 ***
	(0.049)	(0.032)	(0.027)

Estimation method: Two Stage Least Squares (labour and capital variables are instrumented with their own 5-year lag)
All variables are log-transformed
Quality of Institutions and contextual variables are 5-year lagged
South, dummy variable = 1 for the eight Southern regions and 0 for the remaining regions
All models include time dummies and a constant
Robust Standard Error, in parentheses, are clustered at region level
Significance levels: ***(1%), **(5%), *(10%).
Cross-section observations (regions): 21
Number of panel observations: 315

In column 2 we include the capital stock according to its two components, private and public capital. They turn out to be both significant with the public stock displaying a higher elasticity (0.36) than the private one (0.23). The public capital elasticity is three times higher than the one Marrocu and Paci (2010) estimated for 1996-2003. Therefore, it seems that in recent years the role of public institutions in affecting production levels has increased.[7]

[7] We have also computed a more restricted definition of public capital, excluding the transfers to families and firms. Estimation results using the narrower definition of public capital for the baseline model (model 2, Table 4) are very similar. However, the public capital elasticity using the narrow definition (0.29) is lower with respect to the wider one (0.36).1

Interestingly, the human capital endowment turns out to be significant. The quality of institutions maintains its significance and shows a higher elasticity; this is also the case for population density. In this specification, the dummy South has a negative and significant coefficient signaling that, holding all other variables constant, the Mezzogiorno's regions are less than in the rest of the country.

As expected, the social capital coefficient is still not significant due to the high correlation with institutional quality (0.78). To avoid multicollinearity problems, we exclude the social capital variable in the subsequent analysis. Therefore, in (3) we report the estimation results obtained by excluding this variable.

In Table 5 we propose the results for models in which the public capital stock is included according to the institutional level of the administrative bodies in charge of carrying out public investments. We distinguish between c*entral* bodies (central administration and national public companies) and *local* bodies (regional and local administrations, local public companies). In model (1) of Table 5 we restrict the elasticities of public capital to be the same for the whole country and find that local bodies are slightly more effective (0.079) than central ones (0.060), as in Bom and Ligthart (2014). In model (2), when we allow the elasticities to vary between the two main macro-areas of the country, sizeable and significant differences emerge. Central bodies in the Southern regions exhibit a significantly higher elasticity (0.093) with respect to Centre-Northern ones (0.060), whereas the opposite is the case for local bodies. Northern regions exhibit an elasticity (0.092) much higher with respect to Southern ones (0.064).

Since our models include the quality of institutions and several other factors that are expected to account for North-South differences, varying administrative level elasticities could be due to such variables not being adequate to control for latent traits related to institutional quality (Durlauf, 2002), as they are inherently difficult to measure.

As explained in section 1.3.2, low levels of institutional quality are mostly found in southern regions; thus, to gain more insights and enhance our understanding of how the functioning of the institutions may influence the effectiveness of public investment, we propose an alternative specification in model (3). This is obtained by augmenting model (1) with four interactive variables. Both central and local bodies are interacted with two dummy variables capturing low/high levels of institutional quality. More specifically, the first dummy takes the value of 1 when the regional level of institutional quality is in the first quartile of its distribution (low level ofinstitutional quality), whereas the second dummy is equal to 1 for levels of institutional quality in the highest quartile (high levels of institutional quality).

Table 5. The effect of public capital by government bodies, 2000-2019

Dependent variable: value added

	(1)	(2)	(3)
Labour	0.620 ***	0.583 ***	0.477 ***
	(0.077)	(0.055)	(0.076)
Private capital	0.092 **	0.107 ***	0.209 ***
	(0.042)	(0.030)	(0.054)
Public capital:			
central bodies	0.060 ***	0.060 ***	0.069 ***
	(0.019)	(0.017)	(0.013)
local bodies	0.079 ***	0.092 ***	0.084 ***
	(0.012)	(0.009)	(0.011)
central bodies * South		0.033 *	
		(0.021)	
local bodies * South		-0.028 **	
		(0.015)	
central bodies * QI lowest quartile			0.018
			(0.013)
local bodies * QI lowest quartile			-0.018 **
			(0.010)
central bodies * QI highest quartile			-0.045 ***
			(0.013)
local bodies * QI highest quartile			0.027 ***
			(0.009)
Quality of Institutions (QI)	0.078 ***	0.072 ***	0.052 ***
	(0.014)	(0.017)	(0.010)
Contextual factors	yes	yes	yes
South	yes	no	yes

Estimation method: Two Stage Least Squares (labour and capital variables are instrumented with their own 5-year lag)
All variables are log-transformed
Quality of Institutions and contextual variables are 5-year lagged
Contextual factors: human capital, technological capital, population density
South, dummy variable = 1 for the eight Southern regions and 0 for the remaining regions
All models include time dummies and a constant
Robust Standard Error, in parentheses, are clustered at region level
Significance levels: ***(1%), **(5%), *(10%).
Cross-section observations (regions): 21
Number of panel observations: 315
See Table 2 for the list of bodies

When local bodies are in charge of public investments the effectiveness of public capital significantly increases with the level of institutional quality: the elasticity increases from 0.066 for the lowest levels of QI to 0.084 for the intermediate levels and up to 0.111 for the highest levels. Therefore, the high quality of regional institutions is particularly relevant for the local level of government.

As for central bodies, no significant differences in public capital elasticity (0.069) are detected between the case of regions with low vs intermediate (second and third quartiles) levels of institutional quality. On the contrary, at the highest level of institutional quality, public capital turns out to be less effective (0.024) compared to the intermediate-level case. Although this result is somewhat unexpected and deserves further investigation in future research, it seems to suggest

that in regions with the highest levels of QI, local bodies outperform central ones (public capital elasticity almost five times higher, 0.111 vs 0.024) because they are more capable of leveraging the direct knowledge of their territories and stakeholders and to benefit from a general level of trust in delivering their public interventions.

In general, the differences between central and local bodies could be related to the way of functioning of Italian public administrations, rooted in the country's historical development, so strongly influenced by its geography. As argued by Daniele et al. (2018), the process of modern growth that started in Italy in the late XIX century brought about structural changes, differentiated access to markets agglomeration dynamics that set the two macro-areas of the country on quite diverging paths, with the Northern one more densely interconnected with the wider and competitive European continental markets resulting in a more open and vibrant socio-economic environment (see also Felice 2019). Moreover, national economic policies have favored the Northern regions thus worsening the Italian territorial gap (Viesti, 2021). In recent years this process has been exacerbated by a strong migratory flow of highly qualified young people from the southern to the northern regions (Ballarino et al., 2022). This "brain drain" has further impoverished the endowment of human and technological capital in the South. Such a dualistic development process reasonably had important effects also on the administrative practices and ruling approaches of local government bodies in the North and in the South of Italy, although the legislation and the normative setting have been the same across the whole country. Additional arguments have been advanced by Bigoni et al. (2016) which, using a lab-in-the-field experiment, show that the persisting North-South divide can be explained in terms of a behavioral gap in cooperation due to differences in preferences, expectations, and social norms. At the same time, it can be argued that such a cooperative gap may be in turn the effect of the lack of development factors in the South (public infrastructures and services, human capital, innovation) rather than its cause.

No matter what, in the last three decades, Southern territories were incapable of taking advantage of the regional autonomy, enhanced by the 2001 devolution reform of Title V of the Italian constitution. For the Southern regions, the devolution resulted in a more fragmented political environment, higher pressure from specific stakeholders, and narrow administrative-decision capabilities to deal with the challenges the Mezzogiorno must confront. These include persistent issues, such as demographic trends, brain drain, low attractiveness for external investment, and the new ones brought about by the pandemic crises and the severe instability of the international scenario. These considerations help in explaining the estimated lower elasticities of Mezzogiorno's public capital once controlling for the positive role of institutional quality.

1.6. Policy implications and recommendations

This study has analyzed how the public capital stock and the institutions' quality influence regional economic performance. Such analyses are crucial to advance our understanding of the effectiveness of European and national economic growth policies and to assess the ability of the

local institutions in Italy to efficiently invest the vast NRRP resources they are about to receive to boost the economy after the pandemic crisis.

The first result is that public capital stock plays a positive role in driving the production level, with a higher elasticity than the private one. A second important finding is the role played by the quality of institutions; a factor often neglected in previous studies on production function estimation because of a lack of reliable data. The positive and significant elasticity exhibited in all specifications remarks the importance of public institutions for fostering the development processes and enhancing economic growth. On this regard, more research is needed to disentangle the complex mechanisms through which local institutions, directly and indirectly, influence the regions' economic performance (Rodriguez-Pose, 2020).

Considering the disaggregation into government levels, it turns out that in Southern Italy, central bodies display a higher elasticity than the Centre-North. The opposite result is found for the local bodies, which prove much less effective in the Southern regions. Our analysis provided sound evidence that the effectiveness of public capital managed by local bodies significantly increases with the level of institutional quality, which has been persistently low in the Mezzogiorno of the country.

This might be rooted in the country's historical development strongly influenced by its geography. Moreover, the macroeconomic factors and the economic policy choices of the national governments contributed to worsen the North-South gap triggering a vicious circle. The Southern regions have been characterized by less development, less provision of public services and infrastructures, less employment opportunities, brain drain, and further reduction of human capital and innovation. The combination of these deep-root factors with current economic dynamics could also have shaped the different ways of public administrations functioning across the macro-areas of the country.

The low elasticity estimated for the public capital stock realized by Southern local administrations cast shadows on the success of NRRP and other cohesion policies. More than 120 billion euros should be invested by the local institutions in the Southern regions respecting the EU rigorous rules in the next years. The inefficiency and inadequacies that characterized Southern local administrations might have determined the policy's failure, losing a unique opportunity to narrow the economic gap between North and South Italy.

To avoid these negative consequences, it is necessary to act urgently at least in two directions. In the short run, since the programs must be in place immediately and the expenditures completed in a few years, the central government must help the local administrations by making available in each Southern region a task force of experts to follow the implementation phases of the programs.

At the same time, it is imperative to urgently adopt long-term policies to address the profound and structural issues related to the low institutional quality of the Southern regions in Italy. As our results have shown, Mezzogiorno's low quality of institutions is one of the most relevant factors that continue to slow down its development. As previously discussed, the causes of such negative features are numerous, complex, intertwined, and deep-rooted in the historical and economic development of the South. Therefore, improving the quality of the local institutions is not an easy task, as demonstrated by decades of failures of the North-South territorial rebalancing policies in Italy. If local institutions' quality is rooted in the country's historical development and in decades

of vicious economic twist, it cannot be simply changed or improved by a central government law. What is needed is a profound change in the Southern regions in people's social norms and individual behaviors, which can be attained, in our opinion, only through a long-term education policy. Investing, for a long period, considerable human and financial resources in the schooling and university system in the Southern regions seems the only policy able to break the persistent territorial divide in Italy and activate a virtuous and self-reinforcing mechanism by which increasing levels of human capital create a more favorable local environment for families and firms and contribute to further enhance the quality of institutions.

Finally, it is worth noting that our results also have external validity. Several European regions, or even countries, share with the Italian Mezzogiorno similar structural gaps – in terms of human capital, quality of institutions, innovative capacity, and per capita income – and have to confront the challenge of effectively managing the EU Next-generation funds to recover from the pandemic crisis and to counterbalance the international scenario instability.

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1.8. Technical Appendix

Table A1. Data sources and definition

Variable	Primary Source	Years	Definition
Value Added	Eurostat	2000-2019	Millions euros, constant price 2010
Labour	Eurostat	2000-2019	Units of labour, thousands
Gross fixed capital	Istat	2000-2019	Millions euros, constant price 2010
Public investment	Conti Pubblici	2000-2019	Millions euros, constant price 2010
Total capital stock	Own calculation	2000-2019	Millions euros, constant price 2010
Public capital stock	Own calculation	2000-2019	Millions euros, constant price 2010
Private capital stock	Own calculation	2000-2019	Millions euros, constant price 2010
Quality of Institutions	Nifo & Vecchione (2014)	2000-2019 **	Composite index based on Corruption, Government effectiveness, Regulatory quality, Rule of law,
Human Capital	Eurostat	2000-2019	Population aged 25-64 with tertiary education (Isced 5-8) over total population 25-64, %
Technological capital	Eurostat	2000-2019	R&D expenditure over GDP (%, variables in 2010 prices). R&D computed as 3-yeras moving average
Social capital	Istat, Multiscopo	2000-2018 *	People aged 14 and over who volunteered on the total population aged 14 and over (percentage)
Population density	Eurostat	2000-2019	Persons per square kilometre

* Year 2019 has been assumed equal to 2018

** Years 2000-2003 have been computed using the time dynamics over the years 2000-2004 for the available simple indicators

2. Modelling Infrastructure Gaps in Italian Municipalities (2016-2022) *(Angela Stefania Bergantino, Giuseppe Di Liddo, Mario Intini, Francesco Porcelli - UniBA)*

2.1. Introduction

Focusing on the period from 2016 to 2022, leveraging data from the Banca Dati delle Amministrazioni Pubbliche (BDAP), we constructed a granular dataset comprising over 1,000 variables to assess municipal expenditures and infrastructural characteristics of Italian municipalities. Our study develops and applies a series of gap indicators to measure the discrepancies between actual and standard capital expenditures across various sectors, including waste management, local transport, roads, and cultural services.

The aim of the analysis is to propose a quantitative procedure concerning two objectives: i) the construction of an original dataset including structural and financial information, and ii) the evaluation of the gap between the actual capital expenditure and the infrastructure needs.

We introduce a methodological framework that utilizes advanced data fusion and integration techniques, providing a robust basis for longitudinal analysis. Key indicators, such as the Waste Management Gap Indicator (WMGI), Local Transport and Roads Gap Indicator (TRGI), and Cultural Services Gap Indicator (CSGI), highlight the infrastructural gaps at the municipal level. These indicators are illustrated through cartograms that illustrate geographical disparities and improvements over time.

Our analysis includes all Italian municipalities. We examine municipal data such as capital transfers, expenditure rigidity, and loan repayment expenditures, highlighting municipalities' fiscal constraints and capabilities. Our data show that municipalities account for 20% of total public investments, with total capital expenditure exceeding €15 billion in 2022, marking a 36% increase since 2016. However, there are stark differences in expenditure capacity between northern and southern municipalities, with the latter facing significant challenges in implementing investments. Our findings reveal significant regional disparities in infrastructure endowment and service delivery, underscoring the critical need for targeted investments to enhance local resilience and attractiveness. The study also proposes the Total Services Gap Indicator (TSGI) to evaluate the overall infrastructural gap, integrating data on population, municipal area, and urbanization levels.

The rest of the paper is organized as follows: section 2 presents a critique literature review of the existing methodologies related to the estimation of standard capital expenditure requirements at local level, section 3 illustrates the data used in our analysis, section 4 details the empirical methodology and gap indicators developed for this study, and section 5 discusses the results, highlighting regional disparities and the effectiveness of current investment strategies. Finally, section 6 concludes with policy recommendations aimed at improving infrastructure investment and management across Italian municipalities.

2.2. Literature review

This research contributes to the literature on fiscal federalism by providing empirical insights into the capital LENs of Italian municipalities. It offers a quantitative procedure for assessing infrastructure gaps, which is essential for designing efficient equalization transfers and strategic planning.

Estimating standard requirements is a first necessary step towards building an efficient and mechanism for the distribution of equalization transfers. In literature (see Dafflon and Mischler, 2007 for a complete survey) several allocation techniques have been proposed in recent years which differ for their complexity and the informative setting size they needed. The most used methods, namely those based on the cost function - in the full or reduced form - focus, however, on Local Authorities current expenditure part and do not propose any solution for the capital part (Herrero-Alcalde et al., 2010; Porcelli 2015).

Among the few methodological published contributions (see Levtchenkova and Petchey, 2007, Petchey et al., 2000, Sharma and Bhanumurthy, 2011) it's hard to find a basic theoretical model that can be used as a reference for the Italian infrastructure local expenditure needs. Notwithstanding the absence of benchmark model, however, in the literature, an important common thread can be found: the need to evaluate the existing capital stock both in physical and monetary terms; this twofold requirement represents an important dissimilarity factor with respect to the methodological paths usually follow for the standardization of current expenditure.

In the literature, there are two main approaches to measuring infrastructural endowment (public capital): estimating it in physical terms or in monetary terms by means of Perpetual Inventory Method, suggested by Goldsmith (1951) and now used by most national statistics institutes (a critical survey of both applications is in Mazziotta, 2005). The monetary measurement of public capital certainly has advantages (great uniformity and flexibility, properties of additivity, etc.). Nevertheless, regional disparities in infrastructural transport endowment can probably be better grasped by estimates expressed in physical terms. This is above all because sometimes radically diverse topography (chiefly, mountainous terrain in some places) means that equal investment in money amounts is not equivalent.

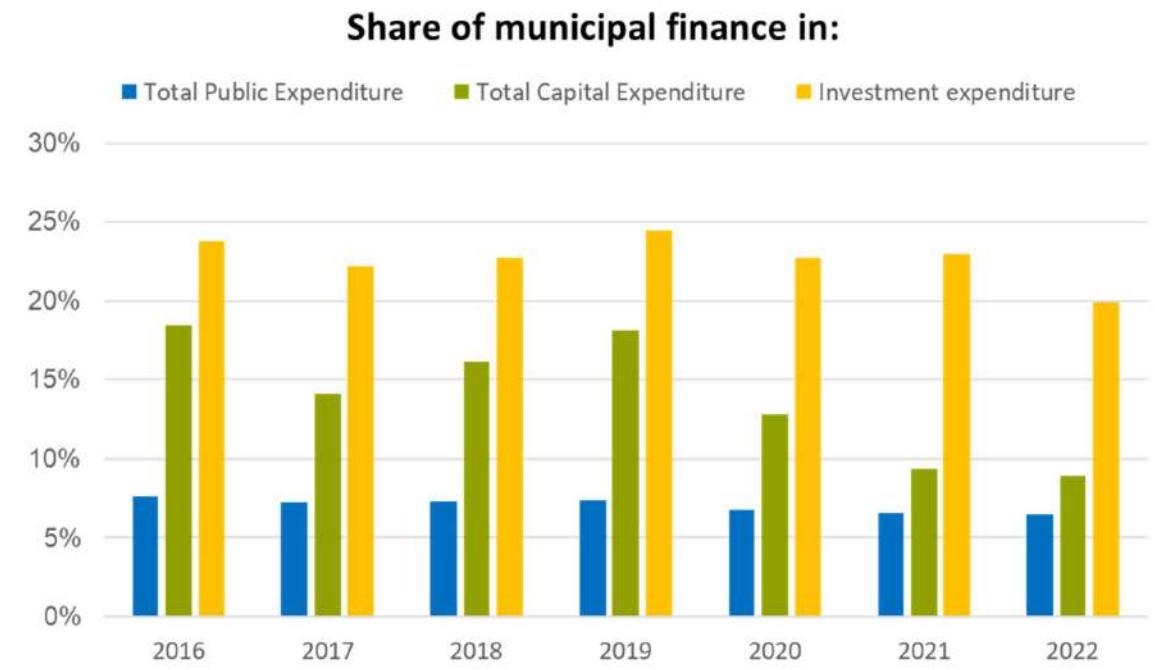
The two mentioned approaches are usually alternatives; however, in our analysis, we will concentrate on the monetary evaluation, specifying a representative expenditure system model for capital expenditure which relates historical capital expenditures to local context characteristics. We will then use the fitted values of the model to obtain an estimate of capital expenditure needs in order to estimate the infrastructural gap in monetary terms as the difference between standard and historical expenditures when the former is larger than the latter.

2.3. Empirical analysis

2.3.1. Data

The assessment of the Italian infrastructural gap relies on the measurement of actual capital expenditure, providing a direct evaluation of ongoing and completed investments.
Since local governments manage 20% of public investment, municipalities play a central role in determining Italy's infrastructural landscape. The Banca Dati delle Amministrazioni Pubbliche (BDAP) serves as the primary source of detailed municipal financial data. This database provides comprehensive information on both current and capital expenditure, broken down by service categories such as "missioni" and "programmi," and includes both accrual and cash values. The panel structure of this data spans from 2016 to 2022, covering all 7,901 Italian municipalities and incorporating over 1,000 variables.
Data for the computation of the indicators are primarily sourced from the "Banca Dati delle Amministrazioni Pubbliche (BDAP)", focusing on accrual-based capital expenditures by service. The period of analysis spans from 2016 to 2022, encompassing all Italian municipalities (7,901 local authorities) and integrating expenditures with contextual variables such as population, municipal area, and urbanization level. This comprehensive approach allows for a robust evaluation of infrastructural needs across Italy, where municipalities account for 20% of total public investments.

Figure 1- Share of municipal finance



Source: General government statistics (annual account)

The measurement of actual capital expenditure is a critical factor in evaluating infrastructural gaps and future needs across municipalities. This data provides valuable insight into the allocation and execution of public investments. Municipalities are pivotal actors in Italy's public investment framework, playing a crucial role in addressing local infrastructural needs and

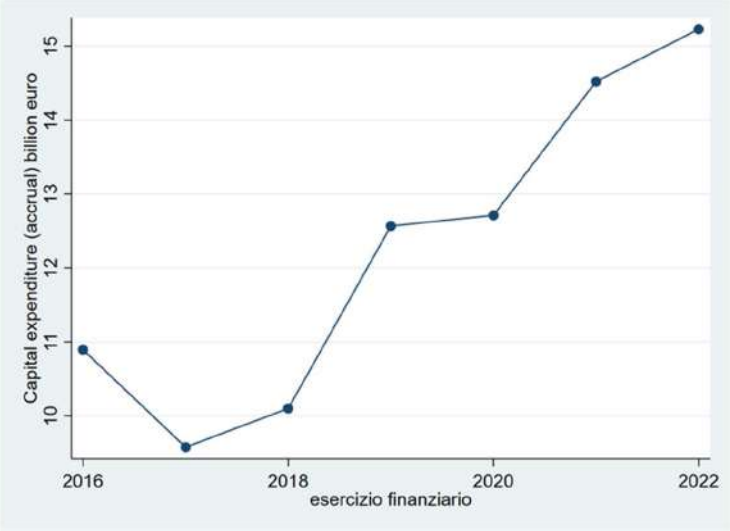
contributing to the nation's overall economic development. Although municipalities manage only 7% of total public expenditure, they are responsible for 9% of the total capital expenditure, demonstrating their significant influence in areas requiring long-term investment and development.

As shown in Figure 1, In terms of public investments, municipalities oversee 20% of the total, highlighting their central position in executing projects aimed at improving local infrastructure, services, and economic growth. These investments are essential not only for urban centers but also for more remote areas, where they address specific needs in mobility, public services, and other sectors critical for local development.

The ability of municipalities to manage and execute these investments directly impacts regional development patterns, influencing disparities between urban and rural or inland areas. Their allocation of resources, particularly in sectors such as transportation and public services, directly shapes the quality of life and economic opportunities within their jurisdictions.

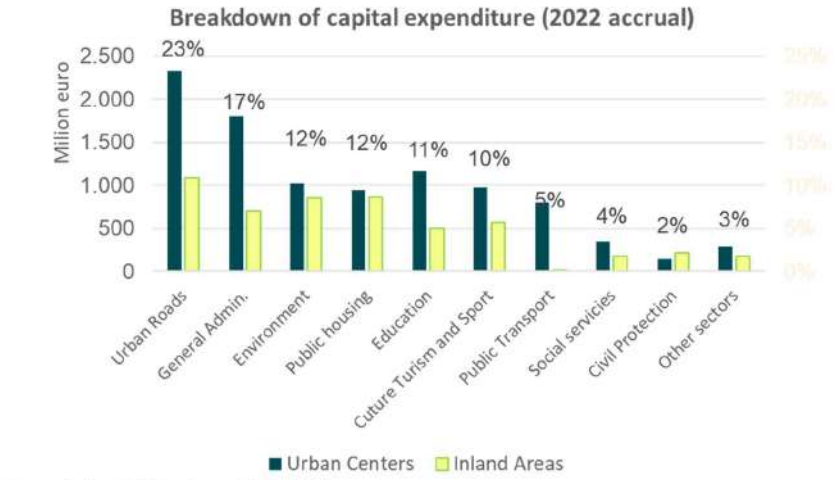
As shown in Figure 2, Italian municipalities have seen a notable rise in capital expenditures over recent years, reflecting their increasing role in driving local infrastructure development and public investment. In 2022, the total capital expenditure by municipalities surpassed 15 billion euros, marking a significant contribution to public investments. From 2017 onwards, there has been a clear upward trend in municipal capital spending, with a real-term increase of 36% since 2016, mainly as a result of the introduction of new fiscal rules. This growth underscores the expanding scope of municipal involvement in critical infrastructure projects, such as transportation, public services, and urban development, which are crucial to regional development and addressing infrastructural gaps across the country. This rising trend demonstrates municipalities' growing capacity to manage and execute substantial investments, reinforcing their role in shaping Italy's economic landscape at the local level.

Figure 2 – Trend in municipal capital expenditure



Source: Authors' elaboration on BDAP database (real values, 2022 base year)

Figure 3 – Structure of municipal capital expenditure



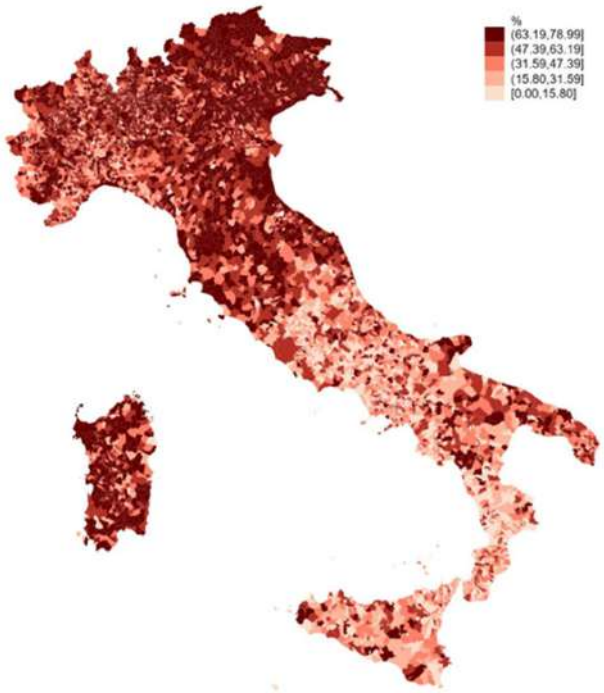
Source: Authors' elaboration on BDAP database

As shown in Figure 3, in 2022, Italian municipalities allocated a significant portion of their capital expenditures toward enhancing mobility, a critical sector for both urban and rural development. 23% of total municipal capital expenditures were directed toward urban roads, while 5% went to public transportation. These investments reflect the focus on improving transportation infrastructure, which is vital for connectivity, economic activity, and quality of life in both densely populated and remote areas. However, urban centres and rural or inland areas display differing patterns in how these funds are utilized. While urban regions generally benefit from more efficient investment, the southern and rural areas of Italy face persistent challenges in implementing infrastructural projects. These disparities underscore the difficulties in addressing the needs of more isolated or economically disadvantaged regions. Urban centres tend to focus more on projects aimed at modernizing transportation networks, improving public transit systems, and

addressing the needs of a growing population. In contrast, inland and rural areas often face challenges in implementing such investments due to geographical, economic, or logistical constraints, leading to slower progress in infrastructure development. This divergence in spending patterns highlights the differing needs and priorities of municipalities across Italy, as well as the ongoing effort to address infrastructural imbalances between urban and rural regions.

The capital expenditure capacity of municipalities, defined as the ratio between cash and accrual values, provides key insights into the efficiency of investment implementation across regions. At the national level, the average expenditure capacity stands at 55%, indicating that just over half of the planned investments are executed in cash terms relative to their accrual commitments.

Figure 4 – Geographical distribution of Capital Expenditure Capacity



Source: Authors' elaboration on BDAP database (year 2022)

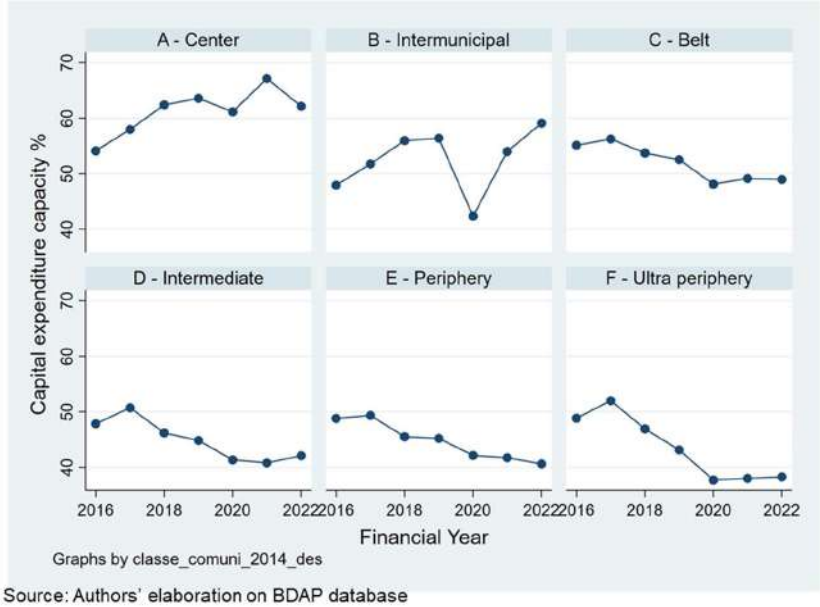
However, as shown in Figure 4, there is a notable divide between northern and southern municipalities. Northern municipalities tend to outperform the national average, demonstrating a higher capacity to execute planned investments efficiently. In contrast, southern municipalities typically fall below the national average, reflecting greater challenges in translating planned investments into tangible projects. Despite these difficulties, certain regions in the South, such as Sardegna, Puglia, and Basilicata, serve as exceptions. These regions have managed to overcome some of the common barriers to investment and exhibit relatively higher capital expenditure capacities compared to their southern counterparts. Nonetheless, the broader trend indicates persistent challenges in implementing investments in the South, which can hinder efforts to address regional disparities in infrastructure development.

As reported in Figure 5, when analysing the capital expenditure capacity (cash/accrual values) across urban and rural areas, a clear contrast emerges in the ability to implement planned investments. In urban areas, the expenditure capacity is generally above 50% and has been increasing over time. This indicates that municipalities in urban centres are progressively becoming more efficient in executing their investment plans, reflecting better infrastructure, financial management, and project execution capabilities.

Conversely, in rural areas, the expenditure capacity tends to fall below 50% and has been decreasing over time. This suggests increasing difficulties in implementing planned investments in these regions, where logistical, financial, and administrative barriers may impede the effective execution of projects.

These trends underscore the challenges rural areas face in infrastructure development, leading to a growing disparity between urban and rural regions in terms of capital investment capacity. The lower efficiency in rural areas further exacerbates existing infrastructural gaps, limiting growth and development in the periphery compared to more dynamic urban centers.

Figure 5 – Distribution of Capital expenditure Capacity between central and peripherical municipalities



Source: Authors' elaboration on BDAP database

2.3.2. Methodology

According to fiscal federalism principles, implementing efficient infrastructural equalization, provides that a comparison of the infrastructure service levels with the corresponding service standards should be implemented using appropriate indicators to measure any deviations. The literature provides several contributes about current expenditure connected to local services, but

it is hard to find significant proposals for public capital expenditure estimation. The research package will aim to propose a quantitative procedure concerning two objectives: i) the evaluation of the gap between the effective infrastructural endowment and the infrastructure needs deduced from the factors of demand generation; ii) the conversion in monetary terms of this gap.

Estimating standard requirements is a first necessary step to design an efficient mechanism for the distribution of equalization transfers. The literature (see Dafflon and Mischler, 2007) provides several allocation techniques with different degrees of complexity and informative setting size. The most used methods, namely those based on the cost function - in the full or reduced form - focus, however, on Local Authorities' current expenditure and do not propose any solution for capital expenditure (Herrero-Alcalde et al., 2010; Porcelli, 2015). Among the few methodological articles (see Levtchenkova and Petchey et al., 2000, Sharma and Bhanumurthy, 2011), it's hard to find a basic theoretical model that can be used as a benchmark for the Italian local expenditure needs in infrastructure. However, an important common characteristic can be found in the theoretical literature: the need to evaluate the existing capital stock in physical and/or monetary terms (Goldsmith, 1951; Mazziotta, 2005).

The objective of our analysis is to propose an empirical framework to evaluate the local expenditure needs in infrastructure, considering the supply and demand factors measuring the existing infrastructural gap. The focus will be on the local transport, culture and environmental (waste management) infrastructure for the Italian territories (municipalities, provinces, metropolitan districts and regions) where municipal expenditure covers almost all the public investments in those public functions.

Regional disparities in infrastructural transport, culture, and waste management endowment could be better grasped by estimates expressed in physical terms. Indeed, sometimes radically diverse topography means that equal investment in money amounts is not equivalent in physical unity across the regions. However, the monetary measurement of public capital certainly has advantages in terms of great uniformity and flexibility, properties of additivity, etc. The estimated monetary differences between expenditure and physical endowment allows us to obtain the representative estimated price/cost of the considered infrastructure.

The Infrastructure Gap Indicator (GAP) measures the per capita monetary difference between actual and standard capital expenditures in a due sector (waste management, local transport, etc.) or more sectors (sum of expenditures in different sectors) at the municipal level. The standard is defined as the national average capital expenditure from 2016 to 2022, weighted by the following variables:

Resident population,
Municipal area in square kilometres,
Classification of municipalities into six urbanization clusters: Center, Intermunicipal, Belt, Intermediate, Periphery, and Ultra-periphery.

The evaluation of the Capital Expenditure Gap for the year 2022, for each municipality i, corresponds to the following formula in equation (1):

$$\mathrm{GAP}_i^{2022} = \frac{SEXP_i - HEXP_i^{2022}}{Pop_i^{2022}}, \quad if\ SEXP_i > HEXP_i^{2022}$$

Where:

- *i* indicates the municipality index;
- $HEXP_i^{2022}$ corresponds to the historical capital expenditure allocated to the waste management service in 2022;
- Pop_i^{2022} corresponds to the resident population of the municipality in the year 2022;
- $SEXP_i$ corresponds to the standard capital expenditure computed as the average capital expenditure at the national level between 2016 and 2022 conditional on the population of the municipality, the surface of the municipality in Km sq. and, finally, to the classification of the municipalities into six urbanization clusters (Center, Intermunicipal, Belt, Intermediate, Periphery, and Ultra-periphery).

In particular, $SEXP_i$ is obtained from the fitted values of the following regression model and reported in equation (2), estimated using Ordiary Least Squares (OLS) with robust standard errors:

$$HEXP_{it} = \beta_0 + \sum_b \beta_b Pop_dummy_{it}^b + \beta_2\, Kmsq_i + \sum_r \gamma_r Rural_dummy_{it}^r + \varepsilon_{it} \qquad (2)$$

Where:

- *i* indicates the municipality index;
- *t* indicates the year indicator since we employ a panel of seven years for the analysis;
- $Pop_dummy_{it}^b$ corresponds to the resident population brackets to which of the municipality belongs to;
- $Kmsq_i$ corresponds to the surface in km sq. of the municipality;
- $Rural_dummy_{it}^r$ corresponds to the specific classification of the municipalities among the six categories of the rural vs urban area;
- β_0 is the constant of the model;
- β_b are the coefficients associated with the population brackets;
- γ_r are the coefficients associated with the rural vs urban categories;
- ε_{it} is the idiosyncratic error of the model.

We apply this methodology to three expenditure categories which have particular importance in the modern systems of decentralized finance: waste management, local transport, and cultural services.

Municipal waste management expenditure has a significant impact on environmental sustainability. Proper waste management practices are essential for reducing the environmental footprint of communities and promoting a healthier planet. When municipalities invest in waste management infrastructure and programs, they can effectively mitigate the negative effects of waste on the environment.

Municipal waste management expenditure plays a critical role in promoting environmental sustainability. Investments in infrastructure, recycling programs, and effective policies can lead to significant environmental benefits, including reduced pollution, resource conservation, and lower greenhouse gas emissions. However, the success of these expenditures hinges on equitable funding distribution, efficient management, and strong policy frameworks. As municipalities continue to grapple with waste management challenges, it is essential to prioritize sustainable practices and ensure that expenditure translates into tangible environmental benefits.

Effective **local transport** systems are vital for economic development. They facilitate the movement of goods and people, reducing travel time and costs associated with commuting. Improved transport connectivity attracts businesses, boosts local economies, and creates job opportunities. For instance, cities with well-developed public transport networks, such as New York and Tokyo, experience robust economic activity and higher employment rates. Public transit systems also enhance property values, as areas with good accessibility become more desirable for residential and commercial investments.
Local transport systems play a crucial role in promoting social inclusion and accessibility. Reliable and affordable public transport ensures that all individuals, including those from low-income backgrounds and people with disabilities, have access to essential services such as healthcare, education, and employment. In cities like Copenhagen, the extensive bike-sharing programs and pedestrian-friendly infrastructure exemplify how thoughtful transport planning can enhance accessibility and inclusivity. Improved transport systems reduce social isolation and enable greater participation in community activities, fostering a more cohesive society.

Local culture expenditure significantly contributes to the economic vitality of municipalities. Funding cultural events, museums, theatres, and other cultural institutions stimulates the local economy by attracting tourists, generating revenue, and creating jobs. For instance, cities like Edinburgh, known for its renowned festivals, benefit economically from cultural tourism, which supports local businesses and increases tax revenues. Additionally, cultural investments can lead to the regeneration of urban areas, turning neglected neighbourhoods into vibrant cultural districts, thereby attracting further private investment and boosting property values.
The cultural life in a municipality is closely linked to the quality of life too. Cultural amenities such as theatres, galleries, music venues, and public art installations enrich residents' lives, providing leisure and educational opportunities. Cities like Paris and Vienna, renowned for their rich cultural offerings, consistently rank high in quality-of-life indices, attracting new residents and businesses. Furthermore, cultural vibrancy makes cities more attractive to skilled professionals and creative industries, fostering an innovative and dynamic urban environment. This, in turn, can lead to a virtuous cycle where increased attractiveness attracts more cultural investments, further enhancing the city's appeal.

In general, local capital expenditure refers to the funds allocated by municipalities towards the development and maintenance of long-term assets, such as infrastructure, public facilities, and technological systems. These investments are critical for enhancing local resilience, which is the ability of a community to withstand, adapt to, and recover from adverse situations such as

economic downturns and social challenges. This essay explores how local capital expenditure influences local resilience, focusing on infrastructure, public services, and technological advancement.

Despite the clear benefits, there are challenges associated with capital expenditure. Ensuring equitable distribution of funds and prioritizing projects that offer the most significant resilience benefits can be difficult. Additionally, long-term planning and sustained investment are required to realize the full potential of capital projects, which can be challenging in the face of budget constraints and political changes. Municipalities must also balance immediate needs with future risks, ensuring that capital expenditure addresses both current vulnerabilities and anticipated challenges.

2.3.3. Results

The Waste Management Gap Indicator (WMGI) measures the per capita monetary difference between actual and standard capital expenditures in waste management at the municipal level. The standard is defined as the national average capital expenditure from 2016 to 2022. The indicator is depicted in three panels on a cartogram in Figure 6.

Similarly, the Local Transport and Roads Gap Indicator (LTRGI) measures the per capita monetary difference between actual and standard capital expenditures in local transport and road maintenance at the municipal level. This standard is also defined as the national average capital expenditure from 2016 to 2022. The indicator is depicted in three panels on a cartogram in Figure 7.

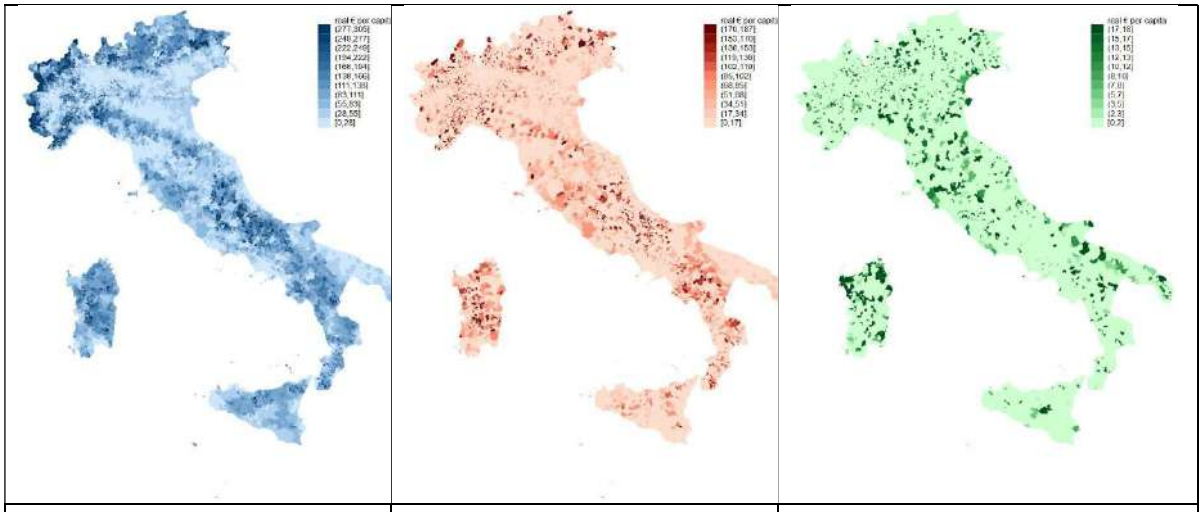
Using the same graphical analysis, Figure 8 reports the Cultural Services Gap Indicator (CSGI), which measures the per capita monetary difference between actual and standard capital expenditures in cultural services at the municipal level. This standard is defined as the national average capital expenditure from 2016 to 2022.

Finally, Figure 9 displays the Total Services Gap Indicator (TSGI), which measures the per capita monetary difference between total actual and standard capital expenditures at the municipal level. This standard is defined as the national average capital expenditure from 2016 to 2022.

In all figures from 6 to 9, the left panel shows the geographical distribution of the standard capital expenditure per capita, reflecting the infrastructural needs. The middle panel displays the infrastructural gap, defined as the difference between the standard and the actual capital expenditures in 2022, when the standard is higher than the actual expenditure. The right panel highlights municipalities that reported a gap smaller than in 2016 in real terms in 2022, indicating some progress in bridging the gap.

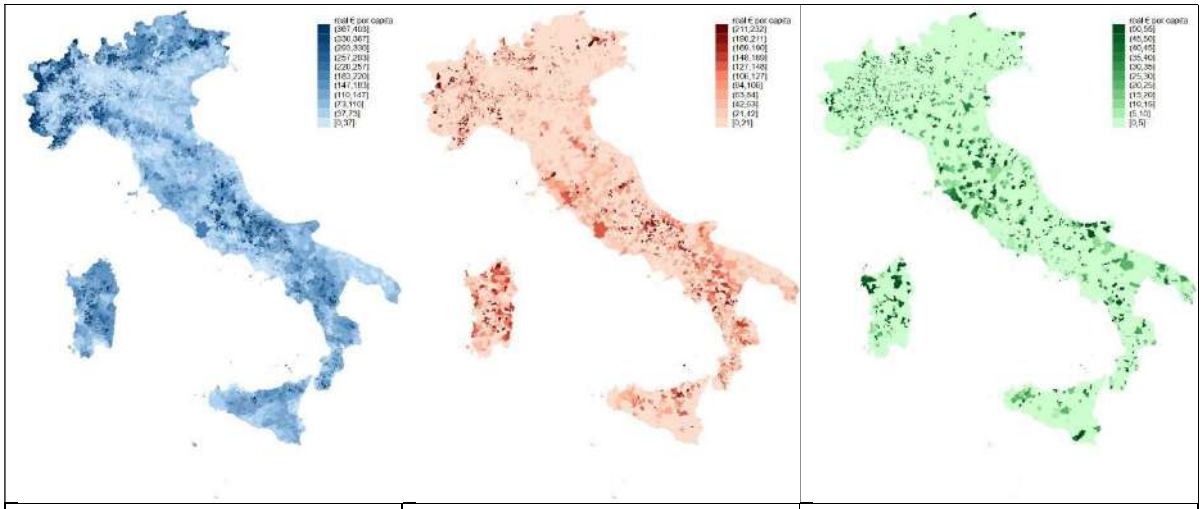
Each indicator provides an estimate of the infrastructural gap in monetary terms for the respective sector at the municipal level as measured in 2022, considering changes from 2016 to 2022."

Figure 6: Waste management capital expenditure gap, euro per capita



WSEXP	WGAP	WGAP2022 – WGAP2016
Waste management Standard Capital Expenditure (average over 2016-2022) (a)	Waste management Capital expenditure Gap 2022 = (Standard capital expenditure – Historical Capital expenditure 2022, if Standard > Historical) (b)	Waste management Gap improvement (Gap 2022 – Gap 2016. if Gap 2022 < Gap 2016) (c)

Figure 7: Local Transport and Roads capital expenditure gap, euro per capita



LSEXP	LGAP	LGAP2022 – LGAP2016
Local Transport and Roads Standard Capital Expenditure (average over 2016-2022) (a)	Local Transport and Roads Capital expenditure Gap 2022 = (Standard capital expenditure – Historical Capital expenditure 2022, if Standard > Historical) (b)	Local Transport and Roads Gap improvement (Gap 2022 – Gap 2016. if Gap 2022 < Gap 2016) (c)

Figure 8: Cultural services capital expenditure gap, euro per capita

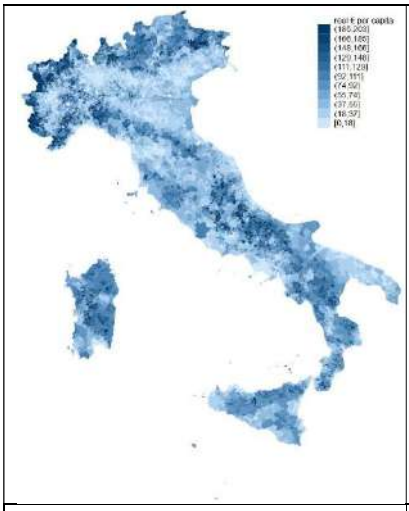
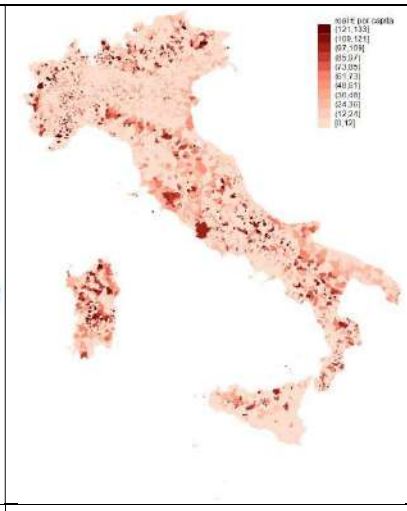
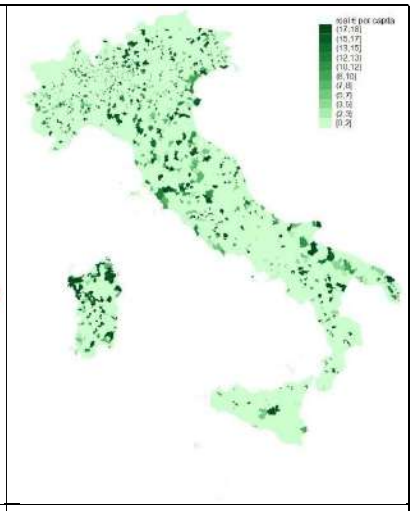
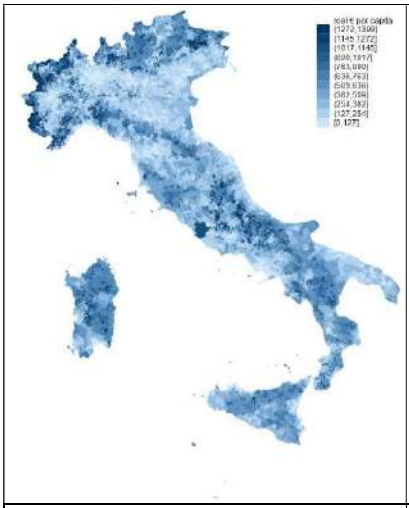
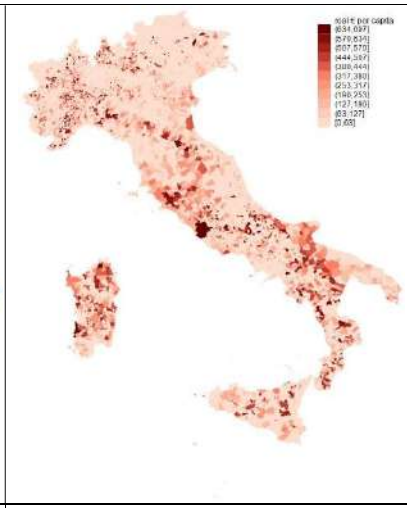
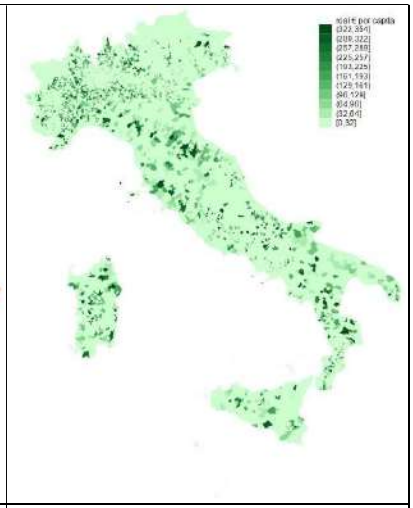
		
CSEXP **Cultural services** **Standard Capital Expenditure** **(average over 2016-2022)** **(a)**	**CGAP** **Cultural services** **Capital expenditure Gap** **2022 = (Standard capital** **expenditure – Historical** **Capital expenditure 2022, if** **Standard > Historical)** **(b)**	**CGAP2022 – CGAP2016** **Cultural services** **Gap improvement** **(Gap 2022 – Gap 2016.** **if Gap 2022 < Gap 2016)** **(c)**

Figure 9: Total capital expenditure gap, euro per capita

		
TSEXP **Total services** **Standard Capital Expenditure** **(average over 2016-2022)** **(a)**	**TGAP** **Total services** **Capital expenditure Gap** **2022 = (Standard capital** **expenditure – Historical** **Capital expenditure 2022, if** **Standard > Historical)** **(b)**	**TGAP2022 – TGAP2016** **Total services** **Gap improvement** **(Gap 2022 – Gap 2016.** **if Gap 2022 < Gap 2016)** **(c)**

2.4. Discussion

The environmental dimension of the infrastructural gap in waste management services measures how inadequacies affect ecological systems. It focuses on aspects like pollution levels (air and water), waste accumulation (landfill overflow and illegal dumping), resource depletion (recycling rates and waste diversion), and biodiversity impact (habitat disruption and species at risk). This indicator helps governments assess the effectiveness of their waste management systems and guides policy decisions to address infrastructure gaps.

The static dimension of the infrastructural gap in waste management service focuses on the status and characteristics of existing waste management facilities. It typically includes data such as the number and capacity of waste processing and disposal facilities, the geographical distribution of these facilities, and the extent of technological adoption (e.g., advanced recycling processes and waste-to-energy systems). This dimension helps in understanding the baseline infrastructure available and identifies areas lacking sufficient waste management capabilities, crucial for strategic planning and development.

The accessibility dimension of the indicator for the infrastructural gap in the transport and road maintenance sector for municipalities evaluates how limitations in infrastructure affect transportation efficiency and access. It concentrates on aspects such as road network density (coverage of roads in relation to area and population), road condition (percentage of roads in good, fair, and poor condition), public transport availability (frequency and reach of buses, trams, etc.), and connectivity (ease of access to main economic centres and services). This indicator assists local governments in assessing the adequacy of their transportation networks and supports decision-making to enhance mobility and accessibility across municipalities.

The static dimension of an indicator for the infrastructural gap in the local transport and road maintenance sector of municipalities focuses on the status and characteristics of existing transport infrastructure. It typically includes data such as the length and condition of road networks, the number and types of public transportation facilities (bus stations, tram lines, etc.), the geographical distribution of these assets, and the extent of technological adoption (e.g., smart traffic management systems, electronic toll collection). This dimension aids in understanding the baseline transport infrastructure available and identifies areas lacking sufficient road maintenance and transportation services, crucial for strategic planning and urban development.

The attractiveness dimension of the indicator for the infrastructural gap in the cultural sector of municipalities measures how inadequacies affect the sector's appeal and vitality. It focuses on aspects like the variety and quality of cultural offerings (performances, exhibitions, workshops), the condition and appeal of cultural facilities (museums, theatres, galleries), community engagement levels, and the economic impact of cultural activities (tourism, local business support). This indicator helps local governments assess the attractiveness and competitiveness of their cultural infrastructure and guides policy decisions to enhance the cultural appeal, drawing both residents and visitors to enrich the local community.

The static dimension of the indicator for the infrastructural gap in the cultural sector of municipalities focuses on the current status and characteristics of existing cultural facilities and services. It typically includes data such as the number and types of cultural institutions (museums, theatres, libraries, etc.), the capacity and utilization rates of these facilities, the geographical distribution across the municipality, and the extent of technological adoption (e.g., digital archives, online access to collections). This dimension aids in understanding the baseline cultural infrastructure available and identifies areas lacking sufficient cultural services, crucial for strategic planning and enhancing cultural accessibility and engagement.

The resilience dimension of an indicator for the total capital expenditure in infrastructural services provided by municipalities measures how robustly these services can withstand and adapt to various challenges. It focuses on aspects like the durability and maintenance of infrastructure (roads, bridges, public buildings), the flexibility of systems to adapt to technological advancements and changing needs (upgradable transport systems, modular cultural venues), emergency preparedness levels (flood defenses, earthquake-resistant structures), and the financial sustainability of infrastructure investments (long-term funding strategies, efficient allocation of resources). This indicator helps local governments assess the resilience and long-term viability of their infrastructure across all sectors, guiding policy decisions to bolster resilience, ensure continuity of services, and enhance overall community stability.

The static dimension of the indicator for the total capital in infrastructural services provided by municipalities focuses on the current status and characteristics of existing infrastructure across all sectors. It typically includes data such as the number and types of public facilities (roads, bridges, public buildings, cultural institutions), the capacity and current usage rates of these facilities, the geographical distribution throughout the municipality, and the extent of technological adoption (smart city technologies, digital traffic management systems, online public services). This dimension aids in understanding the baseline infrastructure available and identifies areas lacking sufficient resources, crucial for strategic planning and enhancing service delivery and accessibility across the community.

2.5. Conclusions and policy implications

The disparities in infrastructure endowments across Italian municipalities, as evidenced by the analysis of gap indicators for waste management, transport, and cultural services, necessitate a targeted approach to infrastructure investment. A prioritization strategy is essential, focusing on allocating resources to regions exhibiting the most significant infrastructural gaps to promote equitable development and enhance national connectivity and competitiveness.
Enhancing the fiscal capacity and autonomy of municipalities is paramount, especially given the notable discrepancies between northern and southern regions. Policies should aim to revise the current allocation formulas to provide increased support to regions with limited fiscal capabilities, thereby enabling them to undertake necessary capital investments. Additionally, municipalities

should be encouraged to improve their financial management and planning capacities through access to better financial tools, resources, and training programs.

As sustainability and resilience become increasingly critical in municipal planning, local governments should focus on developing infrastructure that meets current needs while anticipating future challenges. This approach includes promoting the adoption of green infrastructure practices in waste management to enhance environmental sustainability and integrating climate resilience into infrastructure planning, especially in vulnerable southern and coastal areas.

The foundation of effective infrastructure policy is robust data collection and monitoring. Enhancing the capabilities of the BDAP to ensure more detailed and frequent data collection will be crucial. Implementing standardized reporting and evaluation frameworks across municipalities will enable more effective comparisons and benchmarking, allowing for better-targeted interventions.

Moreover, public-private partnerships (PPPs) represent a significant opportunity to leverage private sector expertise and funding to supplement public investments in infrastructure. Developing a regulatory framework that encourages private investment in public infrastructure projects and offering incentives for private entities to invest in regions with significant infrastructural deficits can dramatically enhance the scope and scale of infrastructure development.

Finally, a concerted effort must be made to address the stark regional disparities highlighted by the infrastructural gap analysis. This involves designing targeted interventions that specifically address the unique challenges faced by rural and southern municipalities and increasing transparency in the distribution and utilization of funds to ensure accountability and efficient use of resources.

Through these comprehensive and strategically focused actions, Italy can create a more balanced developmental landscape across its municipalities, ensuring that infrastructure investments are both strategic and inclusive. This approach will foster long-term economic growth and stability, ensuring that all regions are equipped to meet the challenges of the future effectively.

In addressing the significant regional disparities between northern and southern Italy, as highlighted in the infrastructure gap analysis, it is crucial to tailor policies that specifically cater to the unique challenges faced by different regions. The stark differences in expenditure capacity and infrastructural endowments underscore the necessity for targeted interventions to ensure equitable development across all Italian municipalities.

The analysis reveals that southern municipalities face notable challenges in translating planned investments into tangible projects, with their capital expenditure capacities generally falling below the national average. This contrast sharply with northern municipalities, which not only meet but often exceed the national benchmarks in terms of executing planned investments efficiently.

To mitigate these regional disparities, the following policy implications are drawn from the document's findings:

Revising Allocation Formulas: There is a critical need to adjust the allocation formulas used to distribute funds across municipalities. These formulas should be designed to provide additional

support to southern regions, where fiscal constraints significantly hinder local governments' ability to finance and implement necessary infrastructure projects. By ensuring that these regions receive a proportionate share of national investments, Italy can promote a more balanced economic development.

Enhancing Fiscal Autonomy: Policies aimed at enhancing the fiscal autonomy of southern municipalities could empower them to make strategic decisions that align with their specific developmental needs. Increasing fiscal autonomy involves not only reallocating resources but also building local capacities in financial management and strategic planning.

Infrastructure Development Incentives: Establishing incentives for infrastructure development specifically in the south can attract private investments and public-private partnerships, which are crucial in areas lacking adequate public funding. These incentives could include tax breaks, subsidies, and other financial benefits to encourage investment in infrastructure projects that address critical gaps.

Focused Investment in Critical Sectors: Identifying and investing in critical sectors such as transportation, public services, and environmental infrastructure in southern regions can significantly impact overall regional development. Such investments should aim to improve connectivity, enhance service delivery, and promote sustainable practices, directly addressing the infrastructural deficits that impede economic growth.

Transparent Monitoring and Reporting: To ensure that the interventions are effective and that funds are used efficiently, establishing a robust monitoring and reporting system is essential. This system should provide transparency in how resources are allocated and spent, allowing for adjustments in policies and strategies as needed to better serve the target regions.

By implementing these policy measures, Italy can address the profound disparities between its northern and southern regions, promoting a more equitable and sustainable development path that leverages the unique strengths and addresses the specific needs of each area. This approach not only aligns with principles of fiscal federalism but also ensures that all Italian municipalities are equipped to contribute to the nation's overall prosperity.

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3. Cohesion Policy Impact on Tourism in Italy: a municipality-level assessment *(Marika Arena, Angela Stefania Bergantino, Alessandro Buongiorno, Maria Grazia Cito, Mario Intini, Francesco Scotti - POLIMI and UniBA)*

3.1. Introduction

The European Union's Cohesion Policy (CP) is a comprehensive regulatory mechanism aimed at supporting economic and social development and reducing inequalities within the Union's territories, development by allocating financial resources to less developed regions and sectors, fostering economic growth, competitiveness, and employment opportunities. The European Union invests significant financial resources in the tourism sector through the CP. In Italy for the 2017-2013 and 2014-2020 programming cycles, 11.9 billion euros public funds were dedicated only to the thematic objective "Culture and Tourism". To date, the literature has cantered on analysing the territorial effects of all funded projects, primarily at regional and provincial levels. Nevertheless, it is imperative for policymakers to possess evidence of the economic ramifications of these investments not solely at a disaggregated geographical level, but also concerning different sectors. This consideration is crucial due to the potential for varying degrees of local development, contingent upon the economic activities to which public funds are allocated.

The aim of this study is to assess the impact of EU Cohesion Funds for tourism on improving territorial tourist attractiveness, understood as an important component of broader territorial economic development. Tourism is closely connected to territorial attractiveness, and it plays an important role as a driving force of economic development, through the generation of income, employment, and foreign-exchange earnings. Several studies have empirically demonstrated the positive relationship between tourism expenditure and economic growth in the long term and short term (Yazdi, S. et al., 2017; Alam, 2016). We focus on tourism, not only for its substantial economic contributions to developing countries and regions, through bolstering the labour market and enhancing international trade in services, but also for its pivotal role in Cohesion Policies.

We selected Italy for our case study due to its status as the world's fifth most visited tourism destination, with 64.5 million international visitors, according to UNWTO (2019), following France, Spain, the USA, and China. Moreover, it holds the distinction of being one of the earliest established tourism destinations globally, particularly renowned for its art, cultural tourism, and beach attractions since the 1930s. Today, Italy's appeal remains strong, offering a unique blend of art, culture, and lifestyle that continues to attract travellers worldwide. Having an enormous cultural heritage and numerous tourist attractions, as evidenced by the highest number of UNESCO sites in the world (60 in 2024), Italy is a particularly interesting case study to evaluate the effectiveness of European Cohesion Policy on tourism development.

Utilizing data sourced from Open Cohesion, our analysis is conducted at the municipality level to assess the impact of CP on tourism development and attractiveness (in terms of number of

arrivals, overnight stays, average stay, average tourist expenditure, etc.). The contribution of this paper is threefold. First, none of the works we reviewed focus on the municipal level at such a large scale as the national level. Impacts within a country or across Europe are often analyzed at the regional level (NUTS 2) or for individual member states at the provincial level (NUTS 3). Our study, instead, focuses on all Italian municipalities. The analysis includes over 2,000 municipalities where these investment projects are located, representing a significant portion of Italian municipalities. Second, to the best of our knowledge, this is the first study analysing the impact of CP's impact on tourism at a municipality level. Very few studies have analysed the impact of tourism projects funded by CP. It is important for policymakers to have evidence of the economic impact of these investments not only at a disaggregated geographical level, but also with reference to different sectors, considering that heterogeneous levels of local development can be achieved depending on the economic activity to which Cohesion funds are allocated. This research therefore focuses on the tourism sector, examining territorial attractiveness for tourists. Third, a key element contributing to the originality of this work is that the analysis spans all four programming cycles of EU Cohesion Funds (2000-2006, 2007-2013, 2014-2020, 2021-2027) and considers all projects completed over a period of nine years, from 2014 to 2019, an area that remains unaddressed in the existing literature. Unlike typical studies, which often focus on a single budgetary period, our analysis is centered on all projects that were completed during this 6-year period.
The rest of the paper is organized as follows. Section 2 reviews the literature background on CP and the evaluation of its impact on regional growth, with a specific focus on tourism. Section 3 presents the data used and some descriptive statistics. Section 4 shows the methodology employed. Section 5 discusses the results. Section 6 concludes, presents policy recommendations, and highlights limitations and further developments.

3.2. Outline of literature background

Although the literature on the impacts of CP has notably expanded, empirical evidence still provides varying results ranging from positive (Giua, 2017; Fratesi & Perucca, 2019; Arbolino & Boffardi, 2017; Gagliardi & Percoco, 2016) to non-significant effects (Dall'Erba & Le Gallo, 2008; Aiello & Pupo, 2010) of cohesion policies on regional development. Becker et al. (2012) analyse to what extent the objective of fostering growth in the target regions was achieved with the funds provided and whether more transfers generated stronger growth effects. Using data at the NUTS3 level from two EU budgetary periods (1994–1999 and 2000–2006), the authors demonstrate that in 36% of the recipient regions the transfer intensity exceeds the aggregate efficiency maximizing level and in 18% of the regions a reduction of transfers would not even reduce their growth.
Accetturo et al. (2014) employ a Fuzzy Regression Discontinuity Design to examine the impact of EU structural funds on trust and cooperation levels in NUTS2 EU regions from 2000 to 2006. They compare regions just below the 75% cutoff (eligible regions) with those just above the cutoff (non-eligible regions) and find negative and significant coefficients for all the indicators of local endowments of trust and cooperation they considered (European Social Survey). The Regression Discontinuity Design is exploited also by Giua (2017), which uses a novel spatial discontinuity represented by the administrative boundaries between municipalities belonging to Objective 1

and non-Objective-1 regions in central Italy within the period 1988–1999. Results show that EU Regional Policy increases employment of Objective 1 areas by 15% over 10 years and that the impact is positive and significant for the targeted strategic sectors. The main downside of this approach is that using a dummy variable instead of the actual treatment intensity increases the risk of mistakenly categorizing eligible observations as treated when no treatment was administered. While there is a substantial body of literature exploring the effects of CP on regional growth, research specifically investigating the influence of EU Cohesion Policy (CP) on the tourism sector is scant and predominantly focus on identifying potential correlations between investments made with cohesion funds and key tourism metrics (Del Vecchio and Passiante, 2017; Giaccio et al., 2018; Bellini et al., 2017; Benner, 2017 and 2020; Smarandake, 2018 and 2020; Valente & Medeiros, 2022; Weidenfeld, 2018). To the best of our knowledge, only a few of these studies investigate causal relationships between invested funds and tourism variables (Colaizzo et al., 2018; Brandano & Crociata; 2023).

Smarandake (2018 and 2020) find a positive correlation between EU Structural Funds and respectively tourism development in Romania, evidenced by increased arrivals and accommodation facilities from 2007 to 2017. Giaccio et al. (2018) focuses on the impact of EU rural policies on agritourism development in Italy. They find that the rural development policy has mainly supported small and medium-sized farms with tourism activities and located in disadvantaged areas. Valente & Medeiros (2022) use the Territorial Impact Assessment (TIA) methodology to analyse the impact of POSEUR, an operational programme to implement EU Cohesion Policy funds in Portugal between 2014 and 2020, on sustainable tourism in Algarve. They find that the amount of funding available was insufficient to promote a systemic change in the region towards a sustainable model of tourism, but there are some positive impacts, namely the improvement of water efficiency in golf courses, the renewed coastal areas adapted to the risks of the ecosystem, and the promotion of cleaner methods of public transport.

Brandano & Crociata (2023) stands out as the sole empirical study that evaluates the impact of the Cohesion Policy on tourism and culture in Italy. Utilizing a Synthetic Control Method, the authors use the number nights of stay in low season as a measure of tourism, and the tickets for theatrical and musical entertainment as a measure of culture and consider as a treated group the convergence regions (Campania, Apulia, Calabria and Sicily). The analysis is performed at the NUTS2 level and the programming period 2007-2013 is considered. Results show that CP expenditures have a positive association with the cultural sector but have been ineffective in most regions as for the tourism sector.

Colaizzo et al. (2018) provides a counterfactual assessment on the possible causal effects of Cohesion Policy on tourist attractiveness in the Apulia region. The analysis is performed at the municipality level and the considered period is 2007-2015. They find an overall positive causal relationship between per-capita investments and tourist arrivals.

In conclusion, it is evident that more empirical research is needed to fully understand the impact of EU Cohesion Policy on tourism, and implications for regional development.

3.3. Data and descriptive statistics

After comparing various databases available on Opencoesione, the national web platform coordinated by the Department for Cohesion Policies and for the South of the Presidency of the Council of Ministers, we chose to use the new database of the Policy Focus "Tourism Attractiveness"[8], which represents a cross-sectoral approach of a policy that focuses on protecting and enhancing resources, promoting destinations, engaging stakeholders, and building infrastructure to attract visitors. The choice was driven by several factors: first, it contains a greater number of projects compared to the database for the thematic objective 6 "Culture and Tourism"; second, it cuts across all incentive measures in the sector (businesses, innovation, infrastructures, etc.), while the Objective 6 database doesn't include the numerous and relevant projects of the other Thematic Objectives (e.g. enterprises' competitiveness, mobility, environment, etc.), which might have an impact on tourism development; third, it has been recently released (February, 2023) and therefore it represents a novelty in the literature.

Table 1 ranks regions by the number of projects and total expenditure completed between 2014 and 2019, highlighting Campania, Puglia, and Sicily as the top-performing regions. Together, these three southern regions account for 55% of total expenditure, highlighting the Cohesion Policy's focus on aiding less developed regions by allocating a greater share of funds. In contrast, table 2 ranks the top 20 municipalities by project count and total expenditure over the same period. Perugia leads in project count, while the southern capital cities of Naples and Bari top the list in total tourism-related expenditure. Livinallongo del Col di Lana, a small village of about 1,000 residents in northern Italy, stands out among the municipalities with the highest expenditure, having constructed a new ski lift in its skiing area. Similarly, Castel di Sangro, a town of around 6,000 residents in Abruzzo, has also made significant investments, including two new ski lifts.

Table 1 - Ranking of the Italian regions per number of tourism projects (left) and total expenditure (right) between 2014 and 2019.

Region	nr. projects	%	Region	Total expenditure (€)	%
PUGLIA	1,340	18.59	CAMPANIA	537,000,000	23.12
BASILICATA	833	11.55	PUGLIA	512,000,000	22.05
CALABRIA	698	9.68	SICILIA	237,000,000	10.20
CAMPANIA	621	8.61	VENETO	199,000,000	8.57
LOMBARDIA	601	8.34	BASILICATA	126,000,000	5.43
SICILIA	580	8.04	EMILIA-ROMAGNA	113,000,000	4.87
UMBRIA	406	5.63	CALABRIA	107,000,000	4.61
ABRUZZO	374	5.19	PIEMONTE	104,000,000	4.48
SARDEGNA	321	4.45	TOSCANA	72,400,000	3.12
VENETO	292	4.05	ABRUZZO	71,100,000	3.06
PIEMONTE	260	3.61	SARDEGNA	63,000,000	2.71
EMILIA-ROMAGNA	238	3.3	UMBRIA	44,900,000	1.93
TOSCANA	191	2.65	LAZIO	37,900,000	1.63
MOLISE	182	2.52	LOMBARDIA	31,000,000	1.33
LIGURIA	86	1.19	MOLISE	22,400,000	0.96
TRENTINO-ALTO ADIGE	80	1.11	LIGURIA	16,100,000	0.69
FRIULI-VENEZIA GIULIA	52	0.72	TRENTINO-A.A.	14,000,000	0.60
LAZIO	38	0.53	FRIULI-V.G.	7,016,050	0.30

[8] https://opencoesione.gov.it/it/pillole/pillola-n-38-politiche-di-coesione-e-turismo-focus-sullattuazione-del-ciclo-2007-2013-e-primi-elementi-della-programmazione-2014-2020/

MARCHE	15	0.21	MARCHE	6,442,546	0.28
VALLE D'AOSTA	2	0.03	VALLE D'AOSTA	1,254,826	0.05
Total	7,210	100	Total	2,322,513,422	100

Table 2 - Ranking of the top 20 Italian municipalities per number of tourism projects (left) and total expenditure (right) between 2014 and 2019.

Municipality	nr. Project	Municipality	Total expenditure (€)
PERUGIA	214	NAPOLI	114,000,000
BARI	137	BARI	109,000,000
MATERA	135	POMPEI	50,600,000
PALERMO	99	ROMA	38,100,000
CATANZARO	89	LECCE	37,600,000
POTENZA	87	LIVINALLONGO DEL COL DI LANA	29,900,000
POMPEI	75	MATERA	25,900,000
TORINO	63	MONOPOLI	25,200,000
MILANO	62	CASTEL DI SANGRO	23,100,000
CAGLIARI	58	PALERMO	22,800,000
LECCE	56	VERBANIA	21,400,000
NAPOLI	50	MELENDUGNO	18,700,000
MONOPOLI	49	PERUGIA	18,500,000
TARANTO	45	AGEROLA	18,200,000
COSENZA	42	VENEZIA	18,000,000
L'AQUILA	42	UGENTO	17,800,000
LAMEZIA TERME	37	CAGLIARI	17,600,000
CAMPOBASSO	36	SAN GIOVANNI ROTONDO	16,300,000
REGGIO DI CALABRIA	36	CATANZARO	15,800,000
GALLIPOLI	34	TARANTO	15,400,000

The Tourism Attractiveness database includes over 52,000[9] projects. This analysis focuses on a subset of 7,210 projects completed between 2014 and 2019, regardless of their programming period, to account for the significant overlap between different budget cycles. Table 3 provides a summary of the projects by year and programming period, with the final row showing the percentage completed from 2014 to 2019 for each cycle. Notably, nearly half of these projects are from the previous budgetary period (2007-2013). Excluding them would introduce bias, as it would overlook the impact of projects completed during these years that, despite not being part of the 2014-2020 cycle, contributed to outcomes within this period.

Table 3 –Projects per completion year and programming period

Year	Programming periods			Total
	2000-2006	2007-2013	2014-2020	
2014	2	503	0	505
2015	6	1,413	34	1,453

[9] For further information about the total database: https://opencoesione.gov.it/it/dati/focus/attrattivita_turistica/

2016	13	440	208	661
2017	29	510	792	1,331
2018	31	238	1,425	1,694
2019	21	138	1,407	1,566
Total	102	3,242	3,866	7,210
%	1,41	44,97	53,62	100

While data is available until 2023, the COVID period has been excluded from this analysis to avoid potential biases in the estimates. The pandemic significantly disrupted global travel patterns. By concentrating on the pre-COVID period, this study aims to provide a more accurate assessment of how various tourism investments influence tourism dynamics, thereby enhancing the validity of the findings. Moreover, although the database contains a wide range of variables that allow for project categorization, these variables are insufficient and highly heterogeneous, making it challenging to clearly identify the types of projects included in the analysis. This is an essential consideration, since different categories of projects have varying impacts on a municipality's attractiveness. Therefore, a new project categorization has been implemented to better align with the study's objectives. The categorization process[10] resulted in the following six distinct categories: (1) Projects carried out by accommodation facilities, whose beneficiaries are mainly private. This category includes renovations, new constructions, expansions, and various enhancements of both hotel and non-hotel accommodations, such as bed and breakfasts, farmhouses, holiday homes, hostels, etc. (2) Projects aimed at enhancing cultural and natural heritage. This category encompasses urban redevelopment initiatives, as well as the restoration of churches, monuments, castles, and archaeological sites. It also includes projects to protect and enhance natural areas, such as parks, lakes, rural landscapes, biodiversity, and forests. (3) The "Festivals and Events" category encompasses a wide range of activities, including festivals, exhibitions, workshops, as well as participation in national and international tourism fairs and marketing initiatives. (4) The "Transport and Mobility" category includes projects aimed at building new transportation infrastructure or improving existing facilities, such as roads, bike paths, ski lifts, airports, ports, and railways. (5) The category "Tourism businesses" includes complementary tourism services, such as food and beverage services (cafes, restaurants), travel agencies and tour operators and businesses whose customers are mainly tourists-but they are not accommodation facilities-such as beach clubs. (6) Finally, the category "Non-tourism businesses" includes businesses not specifically within the tourism sector but still incorporated in this database for their contribution to territorial vibrancy and competitiveness. Examples include retail businesses, such as souvenir shops and local craft stores. The residual variable "Others" (1.58% of the total expenditure) includes projects that could not be categorized due to insufficient

[10] The ATECO code (Italian Classification of Economic Activities) allows to identify the specific activities of private beneficiaries; however, this variable alone is insufficient for categorizing all projects, as it is only available for 8% of the projects in the dataset. Among the private businesses, a distinction is needed among accommodations facilities. tourism businesses (except accommodation facilities), and non-tourism businesses that are included in the "Tourist Attractiveness" dataset. In cases where the ATECO code is missing, other available categories ("summary theme", "category description", "type of expenditure") are used to reallocate the projects in the preferred categories. Finally, when none of the available categories is sufficiently clear, a textual analysis is conducted, checking the presence of specific keywords both in the title and summary of the projects.

information in the dataset. Table 4 shows the result of the categorization process, with the number of projects, the total expenditure and the percentage of expenditure per category. The maps in Fig.1, instead, show the spatial distribution of the municipalities involved for each project category.

Table 4 – Number of projects, total expenditure and percentage of expenditure per investment category (2014-2019).

Investment Category	N. projects	Total expenditure (€)	%
Accommodation facilities	1,255	311,700,000	13.42
Cultural and Natural Heritage	3,639	1,246,000,000	53.63
Transport and Mobility	279	154,300,000	6.64
Festivals and events	446	117,900,000	5.08
Tourism businesses	1,099	299,900,000	12.91
Non-tourism businesses	268	156,700,000	6.75
Others	224	36,614,907	1.58

Fig. 1 –Distribution of municipalities where at least one project was funded for each category (2014-2019) A) Accommodation facilities B) Cultural and Natural Heritage; C) Transport and Mobility; D) Festival and Events E) Tourism businesses; F) Non-tourism businesses.

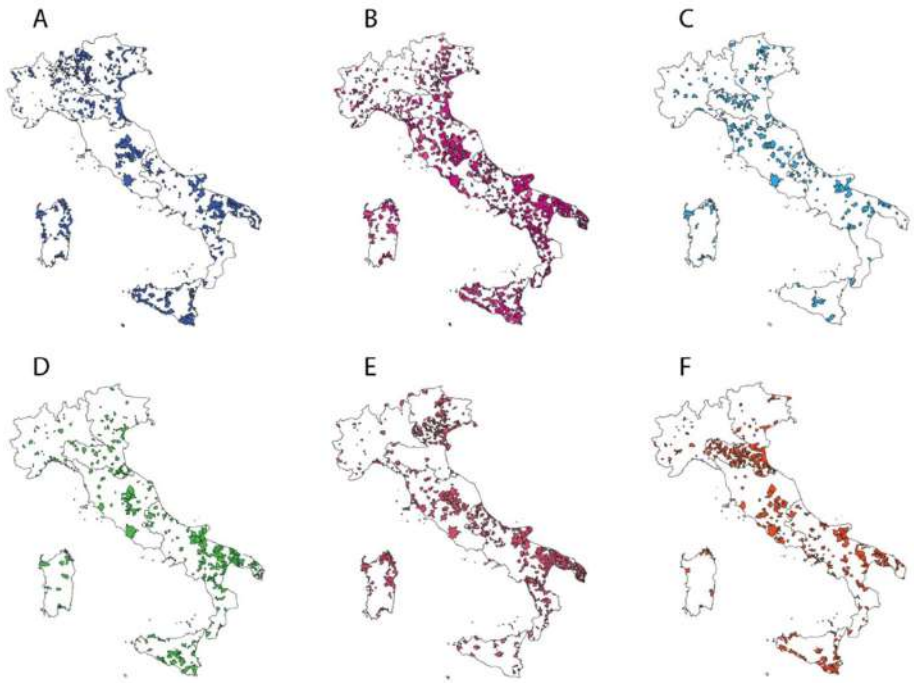

Table 5 – Variables description and source.

Variable	Description	Source
Total Stays	Total number of overnight stays in year t in municipality i	ISTAT
Accommodation facilities	Realized cost for projects concerning accommodation facilities in year t in municipality i	OpenCoesione
Natural and Cultural heritage	Realized cost for projects concerning Natural and Cultural heritage in year t in municipality i	OpenCoesione
Transport	Realized cost for projects concerning Transportation in year t in municipality i	OpenCoesione
Events	Realized cost for projects concerning Marketing and Events in year t in municipality i	OpenCoesione
Non-tourism businesses	Realized cost for projects concerning Non-Tourism businesses in year t in municipality i	OpenCoesione
Tourism businesses	Realized cost for projects concerning Tourism businesses except accommodation facilities in year t in municipality i	OpenCoesione
Per-capita income	Total income per municipality i divided by the number of taxpayers in year t in municipality i	MEF
Population	Resident population in year t in municipality i	ISTAT
Graduates	Number of new graduates in year t in municipality i	ISTAT

Table 6 – Descriptive statistics.

Variable	Obs.	Mean	Standard Deviation	Min	Max
Total Stays	14,046	151,854.60	785,383.50	226	31,000,000
Accommodation facilities	14,046	18,637.47	224,187.60	0	8,813,170

Natural and Cultural heritage	14,046	57,266.97	589,296.30	0	30,900,000
Transport	14,046	9,065.79	266,134.10	0	22,900,000
Events	14,046	9,015.46	134,975.50	0	5,392,742
Non-tourism businesses	14,046	10,134.93	304,470.10	0	21,200,000
Tourism businesses	14,046	17,947.15	351,511.00	0	35,300,000
Per-capita income	14,046	18,048.45	3,396.32	9,263	47,808
Population	14,046	17,161.69	76,316.04	58	2,820,219
Graduates	14,046	90.57	466.18	0	20,052

Table 5 and 6 show respectively the variables used in the analysis with source and description, and some descriptive statistics. The range of values varies significantly across variables. To ensure comparability of coefficients and mitigate issues from differing scales, all variables have been z-score normalized, resulting in a mean of 0 and a standard deviation of 1.
The analysis uses stays as a measure of tourism attractiveness, serving as the dependent variable. The dataset includes all municipalities for which the dependent variable is available for the entire study period. Fig. 2 shows the municipalities included in the present analysis.

Figure 2: Italian municipalities included in the analysis.

The realized cost[11] for each investment category has been selected as independent variables, rather than funds commitments, to avoid potential measurement errors, since commitments may not always be fully executed or may be drawn down with delays, often due to issues like limited absorption capacity. The total realized cost is fully allocated to the completion year of each project, except for projects related to events. While the impact of structural and infrastructural

[11] Value of works and project activities actually carried out as of the reporting date, even if not yet paid. This is an indicator that anticipates cash needs and also provides information on the project's progress in economic terms, using parameters that are comparable across different types of projects. For public works, the realized cost value is derived from the site's analytical accounting and from additional expenses incurred by the implementing entity for other project-related activities, such as technical expenses, expropriations (source: Metadata of the dataset available on https://opencoesione.gov.it/it/opendata/dataset/focus_turismo_3).

projects, such as renovations, can only be assessed upon completion, the effects of festivals or structured events that last several years should be observed throughout the entire duration, from the project's start date to its end date.

Following a well-established literature, population, per capita income, and educational level are used as control variables in this analysis. Larger populations are typically associated with better infrastructure and services, potentially attracting more tourists (Pompili et al., 2019; Khadaroo & Seetanah, 2008). Per-capita income is used to account for living standards following Paci & Marrocu (2014); Patuelli et al. (2014); Romão & Nijkamp (2018); Zamparini et al. (2017), among others. Finally, the number of graduates is used as an indicator of human capital, as higher education levels can indicate a skilled workforce capable of enhancing tourism services and products (Dettori et al., 2012). Additional factors affecting tourism demand include crime rates and environmental conditions, though data limitations restrict their inclusion in this analysis. To address these issues, municipality and time-fixed effects are employed to control for unobserved characteristics that vary across municipalities or over time.

3.4. Methodology

Following Pienkowski and Berkowitz (2016), who advocate for using spatial econometrics to analyse Cohesion Policy impacts, a fixed effects panel spatial model is employed.

The presence of spatial correlation is tested for the main dependent variable (overnight stays), by performing the Moran test (Table 7). The Moran's I is statistically significant and positive for every year under analysis, suggesting that there is strong evidence of spatial autocorrelation. In other words, municipalities with higher tourist stays tend to be near other municipalities with higher tourist stays. Additionally, the declining Moran's I values from 2014 to 2019 suggest a gradual reduction in this clustering effect, likely reflecting a shift in tourist preferences. Over time, tourists may increasingly be exploring less central or alternative destinations, resulting in a more dispersed distribution of tourism activity across municipalities.

Table 7 – Moran's I statistics using a distance spatial matrix with a cut-off at 70 km.

Year	Moran's I
2014	0.0083 ***
2015	0.0072 ***
2016	0.0075 ***
2017	0.0072 ***
2018	0.0065 ***
2019	0.0059 ***

Signif. Codes: 0.001 '***'

To account for spatial correlation, a Spatial Durbin Model (SDM) with two-way fixed effects is employed. The SDM introduces spatial lags of the independent variables in addition to the

dependent variable, which allows us to capture both direct effects (within a municipality) and indirect spatial spillover effects (from neighboring municipalities). The model specification is as follows:

$$y_{it} = \rho \sum_{j=1}^{N} w_{ij} y_{it} + \beta X_{it} + \lambda \sum_{j=1}^{N} w_{ij} X_{it} + \gamma C_{it} + \alpha_i + \theta_t + \epsilon_{it}$$

Where:

- y_{it} is a measure of tourism attractiveness, i.e. arrivals and overnight stays (both resident, non-resident and total) in municipality *i* at time t.
- ρ is the spatial autoregressive coefficient. It captures the spatial dependence of tourism attractiveness in municipality *i* on tourism attractiveness in neighbouring municipalities
- The term $\sum_{j=1}^{N} w_{ij} y_{it}$ represents the spatial lag of the dependent variable;
- w_{ij} is defined as an inverse distance spatial weight matrix with a cut-off of 70 km, representing the spatial relationship between municipalities i and j based on geographic proximity.

X_{it} is a vector of independent variables, representing the total expenditure by municipality i in year t for various project categories, with β measuring their direct impact on tourism attractiveness.
The term $\sum_{j=1}^{N} w_{ij} X_{it}$ represents the spatial lag of the independent variable. This captures how the expenditure per neighboring municipalities j impacts the tourism attractiveness of municipality *i*. The coefficient λ measures this spatial spillover effect.
$C_{it}$is a vector of control variables including population, per capita income, and number of graduates and γ represents the effect of these control variables.
α_i represents the Municipality-Level Fixed Effects, which control for time-invariant characteristics of each municipality, such as historical, geographical, or institutional factors that might affect tourism attractiveness.
θ_t represents the Time Fixed Effects, which account for time-specific factors that affect all municipalities, such as national economic trends.
ϵ_{it} is the idiosyncratic error term.
The Spatial Durbin Model (SDM) is preferred because it introduces spatial lags of the independent variables, in addition to the dependent variable, which allows us to capture both direct effects (within a municipality) and indirect spatial spillover effects, from the neighboring municipalities.

3.5. Findings and Discussion

Table 8 and 9 present the results of the panel fixed effects Spatial Durbin Model analysing the impact of different categories of tourism investments respectively on the number of stays and arrivals, with separate estimations for resident, non-resident and total. Distance spatial weight matrix with a cut-off at 70 km is employed.

Table 8: Results of the panel fixed effects Spatial Durbin Model for tourist stays.

Dep. variable = stays	Resident		Non-resident		Total	
Accommodation facilities	0.0021	**	0.0036	***	0.0033	***
	(0.0009)		(0.0006)		(0.0005)	
λ Accommodation facilities	-0.0017		-0.0003		-0.0008	
	(0.0045)		(0.0030)		(0.0028)	
Cultural and Natural Heritage	0.0008		0.0058	***	0.0043	***
	(0.0010)		(0.0007)		(0.0007)	
λ Cultural and Natural Heritage	0.0068		-0.0003		0.0019	
	(0.0057)		(0.0039)		(0.0037)	
Transport Infrastructure	0.0004		0.0008		0.0007	
	(0.0009)		(0.0006)		(0.0005)	
λ Transport Infrastructure	0.0076		0.0058		0.0065	
	(0.0099)		(0.0068)		(0.0063)	
Events	0.0052	***	0.0084	***	0.0077	***
	(0.0011)		(0.0008)		(0.0007)	
λ Events	0.0170	*	0.0035		0.0079	
	(0.0100)		(0.0069)		(0.0064)	
Non-Tourism Businesses	0.0156	***	0.0144	***	0.0157	***
	(0.0011)		(0.0007)		(0.0007)	
λ Non-Tourism Businesses	-0.0160	***	-0.0305	***	-0.0287	***
	(0.0059)		(0.0039)		(0.0038)	
Tourism Businesses	0.0006		0.0012	**	0.0011	**
	(0.0009)		(0.0006)		(0.0005)	
λ Tourism Businesses	-0.0028		-0.0101	***	-0.0082	***
	(0.0050)		(0.0034)		(0.0032)	
Income	0.0154	***	0.0103	***	0.0119	***
	(0.0052)		(0.0036)		(0.0033)	
Population	2.8210	***	1.2710	***	1.9255	***
	(0.0828)		(0.0565)		(0.0526)	
Graduates	0.8139	***	0.7119	***	0.7923	***
	(0.0182)		(0.0124)		(0.0116)	
λ	0.0950	**	0.2353	***	0.2143	***
N	14,046		14,046		14,046	

Signif. codes: 0.001 '***' 0.01 '**' 0.05 '*'. Standard errors in parentheses.

Table 9 – Results of the panel fixed effects Spatial Durbin Model for tourist arrivals.

Dep. variable= arrivals	Resident		Non-resident		Total	
Accommodation facilities	0.0029	***	0.0030	***	0.0031	***
	(0.0007)		(0.0006)		(0.0005)	
λ Accommodation facilities	-0.0044		-0.0001		-0.0017	
	(0.0034)		(0.0029)		(0.0027)	

Cultural and Natural Heritage	0.0094	***	0.0103	***	0.0104	***
	(0.0008)		(0.0007)		(0.0006)	
λ Cultural and Natural Heritage	0.0031		-0.0002		0.0012	
	(0.0045)		(0.0038)		(0.0036)	
Transport Infrastructure	0.0018	***	0.0007		0.0011	**
	(0.0007)		(0.0006)		(0.0005)	
λ Transport Infrastructure	0.0045		0.0077		0.0067	
	(0.0076)		(0.0065)		(0.0061)	
Events	0.0128	***	0.0120	***	0.0128	***
	(0.0009)		(0.0007)		(0.0007)	
λ Events	0.0018		-0.0028		-0.0001	
	(0.0077)		(0.0066)		(0.0062)	
Non-Tourism Businesses	0.0142	***	0.0092	***	0.0114	***
	(0.0008)		(0.0007)		(0.0007)	
λ Non-Tourism Businesses	-0.0128	***	-0.0173	***	-0.0161	***
	(0.0045)		(0.0038)		(0.0036)	
Tourism Businesses	0.0024	***	0.0023	***	0.0025	***
	(0.0007)		(0.0006)		(0.0005)	
λ Tourism Businesses	0.0010		-0.0056		-0.0033	
	(0.0038)		(0.0033)		(0.0031)	
Income	0.0254	***	0.0164	***	0.0209	***
	(0.0041)		(0.0035)		(0.0033)	
Population	2.4983	***	2.0102	***	2.2602	***
	(0.0636)		(0.0547)		(0.0508)	
Graduates	0.5086	***	0.5513	***	0.5590	***
	(0.0140)		(0.0120)		(0.0112)	
λ	0.4184	***	0.2255	***	0.2957	***
N	14,046		14,046		14,046	

Signif. codes: 0.001 '***' 0.01 '**' 0.05 '*'. Standard errors in parentheses.

Investments in accommodation facilities have a positive and strongly significant impact across all specifications. However, their spatial lags (λ) show no significant spillover effects on neighbouring municipalities. Investments in cultural and natural heritage (including urban redevelopment) show a positive and significant impact across all specifications, except for resident stays. These investments yield the highest coefficients, highlighting the crucial role of cultural and natural heritage in attracting tourists. The spatial lag of these investments, however, shows no significant impact on neighbouring municipalities.

Investments in transport infrastructure, along with their spatial lag, have no significant effect on stays in any specification. However, they show a positive and significant direct impact on resident and total arrivals, suggesting that these projects may enhance accessibility and thus attract more tourists, though they do not affect the length of the stay. These results align with a previous study, Nguyen (2021), which found no significant impact of investment in transport and

communications infrastructure on attracting international visitors to Vietnam in the short-term. Moreover, the enhancement of a single transportation infrastructure does not automatically ensure that a tourist destination becomes more accessible. In fact, tourists typically rely on various types of infrastructures for their travel (Bergantino et al., 2023). These results are also consistent with Scotti (2024), which indicate that a greater availability of tourism accommodations, along with cultural and natural resources, significantly influences overnight stays. Conversely, transportation facilities enhance the attractiveness of municipalities for same-day visits, a factor not considered in this analysis.

Event-related investments, such as festivals, marketing, and tourist information projects, have a positive impact on both stays and arrivals across all specifications, indicating their strong effectiveness in attracting both domestic and foreign tourists. The spatial lag for event investments is marginally significant for Italian stays (at a 95\% confidence level), suggesting that these events may create some spillover effects in neighbouring municipalities.

Investments in non-tourism businesses positively affect stays and arrivals across all specifications, suggesting that these investments may enhance a municipality's appeal by improving the overall environment, services, and amenities, thus making the destination more vibrant and attractive. However, the negative coefficients on their spatial lag indicate a potential competitive effect, where the presence of such investments in neighbouring municipalities may draw tourists away from the focal municipality.

Finally, investments in tourism businesses other than accommodation facilities—such as restaurants, cafes, travel agencies, and beach clubs—have positive and significant effects across all specifications, except for resident stays, while their spatial lags indicate a significant negative effect on neighbouring areas for non-resident and total stays. Similar to non-tourism businesses, these non-accommodation tourism investments appear to generate a competitive effect with neighbouring municipalities.

The control variables – per-capita income, population, and number of graduates - are consistently positive and significant, suggesting that municipalities with higher socio-economic status and educational attainment levels tend to attract more tourists. The spatial dependence parameter, lambda, is always significant, indicating the presence of spatial autocorrelation and validating the use of a spatial model.

It is noteworthy that investments mainly yield localized benefits, as evidenced by the generally non-significant spillover effects. This implies that the positive impacts of tourism investments tend to be confined to the municipalities where the investments are made, rather than extending to surrounding areas. Only specific businesses categories exhibit a negative spillover effect, indicating a competitive dynamic.

3.6. Conclusions

This study examined the impact of EU Cohesion Policy-funded tourism investments on the attractiveness of Italian municipalities. Our findings indicate that Cohesion Policy funds generally have a positive influence on enhancing tourism attractiveness, though the effects vary across different types of investments. Several innovative elements strengthen this analysis. First, the

newly developed policy-focus dataset, "Tourism Attractiveness", has been used instead of the conventional "Objective 6 - Culture and Tourism" dataset. This choice provided a more comprehensive view of tourism investments, which better reflects the cross-cutting nature of tourism. Second, an original re-categorization process clarified the types of investments in the database, allowing to differentiate their impacts on municipal attractiveness. Third, by focusing on the smallest administrative units, this approach provided a deeper and more nuanced understanding of the impact of Cohesion Policy-funded tourism investments.

This research fills a critical gap in the literature by examining the impact of Cohesion Policy-funded tourism projects at the municipal level across Italy. While previous studies often aggregate data at higher levels and fail to focus on specific sectors, this study contributes to the existing body of tourism economics literature by providing empirical evidence on how tourism investments can effectively enhance territorial attractiveness and foster local development. Additionally, it offers practical insights for guiding future investments aimed at promoting territorial development. Policymakers can capitalize on these results to refine their strategies, focusing on targeted tourism investments that enhance territorial attractiveness.

Limitations of this study include data-related and methodological constraints. First, the data on stays and arrivals are only available at the municipal level from 2014 onward and are limited to municipalities classified by ISTAT as tourism-oriented, potentially excluding areas with emerging or unclassified tourism activities. Second, the present analysis omits the COVID-19 period to avoid biases, as the pandemic drastically altered travel behaviour. While this decision enhances the reliability of the results, it restricts our understanding of how Cohesion Policy investments might have either alleviated or exacerbated the pandemic's effects on tourism. The limited availability of municipal data, combined with the external shock of the pandemic, hinders our ability to estimate the long-term effects of funds that are intended to have structural impacts. Finally, this analysis disregards the local contextual factors that could affect the policy's success or failure. Research suggests that the impacts of Cohesion Policy are influenced by a range of local and contextual variables, such as government capacity, social dynamics, community engagement, and environmental conditions.

A potential further development of this work could involve incorporating the COVID-19 period into the model and repeating the analysis after the conclusion of the current programming cycle in 2027. This would enable a more comprehensive understanding of the long-term effects of Cohesion Policy investments. Additionally, it would be beneficial to integrate local contextual factors into the analysis to provide a more nuanced view of how these variables influence the outcomes of CP investments.

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4. The Effect of Special Economic Zones on Firms Behaviour: A Preliminary Case Study of Italian Regions *(Elsa Amaddeo, Angela Stefania Bergantino, Giulio Fusco - UniBA)*

4.1. Introduction

Special Economic Zones (SEZ) are defined as economic policy tools designed to stimulate industrial activity within specific geographic areas. These zones offer businesses located within them special economic, fiscal, and bureaucratic advantages, with the goal of boosting local economies and reducing regional disparities.

Over the years, SEZs have spread rapidly, particularly in emerging and transitional economies. From just 845 zones in 1997, the number of SEZs globally has grown to 5,400 across 147 countries by 2018 (Figure 1) (Ambrosetti, 2023). Countries worldwide have adopted SEZs to promote regional economic growth, create jobs, and attract both national and foreign investments.

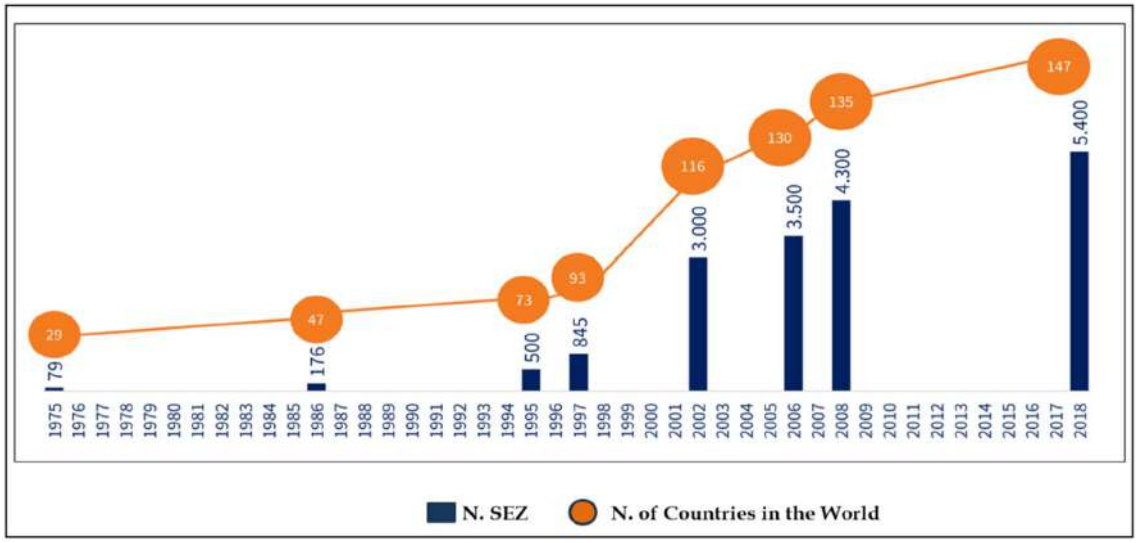

Figure 1: Evolution of the Special Economic Zones in the World (1975 – 2018) (Source: Ambrosetti, 2023)

Italy introduced SEZs in 2017 (Law Decree 91/2017) as part of a strategy to stimulate the lagging southern economy, or Mezzogiorno, which has historically underperformed in comparison to the more industrialized and prosperous North. Italy established 8 SEZs: Abruzzo, Calabria, Campania, Sardinia, Eastern Sicily, Western Sicily, Ionian SEZ (made of municipalities from Apulia and Basilicata) and Adriatic SEZ (made of municipalities from Apulia and Molise). *Table 5* in the Appendix section provides a list of the SEZ municipalities for each SEZ area.

The Mezzogiorno has long faced a significant economic gap with northern Italy. This discrepancy has hampered the national economic growth and fostered a significant gap between the North and South. SEZs were established to close this gap by the attraction of Foreign Direct Investment (FDI) and promoting economic expansion in these underdeveloped areas.

The main features of the Italia SEZs are: the institution of Free Economic Zones (Zone Franche Doganali), where goods from non-EU nations can be stored duty-free, processed, and subsequently re-exported or re-imported under favourable conditions, represent a key component of Italian SEZs; a tax credit for investments in capital goods (at different rates based on the size of the company and the SEZ); a 50% decrease in corporate income tax; simplified bureaucratic processes.

Firms must be located in a SEZ and continue operating there for at least seven years following the implementation of the investments in order to be eligible for these benefits. The eligibility criteria to qualify for these benefits concern the firms industrial sector[12], size and legal and financial conditions[13].

In Italy, cadastral data is used to identify SEZ areas, and a list of suitable zones is published by each region. These regions are defined geographically and, even though they could not be contiguous, they have to show strong economic ties. Furthermore, at least one port with the attributes specified by EU Regulation 1315/2013 must be a part of any SEZ.

With a special emphasis on the advantageous tax laws namely, the 50% decrease in corporate income tax and the provision of tax credits for capital goods investments this study attempts to evaluate the influence of special economic zones (SEZs) on the conduct and performance of businesses operating inside these zones.

This study compares firms' investment behaviour and economic performance before and after SEZ adoption using a Matching Difference in Differences model. In order to determine if Italy's SEZ strategy has resulted in more investments in the targeted areas, the dependent variable is the annual value of total fixed assets, which acts as a proxy for investment levels.

Additionally, for the first time, the study examines the effects of SEZs across all regions, considering both individual regional outcomes and broader national trends.

This approach allows for a comprehensive analysis of whether the SEZ policy can help narrow the long-standing economic divide between northern and southern Italy.

[12] The following sectors are excluded from the SEZs benefits: steel and coal industries, shipbuilding, synthetic fibers, transportation and related infrastructures, production and distribution of energy and energy infrastructures, credit, financial and insurance sectors, agriculture, fishing, and aquaculture.

[13] Firms must be duly registered in the commercial register, must not be in voluntary liquidation nor subject to insolvency proceedings, must not be included among the subjects they have received and, subsequently, not reimbursed or deposited in a blocked account, aids identified as illegal by the European Commission and must not be subjected to interdictive sanctions.

4.2. Outline of literature background

Since their first introduction, SEZs have been studied by the economic literature in order to understand and analyze the effect on the economy of territories. Over the years, several works demonstrated, both at a theoretical and empirical level, that Special Economic Zones, when correctly implemented, can foster the economic growth of the entire country in which the SEZ area is located (Zeng, 2015; Johansson & Nilsson, 1997; Akinci & Crittle, 2008).

One pivotal study by Wang (2013) focused on China's SEZs and used panel data to demonstrate that SEZs had a substantial impact on employment and industrial output, particularly in regions with well-established infrastructure (Wang, 2013). A similar study by Chen (1993) found that China's SEZs were instrumental in introducing foreign capital and technology, leading to broader economic benefits beyond the immediate zones (Chen, 1993).

Johansson and Nilsson (1997) analyzed SEZs in several Asian countries, including Indonesia, South Korea, and Malaysia. Their research demonstrated that SEZs were particularly effective at enhancing export performance, as firms operating within the zones were often more competitive internationally (Johansson and Nilson, 1997). In a more recent study, Zeng (2015) emphasized that SEZs, particularly in developing countries, could serve as testing grounds for broader economic reforms, leading to substantial positive spillovers in terms of foreign direct investment (FDI) and employment creation (Zeng, 2015).

Focusing on Africa, Farole (2011) conducted a comparative analysis of SEZs across various African nations, including Kenya, Ghana, and Tanzania. His findings revealed that SEZs led to increased industrial activity and improved infrastructure, although the results varied significantly based on government support and policy consistency (Farole, 2011).

While much of the literature has focused on the success stories in Asia and Eastern Europe, Farole and Moberg (2017) evaluated the global performance of SEZs, cautioning that success is not guaranteed. They emphasized the need for strong governance, transparent policies, and proper alignment between SEZs and national economic goals to achieve sustained success (Farole and Moberg, 2017).

At the current date, very few works focus their attention on the analysis of the Italian situation. In particular, Buonocore et al. conducted a quantitative analysis of the accessibility characterizing SEZs established in the Campania Region showing the urgent need to fill infrastructural gaps in certain areas and to prevent the creation of new ones in others. Moreover, they highlighted a certain heterogeneity among the existing SEZ areas that might lead foreign investors to choose one specific area over the others (Buonocore et al., 2023) and create disparity in the results also between SEZ of the same region.

Di Ruocco et al. use a Territorial Impact Assessment (TIA) methodology to bolster the role of Special Economic Zones (SEZs) in driving economic growth in the Campania region. This approach seeks to analyze and grasp the distinctive dynamics of Campania's SEZs in comparison to those across the broader Mezzogiorno landscape, highlighting the need for the region of proactive promotion and support from public authorities and stakeholders to ensure that Campania's SEZs can effectively compete with others across Italy (Di Ruocco et al., 2023).

As a conclusion, most of the international literature address to a properly implemented SEZ policy the ability of reducing economic gaps between regional territories boosting the employment

levels and the territorial attractiveness. To the best of our knowledge, there are no scientific papers that analyze the effect on firms performance and behaviour of the introduction in Italy of Special Economic Zones for all the SEZ regions.

4.3. Data

The aim of this study is to assess the impact of the introduction of SEZs on the levels of investment of Italian firms. The empirical analysis is temporarily focused on the firms located in Abruzzo, Basilicata, Calabria and Campania; hence, the current sample includes all manufacturing firms located in those regions for the period 2016 – 2022. The data has been extracted from AIDA, the Bureau Van Dick database which contains information about financial statements of Italian firms. In order to identify the firms located in a SEZ area, the geographical coordinates of each firm have been converted into cadastral data using *Mappe Catasto*, an online service that allows to overlay cadastral and geographic maps in Italy. *Figure 2* shows the geographical distribution of all the Italian SEZ areas.

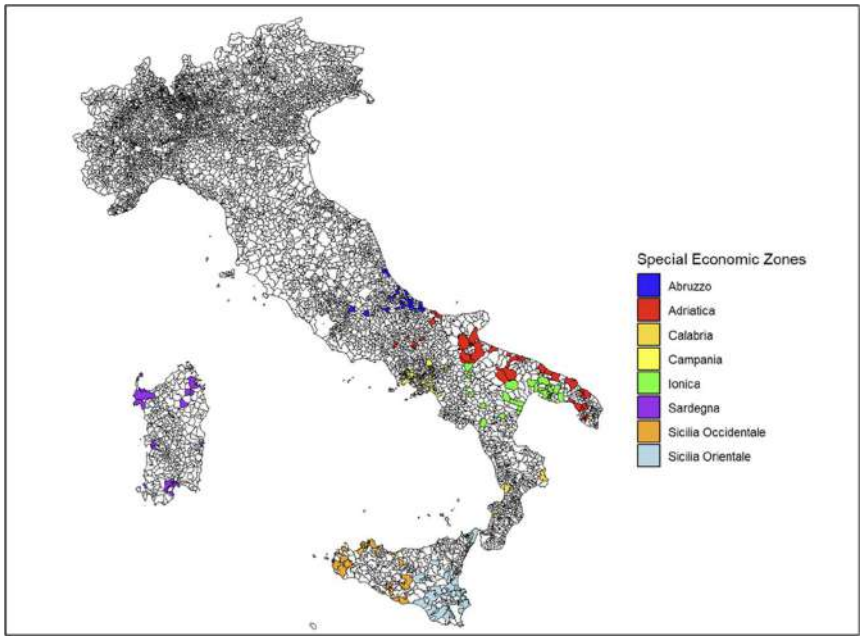

Figure 2: Geographical distribution of SEZ areas (authors' elaboration with R)

The dataset used for this analysis is a balanced panel of 6,472 companies, of which 431 located specifically in a SEZ area. Each firm has been observed for seven years, leading to a total of 45,304 observations.

Figures 3 and 4 show the distribution of firms operating within **SEZ** and those outside these zones, categorized by sector, across the analyzed Italian regions. Looking at SEZ firms, it is worth noting that ***Computer and Electronics Manufacturing*** emerges as the most prominent sector for SEZ firms, particularly in **Campania**, where it significantly surpasses all other sectors with nearly 60 companies (*Figure 3*). The presence of this sector in SEZ areas is far more pronounced compared

to non-ZES zones, suggesting that the incentives provided by the ZES scheme might be particularly appealing to companies in high-tech and electronic industries. In contrast, traditional manufacturing sectors like ***Metallurgy*** and ***Machinery Manufacturing*** show moderate representation in ZES regions, with Campania once again leading, although **Abruzzo** and **Basilicata** also register activity in these fields. The ***Food and Beverage Industries*** also have a modest presence in ZES areas, with **Abruzzo** showing slightly higher numbers than the other regions.

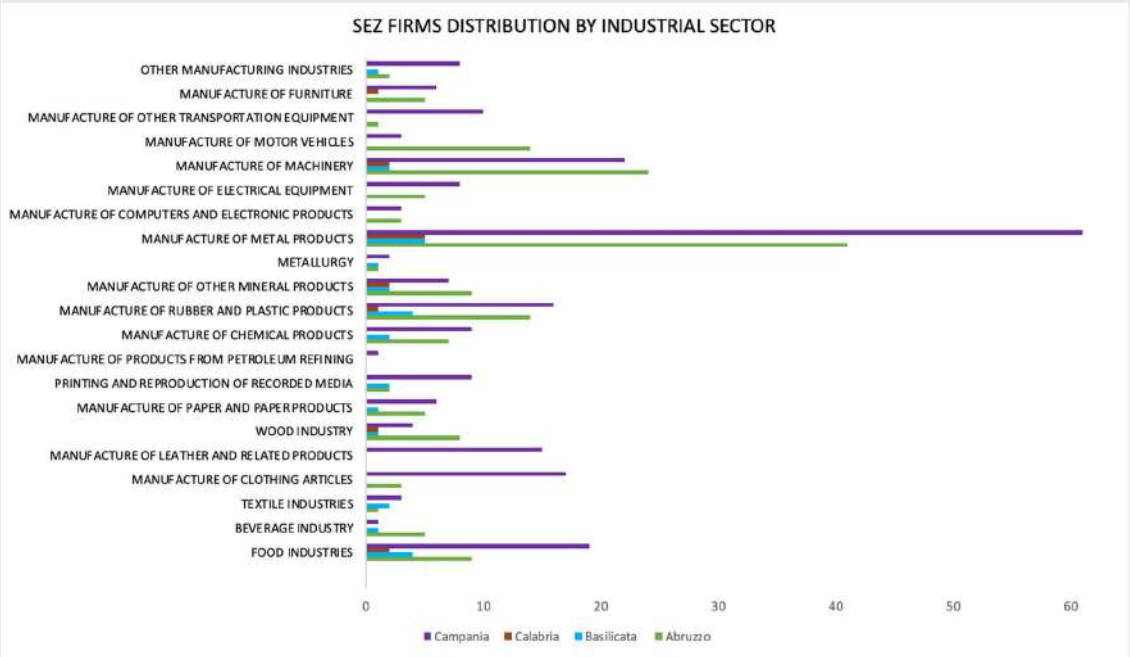

Figure 3: SEZ firms distribution by industrial sector (authors' elaboration)[14]

Turning to the sectoral distribution of **non-SEZ firms (*Figure 4*)**, a much larger and more diversified industrial landscape becomes evident. In this case, ***Metallurgy*** and ***Food Manufacturing*** dominate, particularly in **Campania**, where the number of firms exceeds 500 in the food sector alone. This difference between SEZ and non-SEZ firms indicates that more traditional industries find less incentive to relocate to SEZ regions, remaining highly concentrated in non-ZES areas. Additionally, sectors like ***Paper Products***, ***Wood***, and ***Textile Manufacturing*** are significantly more prevalent outside the SEZ zones. Interestingly, ***Computer and Electronics Manufacturing***, which is so prominent in SEZ areas, has a much smaller diffusion in non-SEZ regions, highlighting the attractiveness of the SEZ policy for this specific sector.

Overall, it is possible to state that **non-SEZ zones** support particularly traditional sectors such as ***Metallurgy***, ***Food Manufacturing,*** and ***Textiles***. In contrast, **SEZ areas** appear to attract more specialized and high-tech industries such as ***Electronics***.

[14] To complete, with the data of the other Regions

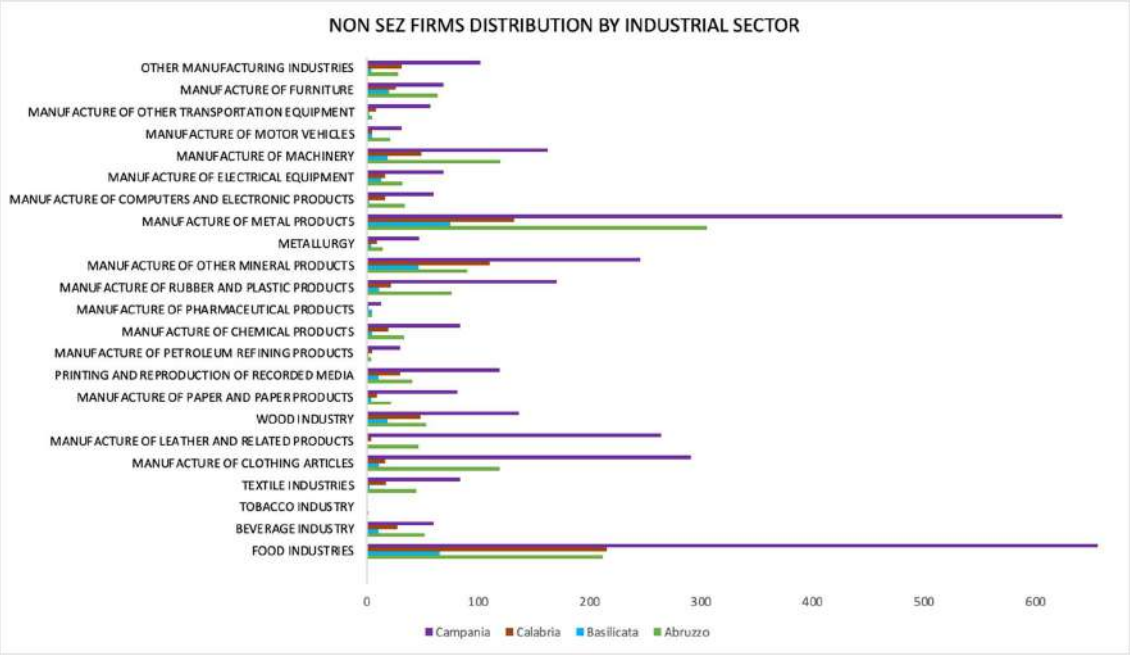

Figure 4: Non SEZ firms distribution by industrial sector (authors' elaboration)[15]

Table 1 shows the data source and the definition of the variables used in this work.

Variables	Unit	Data Source	Definition
Total Fixed Assets	Euro (€)	AIDA	Stock value of total fixed assets.
SEZ	Dummy	-	It takes 1 if a firm is located in a Special Economic Zone and 0 otherwise.
Post	Dummy	-	It takes 1 for the years of treatment (2020-2022) and 0 otherwise.
Value of Production	Euro (€)	AIDA	Annual revenue generated by each firm.
Employees	No.	AIDA	Number of employees in each firm.

Table 1: Data sources, variables and definitions

In order to measure the investment dynamics of firms and their level of efficiency, in line with the literature (Bloom et al., 2002; Klemm and Van Parys, 2012; Liu and Mao, 2019; Lyon, 1989), it has been chosen to use total fixed assets as the dependent variable, which is strictly connected to the firm's level of investment. Using total fixed assets as the dependent variable allows to verify whether the implementation of the SEZ policy in Italy has led to higher levels of investments for the firms located in the area.

[15] To complete, with the data of the other regions

Moreover, to take into account the economic and financial features of each firm and the related production function, value of production and number of employees have been chosen as matching variables.
Finally, two dummy variables have been used: the SEZ variable, indicating the presence of the treatment in case of a firm located in a SEZ area, and the variable Post, which assumes value 1, from the year in which the policy has been introduced (2021-2022) and 0 otherwise (2016-2020). For this work it has been chosen to use 2021 as the cut off year to evaluate the effects of the policy, since in 2021 there has been the introduction of the tax credit for investments in capital goods and the institution of *Sportello Unico*[16] (Law Decree 77/2021).
Table 2 contains the summary statistics of the analyzed variables for the period 2016-2022.

Variables	Mean	Std Deviation	Minimum	Maximum
Total Fixed Assets	2,223.056	12,450.8	0	470,359
Value of Production	5,170.018	24,192.78	-2,528	959,661
Employees	20.15	73.437	0	3,422

Table 2: Descriptive statistics for each variable observed over the period 2016 - 2022.

Table 3 and 4 report the mean values of each variable per year and per region for the treated and the control group. Comparing the values of each group, it is worth noting that, overall, the firms located in a SEZ area show higher values for all the analyzed variables. Moreover, at a general level it is possible to observe an increasing trend from 2016 to 2022 for both groups.

	Value of Production	Employees	Total Fixed Assets
SEZ firms			
2016	10,976.7	39.39252	4,312.698
2017	12,061.35	40.95316	4,557.207
2018	12.183,15	44.96721	4,834.270
2019	12,451.76	45.54245	4,878.236
2020	11,745.15	45.98824	6,137.546
2021	13,527.37	46.22066	6,261.011
2022	16,316.07	47.28806	6,361.877
Non- SEZ firms			
2016	3,893.846	16.29389	1,611.627
2017	4,164.721	17.12820	1,692.332

[16] *Sportello unico* is the unified interface for submitting single authorization applications concerning investment projects located in the eight SEZ regions.

2018	4,357.499	17.57066	1,732.172
2019	4,491.342	19.29260	1,841.552
2020	4,277.321	19.16927	2,258.644
2021	5,095.042	19.49630	2,379.275
2022	6,204.162	20.00808	2,522.844

Table 3: Descriptive statistics (mean values) by year (treated vs control groups)

	Total Fixed Assets		**Value of Production**		**Employees**		**Observations**		**N. of Firms**	
	SEZ	**Non SEZ**	**SEZ**	**Non SEZ**	**SEZ**	**Non SEZ**	**SEZ**	**Non SEZ**	**SEZ**	**Non SEZ**
Abruzzo	7,790	2,677	19,563	6,083	62	25	1,029	9,793	158	1,399
Basilicata	3,890	2,330	8,138	3,714	27	20	196	2,324	28	332
Calabria	1,186	1,001	3,234	1,921	19	10	98	5,698	14	814
Campania	4,189	1,938	9,538	4,784	36	18	1,610	24,178	231	3,454

Table 4: Descriptive statistics (mean values) by region (treated vs control groups)

4.4. Methodology

Difference-in-differences (DiD) is a method frequently used to assess the impact of policies and programs on distinct groups. It contrasts the outcomes of a treatment group that received the intervention with a control group that did not, both before and after the intervention. The treatment effect is identified by comparing the outcome variables between these two groups. Verifying the parallel trend assumption, which posits that the treatment and control groups would have followed similar trends over time in the absence of the intervention, is crucial. This ensures that the effect on the outcome variable can be attributed to the policy or program. For this reason, we employ a two-step analysis in this study, where the first step involves matching. This approach allows us to construct a counterfactual group that closely resembles the treatment group in terms of observable characteristics. In this case, the variables used for matching include Employees, Total Assets, Value Added, and Total Sales.

The possibility of applying statistical inference relies on the assumption of i.i.d. (independent and identically distributed). This assumption holds true only when the sample is obtained through simple random sampling. This approach is valid only when there is an exact match between the treated and control units for the covariates used in the model during the pre-treatment period, while still adhering to the parallel trend assumption. However, in most cases, especially when analyzing finite data and continuous variables, using matching techniques (such as nearest neighbour matching, radius matching, kernel matching, etc.) based on perfect matching via propensity score would result in the loss of a significant number of observations, violating the

requirement for exact matching (Iacus et al., 2012). Iacus et al. (2012, 2019) propose an improvement by demonstrating that replacing simple random sampling with stratified sampling makes matching techniques consistent with their theoretical foundations. Unlike other matching estimators that often violate the principle of simple random sampling, Coarsened Exact Matching (CEM) remains consistent with its theoretical basis (Iacus et al., 2019). Therefore, using CEM as an estimator provides greater credibility to the analysis results. The CEM algorithm falls into a class of matching methods called "monotonic imbalance bounding," which seeks to limit the maximum level of imbalance in distribution characteristics through an ex-ante selection (in the case of CEM, this is coarsening).

Given a sample of n units randomly drawn from a population N $(with\ n \leq N)$ and one unit i that receives treatment, denoted as T_i:

T_i = 1 if the unit receives the treatment, otherwise T_i = 0.

In this context, the outcome variable of interest, Y, takes a value of zero $(Y_i = 0)$ if unit i does not receive the treatment, while it takes a value of one $(Y_i = 1)$ if unit i receives the treatment. The outcome is then given by $Y = T_i\, Y_i(1) + (1 - T_i) Y_i(0)$.

The primary challenge is that $Y_i(0)$ cannot be observed when the unit receives the treatment, and similarly, Y_i (1) cannot be observed when the unit does not receive the treatment, which is the classic issue of causal inference.

The application of the CEM algorithm addresses this challenge by creating a copy of the covariates chosen for matching. The variables X^* (representing the set of covariates) are then divided into meaningful strata (such as equal-sized intervals or intervals of varying sizes).

A unique stratum is then created for each X^*, and each observation is assigned to a stratum. The created strata are added to the original dataset, and any stratum that lacks at least one treated and one untreated observation is excluded from the sample.

It is important to emphasize that the control group comprises only firms not located within SEZs and, therefore, not affected by the policy. The key characteristic of the counterfactual group is that it consists of firms not located within SEZs and thus not subject to the policy. The purpose of the matching process is to balance the distribution of observable characteristics between the treatment and control groups, making them more comparable to isolate the treatment effect.

Our DiD regression model assumes the following specifications:

$$TFA_{i,m,t} = \alpha + \beta_1 SEZ_i + \beta_2 Post_t + \beta_3 SEZ_i\, x\, Post_t + \varepsilon_{i,t} \quad [1]$$

Where the dependent variable TFA measures the *total fixed assets* of a firm *i,* located in the municipality *m,* in year *t*, "*Post*" is a dummy variable that denotes the period after the introduction of the policy (2019), and SEZ is a dichotomous variable indicating whether the company is located in an SEZ territory. Additionally, to isolate the effect of the introduction of the treatment, fixed effects (FE) and time effects (TE) have been included in the estimation.

To enhance the validity of the results, a robustness check has been conducted through the implementation of the Coarsened Exact Matching (CEM), as developed by Iacus et al. (2012, 2019). The implementation of CEM allows to respect the assumption of independent and identically distributed (i.i.d.) observations by replacing simple random sampling with stratified sampling.

Using CEM, observations are assigned to strata based on the values of their covariates. Each stratum created must contain at least one treated and one untreated observation. Strata that do not meet this criterion are discarded and not considered in the sample. This ensures that the matched sample includes only comparable treated and untreated observations.
In order to implement the CEM matching procedure, *value of production* and *employees* have been chosen as matching variables.

4.5. Findings – Discussion

Table 5 presents the results of DiD analysis using 2021 as cut off year. Looking at the Average Treatment Effect on Treated (ATET) results, it is worth noting that the coefficient is positive and highly significant (1%). However, since the P-value resulting from the parallel trend test is lower than 0.10, it is not possible to state the presence of a parallel trend for treated and control groups before treatment. Therefore, the results cannot be considered reliable and it is necessary to use a Matching Difference in Differences.

Total Assets	***Coefficient***	***Rob. Std. error***	***t***	***P>|t|***
ATET Treatment (1 vs 0)	**764.2497**	**272.9045**	**2.80**	**0.005**
Years				
2017	88.65705	16.98378	5.47	0.000
2018	146.9786	36.70525	4.06	0.000
2019	252.4606	41.66398	6.09	0.000
2020	727.4583	73.45636	9.88	0.000
2021	785.729	78.86996	10.02	0.000
2022	922.6161	98.6254	9.33	0.000
Parallel trend Test				0.0083
N.obs				46,545

Table 5: DiD and Parallel Trend test results before CEM matching

Table 6 presents the results of DiD analysis on the matched sample. The findings from the DiD analysis corroborate the results presented in *Table 5*. In particular, the treatment effect remains positive and statistically significant at 1% level, although the coefficient is lower. Specifically, it can be concluded that, on average, companies situated within a SEZ area experience an increase in fixed assets exceeding that of companies outside SEZ areas by more than €432,000.

Total Assets	***Coefficient***	***Rob. Std. error***	***t***	***P>|t|***

ATET Treatment (1 vs 0)	**432.9182**	**181.2581**	**2.39**	**0.017**
Years				
2017	63.56575	12.63387	5.03	0.000
2018	147.1461	24.60788	5.98	0.000
2019	245.0543	29.49280	8.31	0.000
2020	644.0965	58.26821	11.05	0.000
2021	747.5796	73.95162	10.11	0.000
2022	853.6472	78.90113	10.82	0.000
N.obs				44,739

This outcome demonstrates that the SEZ policy implementation has a positive and significant effect on firm behavior, resulting in increased investments in fixed assets. More broadly, it can be stated that the CEM DiD results enhance the robustness of the estimates, ensuring a more balanced comparison between treated and untreated firms and reducing the influence of potential confounding variables.

4.6. Policy implications and recommendations

The findings of this study highlight the relevance of the correct and efficient implementation of the SEZ policy as a tool aimed at reducing territorial gaps, empower local economies and boost the employment levels.

The evaluation of the effects of the SEZ policy introduced in 2018 would also be highly relevant for the development of the Single SEZ policy, adopted in January 2024, which extends the fiscal, economic and bureaucratic benefits to the firms of the whole Mezzogiorno area. Understanding the outcomes of the earlier policy could provide valuable insights to refine and improve the implementation of the new framework, ensuring that it effectively promotes balanced territorial development and supports a broader range of sectors. This evaluation is essential to understand whether the policy has truly benefited the territories involved. The data shows that the sectors most impacted by the policy are those related to high technology and specialization, which were already in a phase of development. Given this, it would be worthwhile to consider strategies to involve other sectors, such as the food industry, which plays a significant role in the Italian manufacturing sector.

Nonetheless, some important considerations regarding our findings must be taken into account. Previous studies have noted that the impact of SEZs on regional economies can differ significantly from one region to another, with some areas experiencing positive economic outcomes while others do not. This study offers an initial examination of the effects of SEZs, taking into account fixed effect and year effects in the DiD model, and the results are expected to become clearer and more established over time. Although our findings suggest that the effects of SEZs in Italy should be consistent across regions, it is crucial to acknowledge the potential for regional variation.

In order to take into account the possible heterogeneity of results across the involved regions, as a future development of this study we plan to perform the analysis for each one of the SEZ regions separately and to further analyzed the possible effects the introduction of the policy might have had on the employment levels.
In addition, it is important to analyze the impact not only on the firms and the sectors directly involved in the policy, but also to measure the effect of the policy on those excluded and on the neighboring areas, assessing the indirect effects.
The future steps of this research are to understand the overall effects of the policy and to investigate the impact produced by the introduction of individual SEZs, first on the economy of the Mezzogiorno, and then on each of the Southern Regions.
Due to the preliminary nature of this study, which is intended to be replicated and expanded to encompass all regions involved in the SEZ policy, the coefficient may be overestimated, as it does not account for potential regional heterogeneity that could mitigate the estimated effect of the policy.

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4.8. Technical Appendix

Abruzzo	**Campania**	**Eastern Sicily**
Alanno	Acerra	Acireale
Arielli	Arzano	Augusta
Atessa	Atripalda	Avola
Avezzano	Avellino	Belpasso
Carsoli	Battipaglia	Caltagirone
Casoli	Bellizzi	Carlentini
Castiglione a Casauria	Benevento	Catania
Chieti	Caivano	Comiso
Cupello	Carinaro	Enna Dittaino
Fara San Martino	Casoria	Floridia
Fossacesia	Castellammare di Stabia	Francofonte
Gissi	Castellano Cisterna	Gela
Giulianova	Fisciano	Lentini
Guardiagrele	Flumeri	Melilli
Lanciano	Frattamaggiore	Messina
Manoppello	Gricignano D'Aversa	Milazzo
Montedorisio	Lacedonia	Militello Val di Catania
Mosciano Sant'Angelo	Maddaloni	Mineo
Mozzagrogna	Manocalzati	Niscemi
Oricola	Marcianise	Pachino
Ortona	Mercato san Severino	Palazzolo Acreide
Paglieta	Montefredane	Paterno'
Pescara	Napoli	Pozzallo
Poggiofiorito	Nocera Inferiore	Priolo Gargallo
Pratola Peligna	Nola	Ragusa
Raiano	Serra	Rosolini
Roseto degli Abruzzi	Pomigliano D'Arco	Scordia
San Giovanni Teatino	Principato Ultra	Siracusa
San Martino sulla Marrucina	Salerno	Solarino
San Salvo	San Marco Evangelista	Tremestieri
Scafa	Sarno	Troina
Sulmona	Teverola	Villafranca Tirrena
Vasto	Torre Annunziata	Vittoria
		Vizzini

Ionian SEZ	**Adriatic SEZ**	**Western Sicily**
Apulia	***Apulia***	Aragona-Favara
Carosino	Altamura	Calatafimi
Faggiano	Ascoli Satriano	Caltanissetta
Francavilla Fontana	Bari	Caltavuturo
Grottaglie	Barletta	Campofelice di Roccella
Manduria	Bitonto	Carini
Martina Franca	Brindisi	Cinisi
Massafra	Candela	Custonaci
Monteiasi	Cerignola	Gibellina
Mottola	Fasano	Licata porto
San Giorgio Ionico	Foggia	Marsala
Statte	Galatina	Mazara del Vallo
Taranto	Soleto	Misilmeri
Basilicata	Gravina in Puglia	Palermo
Atella	Lecce	Palma di Montechiaro
Balvano	Surbo	Partinico
Baragiano	Monte Sant'Angelo	Porto Empedocle
Ferrandina	Manfredonia	Ravanusa
Lauria	Matino	Salemi
Matera	Molfetta	Serradifalco
Melfi	Monopoli	Termini Imerese
Pisticci	Galatone	Trapani
Policoro	Nardò	
Scanzano Jonico	Ostuni	
Senise	Casarano	
Tito	Modugno	
Viggiano	***Molise***	
	Termoli	
	Campomarino	
	Larino	
	San Polo Matese	
	Campochiaro	
	Campobasso	
	Bojano	
	Pozzilli	
	Venafro	

	Carpinone	
	Pettoranello	

Sardinia	**Calabria**
Assemini	Lamezia Terme
Cagliari	Crotone
Sarroch	Corigliano-Rossano
Uta	San Ferdinando
Oristano	Gioia Tauro
Santa Giusta	Rosarno
Portoscuso	Vibo Valentia
Budduso'	Reggio Calabria
Monti	Villa San Giovanni
Olbia	
Alghero	
Porto Torres	
Sassari	
Tortoli'	
Elmas	

Table 6: SEZ municipalities

5. Smart and Green. The spatial effects of the Twin Transition in EU regions *(Emanuela Marrocu, Raffaele Paci, Luca Serafini - UniCA)*

5.1. Introduction

In recent years, the European Union (EU) has actively pursued climate change and digital transformation through the European Green Deal and the Twin Transition (TT) strategy, integrating green and digital shifts. These initiatives aim to drive sustainable development and maintain EU competitiveness. The Green Deal targets climate neutrality by 2050, requiring an extensive transformation across all sectors, while the digital transition focuses on leveraging technology for growth, with an emphasis on sustainability, equity, and inclusivity. At its core, the TT reflects the EU's objectives of climate neutrality and a resilient digital economy, as outlined by the European Green Deal and Digital Compass (European Commission, 2022).

The Smart Specialisation Strategy (S3), traditionally aimed at regional innovation, is now increasingly incorporating green and digital priorities, aligning with EU sustainability goals. This evolution reflects a broader approach to integrating economic, social, and environmental considerations into regional development (European Commission, 2024). Discussions have even proposed evolving S3 into "S4," explicitly including sustainability as a core component.

This paper analyses how regions integrated green and digital priorities into their S3 strategies during the 2014–2020 period, before the EU's focused Green Deal and Digital Strategy frameworks. The study has three main objectives: (1) provide a descriptive analysis of how regions incorporated green and digital transitions into S3 priorities, (2) evaluate whether prioritising these transitions led to better economic outcomes, particularly in lower-productivity regions, and (3) examine the performance of these strategies across pre- and post-pandemic periods to assess the impact of COVID-19 on their effectiveness.

Our findings show that many European regions integrated green and digital priorities into their smart strategies, though with significant variation across regions. Using a growth convergence model, we assessed the impact of TT on regional labour productivity, considering the pandemic's effects. Results indicate that digital technologies significantly boosted productivity in pre-pandemic periods, especially in less productive regions. Post-pandemic, digital prioritisation remained beneficial only for low-productivity regions. Green policies generally posed short-term economic challenges, showing negative impacts overall, but positive effects in low-productivity regions. Similarly, twin transitions had negative overall impacts but yielded positive results in less productive regions, particularly post-pandemic.

The study is divided into six sections. Section 2, following the Introduction, reviews the existing literature on S3 and the Twin Transition, highlighting the primary research gaps and theoretical foundations relevant to our analysis. In Section 3, we detail the data sources and explain how we defined, identified, and quantified the integration of twin transition priorities within regional S3 strategies, laying the groundwork for our empirical analysis. Section 4 outlines the methodology,

including the econometric analysis used to evaluate the spatial effects of these priorities on regional economic performance. Section 5 presents our main findings, offering insights into the effectiveness of these integrated strategies. Finally, Section 6 summarises the study's conclusions and discusses the policy implications for regional policymakers.

5.2. Outline of literature background

The concept of the twin transition, encompassing both the green and digital transformations, represents a pivotal focus in contemporary policy and academic debate. This dual transition seeks to integrate environmental sustainability with technological advancement, aiming to address the pressing challenges of climate change while leveraging digital technologies to enhance efficiency and innovation across sectors. At its core, the twin transition reflects the EU's strategic objectives of achieving climate neutrality and fostering a resilient, digitally empowered economy. The green transition, driven by the European Green Deal, aims to reach climate neutrality by 2050, necessitating comprehensive policies and targets to reduce greenhouse gas emissions, promote renewable energy, and mitigate environmental degradation. Concurrently, the digital transition, encapsulated by initiatives like the Digital Compass, strives to harness the potential of digital technologies to drive sustainable growth and improve societal outcomes (European Commission, 2022).

The interplay between these transitions is multifaceted and complex. Digital technologies such as artificial intelligence, blockchain, and the Internet of Things (IoT) hold significant promise in enhancing resource efficiency, reducing emissions, and supporting the circular economy. For instance, smart grids and energy management systems can optimise energy use and integrate renewable sources more effectively. Similarly, digital twins and advanced data analytics can revolutionise sectors like manufacturing, transportation, and agriculture by enabling more precise and sustainable practices.

Diodato et al. (2023), introducing the special issue of Industry and Innovation on the Twin Transition, emphasize that these green and digital revolutions are crucial in both technological and socio-economic domains. They have the potential to drive industrial innovation and significantly impact social, economic, and geographical inequalities. The special issue on the twin transition explores these implications, highlighting the necessity for diversified technological investments, especially in artificial intelligence, and enhanced digital infrastructures. Policy recommendations from this body of work advocate for aiding firms lagging in digitalisation and developing region-specific innovation policies.

The study by Fazio et al. (2024) further illustrates the spatial dynamics of twin innovation transitions across European regions. Their analysis reveals that ICT-oriented regions are more likely to achieve twin innovation status compared to green-oriented regions. This indicates a stronger synergy between digital and green innovation when regions already have a robust digital infrastructure. The study employs a transition probability approach and spatial methods to estimate the likelihood of regions becoming innovative in either or both technologies and assesses the role of spillovers.

Montresor and Vezzani (2023) add another dimension to this discussion by examining the role of digital technologies in promoting eco-innovation within firms. Their research, based on a large sample of Italian firms, demonstrates that investments in digital technologies, particularly artificial intelligence (AI), significantly enhance firms' capacity to implement eco-innovative production processes. The study highlights that while general investments in digital technologies are beneficial, AI and bundling multiple digital technologies have the most substantial impact on eco-innovation. This underscores the necessity for firms to not only adopt digital technologies but to strategically integrate multiple technologies to maximize their environmental and operational benefits.

Cicerone et al. (2023) investigate the extent to which AI is harnessed by regions specializing in green technologies. Their study explores the relationship between green-revealed technological advantages and local AI for EU-28 regions from 1982 to 2017. The results indicate that AI knowledge favours the green-tech specialization of regions, provided they were already green-tech specialized in the past. Conversely, AI even reduces this capacity in territories that do not specialize in green technologies at present. This finding suggests that AI can significantly enhance the green-tech capabilities of already specialized regions but does not necessarily initiate green specialization in regions lacking prior experience.

Despite the various positive effects of the twin transition, including enhanced regional and firm-level innovation capacities, it may also exacerbate social and economic inequalities. Digital transformation can lead to increased demand for highly skilled workers, potentially widening the gap between those with advanced skills and those without (Diodato et al., 2023). Furthermore, the cost and complexity of adopting new technologies can be a significant barrier for small and medium-sized enterprises (SMEs), potentially widening the gap between large firms and SMEs. Further, regional studies such as those by Santos et al. (2023) and Consoli et al. (2023) reveal substantial heterogeneity in how EU regions leverage structural funds to shift employment towards greener and more competitive sectors, with less developed regions benefiting more significantly. These studies also highlight that developing digital skills can exacerbate income disparities within areas, emphasising the need for inclusive growth policies.

Research by Calza et al. (2023) and Teruel et al. (2023) on firm resilience during the COVID-19 pandemic shows that higher digitalisation levels enhance firm resilience to economic shocks. Additionally, Bellucci et al. (2023) find that firms with a higher share of green patents are more likely to attract venture capital investment, indicating the financial attractiveness of green innovations. These contributions collectively underscore the need for diversified technological investments, particularly in AI, to maximise the benefits of the twin transition. Policy recommendations from this body of work advocate for extending digital infrastructures, supporting firms lagging in digitalisation, and developing region-specific innovation policies.

However, the integration of these transitions also presents challenges. The digital sector's own energy consumption and environmental impact, driven by the proliferation of data centres, electronic waste, and the need for critical raw materials, must be carefully managed. Policies must ensure that digital advancements contribute positively to environmental goals rather than exacerbating resource use and emissions. Furthermore, the geopolitical landscape adds another layer of complexity. The EU's dependence on external sources for critical raw materials necessary for both green and digital technologies highlights the need for strategic autonomy and resilient

supply chains. The recent geopolitical tensions, such as those arising from Russia's aggression against Ukraine, underscore the urgency of accelerating the twin transition to enhance energy security and economic stability.

In this complex context, the Smart Specialisation Strategy (S3), increasingly called S4 to emphasize its sustainability focus, can provide a complementary framework. S3 promotes a place-based approach to regional innovation, leveraging unique regional strengths to foster economic transformation and sustainable growth (Foray et al., 2009; McCann & Ortega-Argilés, 2015).

Montresor and Quatraro (2020) investigate the potential of S3 to drive green innovation through related diversification. Their study shows that regions with existing knowledge bases, whether green or non-green, are more likely to develop new green specialisations. This underscores the importance of leveraging existing capabilities to facilitate transitions to green technologies. Despite its strengths, S3 has faced criticism regarding its implementation. Challenges include engaging stakeholders effectively and ensuring regions focus on their unique strengths rather than mimicking others' strategies or not aligning with their actual specialisation (Iacobucci, 2014; Hassink & Gong, 2019; Di Cataldo et al., 2021, Marrocu et al., 2023). Recent updates to the S3 framework aim to address these issues by enhancing governance structures and increasing stakeholder involvement. These updates emphasise the importance of building robust regional governance mechanisms to oversee the effective implementation of S3 strategies. This includes creating more transparent decision-making processes, ensuring accountability, and fostering greater stakeholder collaboration.

Moreover, there is a growing emphasis on aligning S3 strategies with broader EU initiatives such as the European Green Deal. This alignment seeks to ensure that regional innovation strategies contribute to the EU's sustainability and climate neutrality goals. The integration of S3 with the twin transition initiative is seen as a way to enhance the effectiveness of regional policies by ensuring they are not only technologically advanced but also environmentally sustainable, with S3 concepts that are not designed with a strong environmental focus, but nevertheless, different types of territories have successfully used the S3 approach to promote environment-related priorities (Harding et al., 2021).

Understanding how regions have historically incorporated green and digital transitions into their S3 strategies is essential for refining these frameworks. By analysing how these priorities were integrated and their impact on economic performance, before and after the COVID-19 pandemic, we can uncover effective strategies and pinpoint areas for improvement. We aim to provide valuable insights for developing more effective and resilient S3 policies that support the twin transition, ultimately enhancing regional sustainability and economic growth.

5.3. Data

We analyse how EU regions integrated digital and green initiatives into their S3 priorities during the 2014–2020 programming period. The primary data source was the Eye@RIS3 database from the Smart Specialisation Platform (S3P), which provided detailed insights into regional strategic

priorities and their alignment with twin transition goals. The analysis covers 164 territorial units, mainly focusing on NUTS-2 regions. For consistency, NUTS-3 regions in Sweden and Finland were aggregated to NUTS-2. The final sample includes 12 NUTS-0 units (countries), 23 NUTS-1 regions, 127 NUTS-2 regions, and 2 NUTS-3 regions in Czechia (Table 1).

Table 7 - Territorial levels of S3 in the EU countries

Nuts 0, country		n. units		Nuts 2		n. units
BG	Bulgaria	1		AT	Austria	9
CY	Cyprus	1		CZ	Czech Republic	3
EE	Estonia	1		DK	Denmark	5
HR	Croatia	1		EL	Greece	13
HU	Hungary	1		ES	Spain	16
IE	Ireland	1		FI	Finland	4
LT	Lithuania	1		FR	France	22
LU	Luxembourg	1		IT	Italy	21
LV	Latvia	1		PL	Poland	16
MT	Malta	1		PT	Portugal	5
SI	Slovenia	1		RO	Romania	7
SK	Slovakia	1		SE	Sweden	8
Nuts 1		**n. units**				
BE	Belgium	3				
DE	Germany	16				
NL	Netherlands	4				
				Total areas		164

These regions developed their S3 policies, resulting in 1,145 priorities listed on the platform. On average, each region has about seven priorities, though there is considerable variation. For instance, Peloponnesus has just two, while North & East Finland has 30, largely due to data aggregation from smaller NUTS-3 regions.

We utilised the "Policy Objectives" classification from the Eye@RIS3 database to identify twin transition-related priorities. This classification outlines ten EU-wide policies, divided into 72

objectives, aligned with the "Societal Grand Challenges" of Horizon 2020. The most common objectives and the regions focusing on them are summarised in Tables 2 and 3.

Table 8 - Policy Objective in S3 priorities in 164 EU regions

Policy Objective with highest frequency	n. regions	Policy Objective with lowest frequency	n. regions
G.49 - Public health & well-being	136	D.34 - Quantum computing	18
J.68 - Sustainable energy & renew ables	115	I.58 - Social innovation and environ mental	16
E.38 - Advanced materials	107	B.13 - Offshore mining	15
E.37 - Advanced manufacturing sy stems	105	A.02 - Aeronautics & environment	14
J.65 - Resource efficiency	91	A.03 - Bio fuels & energy efficiency	14
D.27 - e-Health	89	A.05 - Safety & security	14
E.39 - Industrial biotechnology	87	J.64 - High-speed rail-road transportation	12
J.63 - Eco-innovations	86	A.04 - Remotely piloted aircrafts	11
C.16 - Development reg. cultural & creative ind.	82	I.56 - Social innovation to child care	9
J.67 - Sustainable agriculture	82	G.47 - Dual use	4

Table 9 - Regions per coverage of 72 Policy Objectives in S3 priorities

Regions with highest coverage	n. objectives	Regions with lowest coverage	n. objectives
FI19 - Länsi-Suomi	61	AT13 - Wien	7
SI - Slovenia	57	ITC4 - Lombardia	7
FI1C - Etelä-Suomi	52	NL3 - West-Nederland	6
FR52 - Haute-Normandie	52	FR26 - Bourgogne	6
FR30 - Nord - Pas-de-Calais	49	CZ07 - Střední Morava	6
ES30 - Comunidad de Madrid	48	NL2 - Oost-Nederland	5
ITI2 - Umbria	48	EL25 - Peloponnisos	5
ES11 - Galicia	46	NL4 - Zuid-Nederland	4
FI1D - Pohjois- ja Itä-Suomi	46	AT22 - Steiermark	4
FR61 - Aquitaine	40	AT21 - Kärnten	2

Table 4 shows that of the 1,145 S3 priorities, 625 (54.6%) are related to digital initiatives, while 510 (44.5%) focus on green programmes. The most common green category is "J - Sustainable

innovation," with 463 priorities. In 52 cases, two policy objectives overlap; for nine priorities, all objectives are targeted. The top digital policy objective is "D - Digital transformation", with 390 priorities, followed by "E – KETs", with 372. Additionally, 137 priorities target both objectives simultaneously.

Notably, only 235 initiatives (20.5%) integrate both green and digital aspects (TT priorities), indicating that while digital and green initiatives are prominent individually, their combined implementation is less common, suggesting regions tend to pursue them separately.

Table 10 - Table 4 – Count of green and digital projects in S3 priorities

	n. priorities	% on total priorities
Green projects		
J - Sustainable innovation	463	40.4
F - Nature & biodiversity	75	6.6
B.09 Blue renewable energy	42	3.7
Total Green	510	44.5
Digital projects		
D - Digital transformation	390	34.1
E - KETs	372	32.5
Total Digital	625	54.6
Green&Digital	235	20.5
Total number of S3 priorities	1145	100
The sum of categories is higher than the Total since a priority may include more than one category.		

As expected, regions developed their S3 programmes quite heterogeneously, with the number of priorities varying significantly across areas. Relying solely on the count of S3 priorities related to the twin transition could introduce bias into the analysis. To address this, the study introduces green and digital "intensity" measures to allow for more meaningful comparisons across regions. Green and digital intensities are defined as the proportion of priorities related to either green or digital technologies out of the total number of priorities in a region, calculated separately. A twin transition (TT) intensity measure is also derived, identifying a priority as TT only if it addresses both green and digital objectives simultaneously. The top and bottom regions for each intensity measure are listed in Table 5.

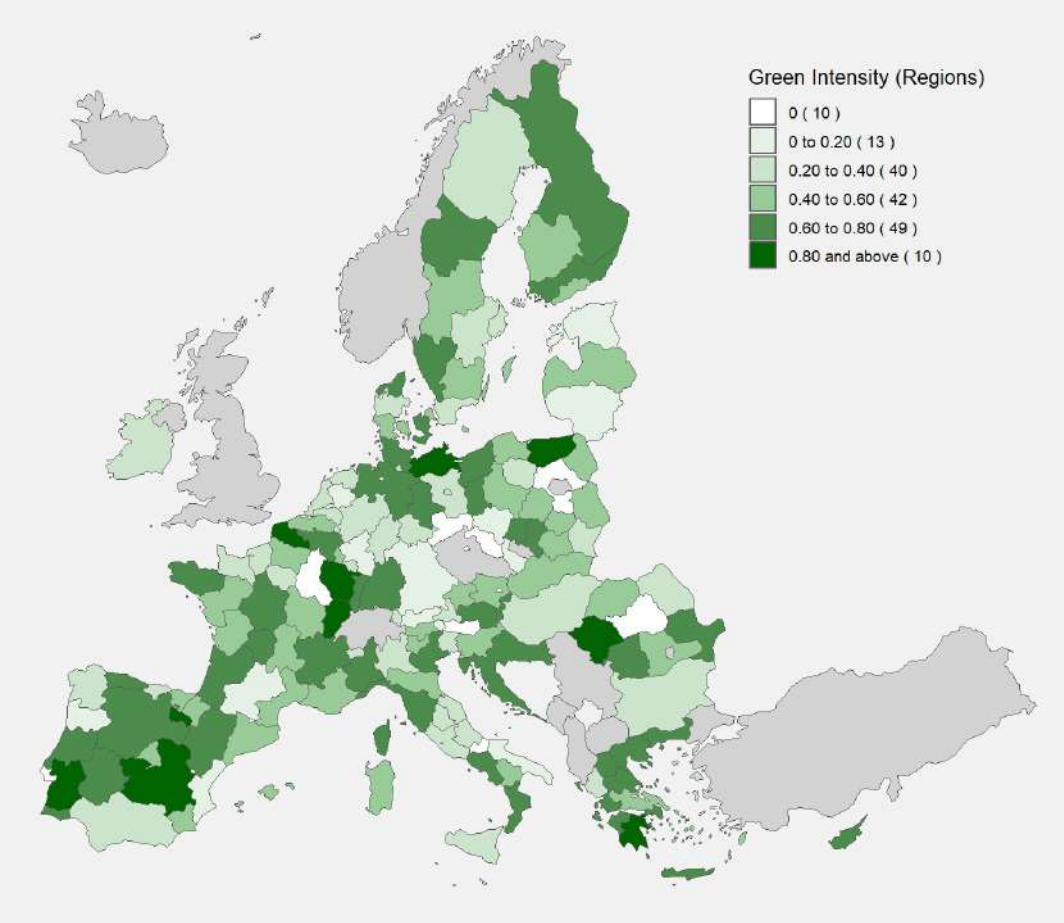
Table 11 - Green, Digital and Twin intensities in S3 priorities

Top regions	Intensity		Bottom regions	Intensity
		Green policies		
EL65 - Peloponnisos	1		AT13 - Wien	0
ES23 - La Rioja	1		AT21 - Kärnten	0
PL62 - Warminsko-Mazurskie	1		CZ01 - Praha	0
RO42 - Vest	1		CZ05 - Severovýchod	0
ES42 - Castilla-La Mancha	0.86		DED - Sachsen	0
DE8 - Mecklenburg-Vorpommern	0.83		FRF2 - Champagne-Ardenne	0
FRC2 - Franche-Comté	0.83		ITF2 - Molise	0
FRE1 - Nord - Pas-de-Calais	0.83		PL92 - Mazowieckie	0
FRF3 - Lorraine	0.8		PT17 - Lisboa	0
PT18 - Alentejo	0.8		RO12 - Centru	0
		Digital policies		
ES23 - La Rioja	1		EL53 - Dytiki Makedonia	0.17
FRE1 - Nord - Pas-de-Calais	1		PT15 - Algarve	0.17
FR3 - Lorraine	1		AT13 - Wien	0.17
BE1 - Brussels-Capital Region	1		PT17 - Lisboa	0.17
ES41 - Castilla y León	1		FRF1 - Alsace	0.14
ITI1 - Toscana	1		PL72 - Swietokrzyskie	0.14
PL43 - Lubuskie	1		ITC4 - Lombardia	0.14
DEF - Schleswig-Holstein	1		ES62 - Región de Murcia	0.13
ES12 - Principado de Asturias	1		NL1 - Northern Netherlands	0.08
PL81 - Lubelskie	1		EL65 - Peloponnisos	0
RO31 - Sud - Muntenia	1		PL62 - Warminsko-Mazurskie	0
ES30 - Comunidad de Madrid	1		EL62 - Ionia Nisia	0
ITH5 - Emilia-Romagna	1		EL42 - Notio Aigaio	0
SE11 - Stockholm	1		ES51 - Cataluña	0
ITI3 - Marche	1		NL4 - Southern Netherlands	0

DED - Sachsen	1	PL92 - Mazowieckie	0
	Twin transition		
ES23 - La Rioja	1		
FRE1 - Nord - Pas-de-Calais	0.83	With the definition of TT priority as being simultaneously Green & Digital, 62 regions have an intensity score of 0	
FR3 - Lorraine	0.8		
DE8 - Mecklenburg-Vorpommern	0.67		
FRC2 - Franche-Comté	0.67		
BE1 - Brussels-Capital Region	0.67		
ES41 - Castilla y León	0.67		
ITI1 - Toscana	0.67		
PL81 - Lubelskie	0.67		
BE35 - Région Wallonne	0.67		

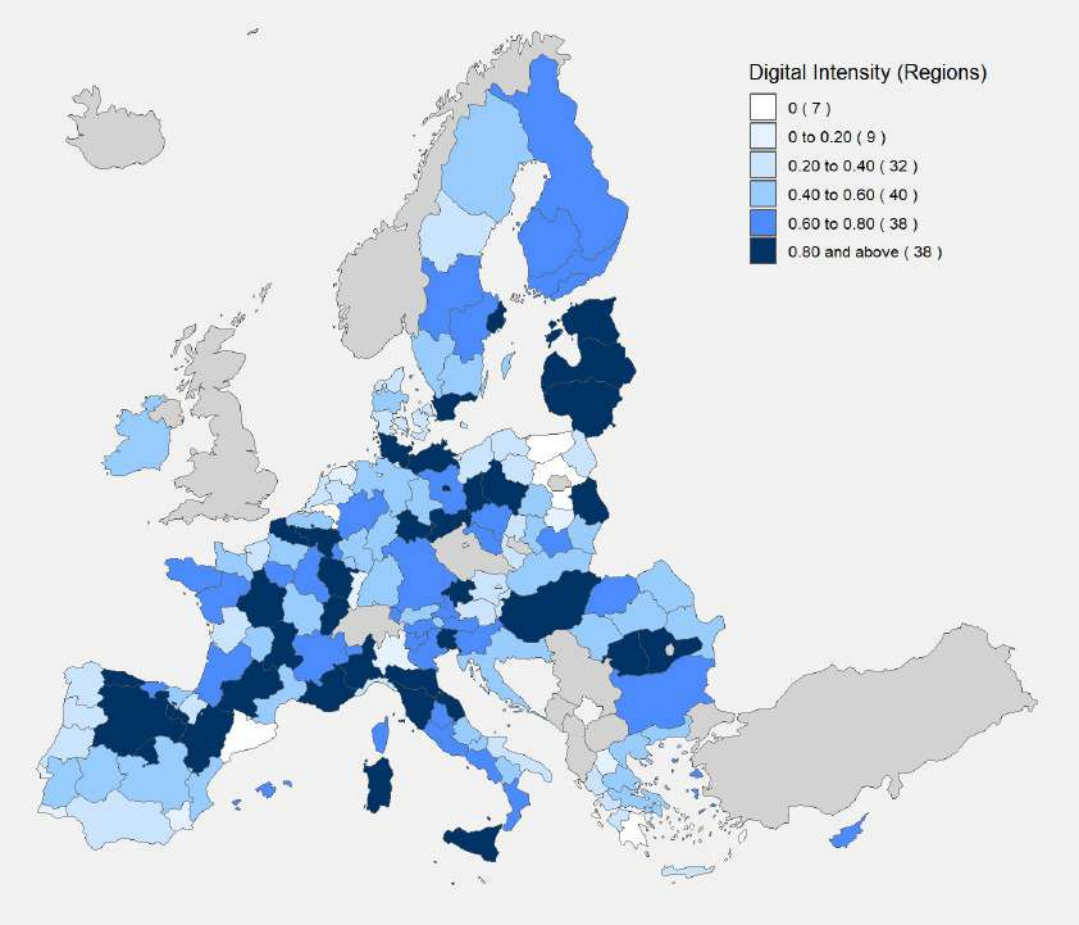
Figure 1 illustrates the distribution of green-related priorities across Europe. Nearly 94% of regions have at least one green priority, with an average green intensity of 0.45. Notably, 65 regions show green intensities above 0.5, highlighting a strong focus on sustainability. Leading regions with perfect scores of 1.00 include Peloponnisos, La Rioja, Warminsko-Mazurskie, and Vest, demonstrating full commitment to green objectives. Other regions like Castilla-La Mancha, Mecklenburg-Vorpommern, Franche-Comté, and Nord - Pas-de-Calais follow closely with scores around 0.83, while Lorraine and Alentejo score 0.80.

Figure 5 - Green-intensity in S3 priorities



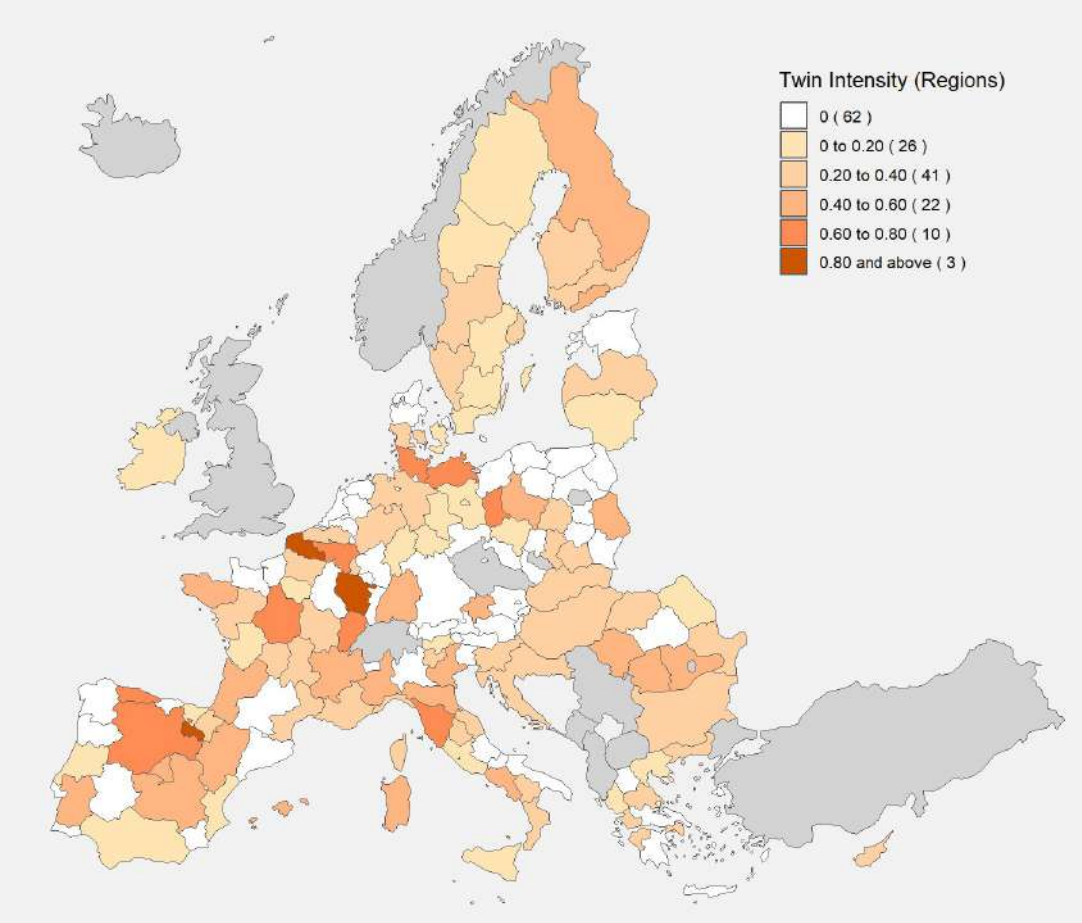
In the digital sphere (Figure 2), an even higher proportion of regions (95.12%) have at least one digital-related priority, with an average intensity of 0.55. A total of 81 European regions show a strong focus on digital innovation, with intensity scores above 0.5. Regions such as La Rioja, Nord - Pas-de-Calais, Lorraine, and Brussels-Capital Region stand out with perfect digital intensity scores of 1.00.

Figure 6 - Digital-intensity in S3 priorities



When considering both transitions simultaneously (Figure 3), there is noticeably less commitment to the twin transition. Only 62.2% of regions have at least one priority that integrates both digital and green objectives, with an average intensity of 0.21 across the sample. Just 17 regions exhibit an intensity higher than 0.5. La Rioja leads with a perfect score of 1.00, showcasing a strong integration of sustainability and digital innovation. Regions like Nord - Pas-de-Calais and Lorraine also demonstrate significant commitment, with scores of 0.83 and 0.80, respectively, while other regions lag behind.

Figure 7 - Twin-intensity in S3 priorities



Overall, the data reveals a significant heterogeneity among European regions. While some regions like La Rioja, Nord - Pas-de-Calais, and Lorraine excel in both green and digital intensities, demonstrating comprehensive strategic commitments, many other regions show varied levels of focus. This diversity suggests that regional strategies towards sustainability and digital innovation are highly context-specific and influenced by local priorities and capacities, as evidenced by the varying intensity scores, which may reflect different regional policies, resource availability, economic structures, and local challenges.

5.4. Methodology

In this section, we outline the main estimation strategy for our empirical analysis, assessing regional growth post-strategy implementation based on Digital Intensity (DI), Green Intensity (GI), or their combined effect (TTI) on economic performance. We use a standard growth regression model:

$$\Delta\, GDPpe_i = \alpha + \beta_1 DI_i + \beta_2 GI_i + \beta_3 TTI_i + \beta_4 GDPpe_i + \beta_5 QI_i + \beta_6 HTEC_i + \beta_7 HK_i + \beta_8 TK_i + \beta_9 DEN_i + \boldsymbol{\varepsilon}_i$$

where $\Delta\, GDPpe_i$ represents the average annual growth rate of GDP per employee in region i, with intensity variables reflecting the share of smart, green, or combined priorities in regional S3

strategies. We control for initial labour productivity (GDPpe) and other regional characteristics, including intangible factors (QI, HK, TK), agglomeration forces (DEN), and production structure (HTEC). Table 6 details the sources and definitions of the variables.

Table 12 - Variables sources and definitions

Variable	Source	Description
Digital Intensity	Own elab. on S3P	Digital priorities / Total number of S3 priorities
Green Intensity	Own elab. on S3P	Green priorities / Total number of S3 priorities
Twin Intensity	Own elab. on S3P	Twin priorities / Total number of S3 priorities
GDP pe growth	Own elab. on Eurostat	Growth rate of GDP per worker (annual average)
GDP pe	Eurostat	GDP per person employed (constant prices)
HTEC specialisation	Own elab. on Eurostat	Specialisation index in High-tech sectors (high-tech manufacturing and knowledge-intensive high-tech services)
Quality of Institution	Univ. of Gothenburg	Composite index based on citizens' perceptions on impartiality, quality of public
Human capital	Eurostat	Number of graduates (ISCEED 5-8) over population aged 25-64 (%)
Technological Capital	Eurostat	R&D expenditure, Euro per inhabitant
Population density	Eurostat	Persons per square kilometre

We use labour productivity, measured as GDP per employed person (GDP pe), as our output variable for several reasons. First, it reflects the efficiency of labour in generating economic output, making it a key indicator of economic performance. Second, implementing smart and green priorities is expected to enhance productivity through innovation and efficiency. By focusing on labour productivity, we aim to assess whether regions prioritising green and digital transitions have experienced better economic outcomes. Lastly, GDP pe is less influenced by factors like labour market participation or regional unemployment, allowing for clearer comparisons across regions with different labour forces and demographics. [17]

Our analysis covers three periods: the full programming period (2016–2022), the pre-pandemic years (2016–2019), and the post-pandemic years (2019–2022). This segmentation is crucial to understand how the COVID-19 pandemic, with its economic disruptions, may have impacted the relationship between twin transitions and regional performance. By examining these sub-periods, we consider how the pandemic might have shifted regional priorities and affected the effectiveness of strategies.

5.5. Findings – Discussion

Overall Period (2016-2022). The analysis of the overall period (Table 7) presents the results of our empirical analysis examining the average annual growth rate of GDP per employee (GDP pe) from 2016 to 2022, focusing on the impact of digital intensity, green intensity, and their combined effect (twin intensity) on regional economic performance.

[17] For robustness, we also conducted our analysis using GDP per capita (GDP pc) as the output variable. However, the results did not yield significant or reliable effects, reinforcing our choice of GDP per employee (GDP pe) as a more appropriate measure for this study.

Table 13 - Twin transition and regional labour productivity (overall period, 2016-2022)

Dependent variable: GDP pe average growth rate	(1)	(2)	(3)	(4)	(5)
Digital Intensity	0.325			0.365	0.694*
	(0.300)			(0.299)	(0.396)
Green Intensity		-0.609*		-0.642*	-0.292
		(0.357)		(0.358)	(0.479)
Twin Intensity			-0.242		-0.625
			(0.374)		(0.609)
Controls					
GDP pe	-1.637 ***	-1.554 ***	-1.627 ***	-1.537 ***	-1.531 ***
	(0.474)	(0.482)	(0.486)	(0.480)	(0.480)
Quality of Institution	0.321 ***	0.278 **	0.281 **	0.308 ***	0.312 ***
	(0.117)	(0.110)	(0.116)	(0.117)	(0.117)
HTEC specialisation	1.304 ***	1.242 ***	1.314 ***	1.222 ***	1.241 ***
	(0.364)	(0.359)	(0.362)	(0.358)	(0.354)
Human Capital	-0.008	-0.003	-0.006	-0.004	-0.004
	(0.010)	(0.011)	(0.011)	(0.011)	(0.011)
Technological Capital	-0.219	-0.229	-0.194	-0.261	-0.271
	(0.209)	(0.210)	(0.210)	(0.209)	(0.211)
Population density	-0.138	-0.168 *	-0.158 *	-0.152	-0.140
	(0.096)	(0.092)	(0.093)	(0.096)	(0.096)
Adjusted R2	0.412	0.418	0.409	0.420	0.419

Significance levels: ***(1%), **(5%), *(10%).
Robust Standard Error in parentheses.
Control variables refer to the initial year of the period considered
All models include a constant.
GDP pe, R&D expenditure and Population density are log transformed.
164 observations

We test the intensity variables using different model specifications: first, each intensity (Digital, Green, Twin) is tested individually (Models 1–3). Next, Digital and Green intensities are tested together (Model 4), followed by a model including all three intensities (Model 5). For the overall period (2016–2022), the results show that the coefficient for digital intensity is positive but not statistically significant across all models, suggesting that selecting smart technologies did not significantly influence labour productivity growth over the long term.In contrast, green intensity has a negative and statistically significant impact in some models (-0.609 in Model 2 and -0.642 in Model 4), indicating that regions with higher green prioritisation saw lower GDP growth during this period. This suggests that green investments may be more focused on long-term sustainability goals rather than immediate productivity gains. The coefficient for twin intensity, representing the combined focus on digital and green transitions, is negative and not statistically significant. This implies that, while regions attempted to balance both transitions, the combined effort did not result in immediate economic benefits during this volatile period. This highlights the need to consider both economic and non-economic outcomes when assessing the success of green transition initiatives.

Table 14 - The differentiated effect by productivity levels (overall periods, 2016-2022)

Dependent variable: GDP pe average growth rate	(1)	(2)	(3)	(4)
Digital Intensity	-0.044			0.325
	(0.292)			(0.297)
Digital Intensity*GDP pe 1st quartile	1.343 **			0.594
	(0.603)			(0.582)
Green Intensity		-1.14 ***		-1.108 ***
		(0.367)		(0.364)
Green Intensity*GDP pe 1st quartile		1.767 ***		1.673 **
		(0.647)		(0.645)
Twin Intensity			-0.530	
			(0.349)	
Twin Intensity*GDP pe 1st quartile			1.645	
			(1.186)	
Adjusted R2	0.431	0.457	0.316	0.464

Significance levels: ***(1%), **(5%), *(10%).
Robust Standard Error in parentheses.
All models include a constant and the control variables as in Table 7
164 observations

Among the control variables, initial GDP pe shows a significant negative effect on growth, confirming that regions with higher initial productivity grow more slowly. Institutional quality and high-technology specialisation (HTEC) positively impact productivity growth, while human and technological capital are not significant, likely due to correlations with other variables. Population density shows a negative effect in some models, indicating weak agglomeration effects.

Table 8 introduces interaction terms between intensity variables (Digital, Green, Twin) and the first quartile of GDP pe to explore their impact on less productive EU regions, primarily in Eastern Europe. Model 1 finds that Digital Intensity alone is not significant (-0.44), but its interaction term is positive and significant (1.343), indicating digital policies boosted growth in less productive regions. Model 2 shows that Green Intensity has a negative effect (-1.14), but its interaction term is positive and significant (1.767), suggesting green technologies fostered growth in these regions. Model 3, focusing on Twin Intensity, finds no significant effects. In Model 4, only Green Intensity remains significant, likely due to multicollinearity..

Pre-Pandemic Period (2016-2019). This period, identified as a time of recovery and "normal" functioning of the international economy following the sovereign debt crisis that heavily hit the European economies, contrasts with the results discussed before for the entire period. Table 9 highlights the impacts of digital, green, and twin intensities on GDP pe growth from 2016 to 2019. Digital Intensity consistently shows a positive and statistically significant effect (0.854 in Model 1 and 0.869 in Model 4), indicating substantial economic benefits from digital prioritisation under stable conditions. This underscores the effectiveness of digital investments in driving regional productivity and growth. In contrast, Green Intensity does not significantly impact GDP pe growth during this period (-0.168 in Model 2 and -0.247 in Model 4), suggesting that green priorities did not translate into immediate economic gains even in a stable economic cycle. Twin Intensity also shows a non-significant effect (0.381 in Model 3), implying that the combined focus on digital and green transitions did not yield strong short-term economic benefits.

Table 15 - Twin transition and regional labour productivity (pre-pandemic period, 2016-2019)

Dependent variable: GDP pe average growth rate	(1)	(2)	(3)	(4)
Digital Intensity	0.854 **			0.869 **
	(0.392)			(0.393)
Green Intensity		-0.168		-0.247
		(0.475)		(0.468)
Twin Intensity			0.381	
			(0.458)	
Adjusted R2	0.476	0.458	0.460	0.474

Significance levels: ***(1%), **(5%), *(10%).
Robust Standard Error in parentheses.
All models include a constant and the control variables as in Table 7
164 observations

Table 10 explores whether the effects of digital, green, and twin prioritisation differed for the least productive regions.

Table 16 - The differentiated effect by productivity levels (pre-pandemic subperiod, 2016-2019)

Dependent variable: GDP pe average growth rate	(1)	(2)	(3)	(4)
Digital Intensity	0.492			0.743 **
	(0.356)			(0.365)
Digital Intensity*GDP pe 1st quartile	1.319 *			0.798
	(0.748)			(0.785)
Green Intensity		-0.569		-0.575
		(0.403)		(0.395)
Green Intensity*GDP pe 1st quartile		1.333		1.277
		(0.860)		(0.845)
Twin Intensity			0.168	
			(0.387)	
Twin Intensity*GDP pe 1st quartile			1.220	
			(1.570)	
Adjusted R2	0.486	0.469	0.461	0.491

Significance levels: ***(1%), **(5%), *(10%).
Robust Standard Error in parentheses.
All models include a constant and the control variables as in Table 7
164 observations

The interaction terms between the intensity variables and the first quartile of GDP pe provide valuable insights. Digital Intensity alone is not significant (0.492 in Model 1), but its interaction with the first quartile of GDP pe is positive and significant (1.811 combined effect), highlighting the substantial benefits of digital prioritisation for the least productive regions. This indicates that digital investments were particularly effective in boosting growth where it was most needed. Green Intensity shows a negative and not significant impact (-0.8569 in Model 2), while the interaction term is positive but not significant (1.333). Twin Intensity is not significant (0.168 in Model 3), neither alone nor with the interaction term (1.220), indicating that the combined digital and green priorities were not particularly effective for the least productive regions in this period.

Post-Pandemic Period (2019-2022). As widely known, the COVID-19 pandemic generated an enormous shock worldwide, creating high fluctuations in economic trends. This global turmoil also influenced the twin transition's impact on regional productivity growth. The results for the post-pandemic period, reported in Table 11, indicate that digital intensity has a negative but not statistically significant impact on GDP growth over the years 2019-2022 (-0.268 in Model 1 and -0.208 in Model 4), suggesting that the pandemic's disruptions overshadowed the potential benefits of digital investments. Green Intensity has a negative and statistically significant impact (-0.987 in Model 2 and -0.969 in Model 4), indicating lower GDP growth in regions with higher green prioritisation. Twin Intensity also shows a negative and marginally significant effect (-0.862 in Model 3), implying that combined digital and green transitions did not yield short-term economic benefits during this volatile period.

Table 17 - Twin transition and regional labour productivity (post-pandemic period, 2019-2022)

Dependent variable: GDP pe average growth rate	(1)	(2)	(3)	(4)
Digital Intensity	-0.268			-0.208
	(0.352)			(0.348)
Green Intensity		-0.987 **		-0.969 **
		(0.465)		(0.465)
Twin Intensity			-0.862 *	
			(0.468)	
Adjusted R2	0.131	0.153	0.147	0.149

Significance levels: ***(1%), **(5%), *(10%).
Robust Standard Error in parentheses.
All models include a constant and the control variables as in Table 7
164 observations

Table 12 explores the impact of prioritisation strategies on the least productive regions during the post-pandemic period. Digital Intensity alone is negative and significant (-0.729 in Model 1), but its interaction with the first quartile of GDP pe is positive and significant (1.688), highlighting substantial benefits for the least productive regions. Similarly, Green Intensity shows a negative impact (-1.701 in Model 2), but the interaction term is positive and highly significant (2.356), indicating significant benefits for the least productive regions. Twin Intensity alone is negative and significant (-1.287 in Model 3), but the interaction term is positive and significant (2.434), underscoring the effectiveness of combined digital and green priorities for the least productive regions. This period underscores the challenges regions faced in balancing long-term sustainability goals with the urgent economic demands prompted by the pandemic. The simultaneous pursuit of green and digital transitions did not yield the anticipated economic benefits during this volatile time, highlighting the complexities of maintaining strategic priorities amid a global crisis. Consequently, this analysis reveals the strain on regions striving to pursue sustainability while managing immediate economic fallout, emphasising the need for adaptable strategies to withstand such disruptions.

Table 18 - The differentiated effect by productivity levels (post-pandemic subperiod, 2019-2022)

Dependent variable: GDP pe average growth rate	(1)	(2)	(3)	(4)
Digital Intensity	-0.729 *			-0.219
	(0.392)			(0.395)
Digital Intensity*GDP pe 1st quartile	1.688 **			0.716
	(0.729)			(0.685)
Green Intensity		-1.701 ***		-1.573 ***
		(0.528)		(0.525)
Green Intensity*GDP pe 1st quartile		2.356 ***		2.07 **
		(0.777)		(0.819)
Twin Intensity			-1.287 **	
			(0.497)	
Twin Intensity*GDP pe 1st quartile			2.434 *	
			(1.232)	
Adjusted R2	0.158	0.214	0.166	0.209

Significance levels: ***(1%), **(5%), *(10%).
Robust Standard Error in parentheses.
All models include a constant and the control variables as in Table 7
164 observations

The analysis reveals several key insights regarding the impact of prioritising digital and green intensities, along with their combined TT intensity, on regional economic performance. First, the significant economic benefits of digital technologies are evident, particularly during the pre-pandemic period and in less productive regions. Regions prioritising digital investments saw notable economic growth, emphasising the importance of digital advancements as a cornerstone of regional development strategies.

However, our findings also reveal varied effects when regions chose green investments in S3. Green intensity showed negative and statistically significant effects on productivity growth during the overall and post-pandemic periods, but these impacts varied notably across regions. Specifically, green and twin intensities had significantly positive effects in lower productivity regions, indicating that these areas can benefit from green priorities. This may be because green investments, while primarily targeting long-term environmental sustainability, also foster productivity gains in regions with lower economic baselines. Understanding these differential impacts is crucial for designing strategies that are both effective and equitable, ensuring that regions can pursue sustainability goals without sacrificing short-term economic growth. Striking a balance between long-term sustainability and immediate economic benefits is essential for fostering inclusive and resilient regional development.

The COVID-19 pandemic caused major disruptions to regional strategies, leading many regions to divert resources to immediate relief efforts, as noted by Aresu et al. (2024). EU regulations such as Regulation (EU) 2020/460 and Regulation (EU) 2020/558 allowed for greater flexibility in using European Structural and Investment Funds (ESIF), enabling regions to reallocate resources, simplify procedures, and extend eligibility for COVID-19-related expenditures. This shift allowed regions to address urgent needs without losing sight of long-term objectives. Consequently, the overall impact of digital and green strategies on regional productivity was diluted, as regions had to prioritise immediate economic challenges brought by the pandemic. These findings

underscore the need for adaptable and resilient economic strategies in the face of unprecedented disruptions.

5.6. Policy implications and recommendations

This study provided an in-depth analysis of integrating green and smart policies into regional S3 strategy across Europe during the 2014-2020 programming period. By examining the extent to which regions incorporated these twin transitions in their strategies, we aimed to assess the subsequent economic impacts across Europe.

Our descriptive analysis reveals that many regions proactively integrated green and digital initiatives into their S3 priorities, reflecting a commitment to aligning with the EU's broader sustainability and digital innovation goals. This integration varied significantly across regions, highlighting diverse approaches to the twin transitions. To evaluate the spatial effect of a greener and smarter policy mix, we estimated the impact of the twin transition intensity in the S3 priorities across European regions, accounting for the shock generated by the pandemic. We assessed how the labour productivity of areas focused on digital and green policies grew during the period considered. The main results indicate that while digital strategies did not grant a long-lasting effect on productivity growth over the entire period considered, its effectiveness was more pronounced in stable pre-pandemic conditions and particularly in less productive regions. This suggests that smart technologies can yield significant economic benefits under certain conditions, highlighting the importance of context in policy implementation. Regions that focused on smart technologies saw notable improvements in their economic outcomes in these specific scenarios, demonstrating the immediate benefits of digital investments. In contrast, regions with a stronger emphasis on green priorities faced challenges in achieving immediate economic productivity, suggesting that green investments are more aligned with long-term environmental sustainability goals rather than short-term productivity gains.

The impact of the COVID-19 pandemic introduced additional complexities, significantly disrupting regional economies and generating extreme fluctuations in economic trends. This disruption led to a redirection of resources towards immediate relief measures, diluting the potential positive impacts of both green and digital transitions. These findings underscore the need for adaptable and resilient economic strategies to balance long-term sustainability with immediate economic demands.

Overall, our findings underscore the necessity of a mixed approach to regional development policies. While digital advancements can yield immediate economic benefits, green investments are crucial for ensuring long-term environmental sustainability. Policymakers should not view these policies in isolation but rather as complementary components of a cohesive strategy. To maximize the effectiveness of S3 frameworks, regions must develop flexible policies capable of adapting to economic shocks, such as those caused by the pandemic, while maintaining a focus on long-term growth objectives.

A crucial insight from our analysis is the differential impact on lower productivity regions. The interaction terms in our models indicate that digital, green, and combined strategies significantly and positively affect Digital technologies markedly boost productivity growth for these regions, as

evidenced by the highly significant interaction terms. Similarly, despite their overall negative impact, green and combined priorities show substantial benefits for lower productivity regions. This underscores the critical role of tailored strategies that address regional disparities, particularly by leveraging digital and green investments to uplift the least productive areas.
In conclusion, while digital strategies prove beneficial across various contexts, green investments require careful integration to avoid short-term economic drawbacks. A balanced, region-specific approach that considers both immediate and long-term goals is essential for fostering sustainable and inclusive economic growth. The twin transition is critical for shifting to a more sustainable society, addressing both environmental and economic challenges. Regions can build resilient, competitive, and sustainable economies by fostering synergies between smart and green priorities. This requires continued investment in digital infrastructure and skills, alongside targeted support for green initiatives that may take longer to manifest economic returns. Furthermore, robust governance and stakeholder engagement are critical to successfully implementing these strategies, ensuring that regional policies are inclusive and responsive to emerging challenges.

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6. Opportunities and challenges for the green industry: specializations of the Italian provinces and implications for the industrial energy policies

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6.1. Introduction

The rapid evolution of the green industry represents both a significant opportunity and a formidable challenge for modern economies, particularly for countries like Italy that are deeply entrenched in traditional industrial practices. As the world increasingly acknowledges the urgent need for sustainable development, the concept of a "green industry" has gained prominence, driving both scientific research and policy discussions at national and international levels. However, despite the growing focus on this sector, there remains a lack of consensus on what exactly constitutes a green industry and how to measure its impact effectively.

This study aims to bridge this gap by offering a comprehensive analysis of Italy's provincial specializations in relation to the green industry. By focusing on Italy's provinces, this research seeks to identify which regions are best positioned to lead the green transition and which may be at risk due to their dependence on industries that could become obsolete in the shift toward sustainability. The goal is not only to map out the current landscape of green and vulnerable sectors across Italy but also to provide actionable insights that can inform energy and industrial policies aimed at facilitating the transition to a sustainable economy.

The objectives of this study are threefold. First, it seeks to define and measure green industries by utilizing a sector-based approach that incorporates recent academic and policy-driven research. Second, the study aims to develop and apply specialized indices of provincial export specialization that highlight regions with significant green exports or those vulnerable to the transition. Third, the study intends to create a taxonomy of Italian provinces based on their potential to either drive or be threatened by the green transition, offering a clear framework for policymakers.

In this study, we employ the Taxonomy Alignment Coefficient (TAC) and Taxonomy Exposure Coefficient (TEC) developed by Alessi and Battiston (2022) as foundational tools to assess the green and vulnerable industries across Italy's provinces. The decision to utilize this taxonomy is driven by its comprehensive and nuanced approach to categorizing industries based on their alignment with sustainability goals and their vulnerability to the green transition. The TAC measures the extent to which a sector's activities are aligned with the objectives of a low-carbon economy, such as through the adoption of renewable energy and energy-efficient technologies, while the TEC assesses the degree of a sector's dependence on fossil fuels and other high-emission activities, which render it vulnerable in the face of regulatory and market shifts towards sustainability. By applying this dual-coefficient framework, we are able to capture the complex and often overlapping nature of industrial specialization, providing a granular and accurate assessment of the economic landscape as it relates to the green transition. This methodology not

only allows us to identify regions that are well-positioned to thrive in a sustainable future but also highlights those that may face significant challenges, thereby offering valuable insights for targeted policy interventions.

To achieve these objectives, the research is guided by several key questions:

How can green industries be effectively defined and measured at the provincial level in Italy?

Which Italian provinces are most specialized in green exports, and what are the implications for their role in the green transition?

Which provinces are at risk of economic decline due to their specialization in industries that are vulnerable to the green transition?

How can industrial policies be tailored to support regions that are well-positioned to lead the green transition, as well as those that may struggle to adapt?

By addressing these questions, the study provides a detailed understanding of the provincial distribution of green and vulnerable industries in Italy. This understanding is crucial for developing targeted industrial policies that can support the green transition in a way that is both economically and socially sustainable. Ultimately, the research aims to contribute to the broader discourse on how regions can navigate the complex process of structural change required to achieve long-term sustainability.

6.2. Outline of literature background

The concept of the green industry has gained significant traction in recent years, driven by the pressing need to address environmental challenges while sustaining economic growth. As governments, businesses, and international organizations increasingly recognize the importance of transitioning to sustainable practices, the definition and scope of green industries have become central to discussions in both academic and policy circles. However, despite the growing consensus on the necessity of green industries, there remains considerable debate over how to define and measure them effectively.

Green industries are generally understood as sectors that contribute to environmental sustainability through the reduction of carbon emissions, the efficient use of resources, and the adoption of clean technologies. The International Labour Organization (ILO) has long emphasized the potential of green jobs in promoting decent work within a sustainable economy (ILO, 2008). Similarly, the United Nations Industrial Development Organization (UNIDO) frames green industry as a critical component of sustainable development, highlighting its role in fostering environmentally responsible investments (UNIDO, n.d.). However, as noted by Salvatelli (2014), the absence of a universally accepted definition complicates efforts to identify green sectors, leading to inconsistencies in both research and policy implementation.

Different approaches have been developed to classify and measure green industries. One widely referenced framework is the U.S. Bureau of Labor Statistics (BLS) classification of Green Jobs, which identifies sectors based on their contribution to environmental sustainability, either through the production of green goods and services or the adoption of green processes (U.S. Bureau of Labor Statistics, n.d.). This sectoral approach provides a foundational method for identifying and

categorizing green industries but does not fully capture the complexities of the global green economy.

The Environmental Goods and Services Sector (EGSS), as defined by Eurostat, offers a broader classification system that includes industries directly involved in environmental protection and resource management (Eurostat, n.d.). This framework is complemented by the System of Environmental-Economic Accounting (SEEA), which integrates environmental data with economic accounts to better identify and measure green sectors (SEEA, 2019). These methodologies represent significant strides in the effort to standardize the classification of green industries, though challenges remain, particularly in adapting these frameworks to different regional contexts.

Technological advancements have introduced innovative methods for identifying green industries. For example, text mining techniques are increasingly used to detect green companies based on corporate descriptions and patent classifications, providing a dynamic understanding of the green industry landscape (Shapira, Gök, Klochikhin, & Sensier, 2014). These methods enable real-time analysis and are particularly useful for identifying emerging sectors within the green economy.

The literature underscores the critical role of green industries in the global transition towards sustainability. According to the International Energy Agency (IEA), the clean energy sector alone employs over 50% of the global energy workforce, highlighting the economic importance of green industries (IEA, 2022). Allan, Lewis, and Oatley (2021) argue that green industrial policy is central to the global transformation of climate politics, emphasizing that green industries can drive both environmental and economic progress.

The European Union's Green Deal and its accompanying Green Deal Industrial Plan further illustrate the strategic importance of green industries in shaping Europe's economic future (Leonard, Pisani-Ferry, Shapiro, Tagliapietra, & Wolff, 2021). These initiatives aim to integrate green industries into the broader economic framework to ensure that the transition to a low-carbon economy is both equitable and effective. The European Commission has also highlighted the importance of maintaining open trade and resource accessibility to support green industries, as articulated in its recent Green Deal Industrial Plan for the Net-Zero Age (Commissione Europea, 2023).

Despite the growing emphasis on green industries, measuring their impact and effectiveness remains a significant challenge. The lack of standardized metrics and the inherent complexity of categorizing industries across different sectors and regions contribute to these difficulties. Bowen, Park, and Elvery (2013) highlight the diversity within green industries, ranging from renewable energy and clean transportation to waste management and sustainable agriculture, which necessitates tailored approaches to both measurement and policy design.

Recent contributions to the literature, such as those by Barbieri, Marzucchi, and Rizzo (2023), emphasize the interdependencies between green technologies and traditional sectors, suggesting that a comprehensive industrial policy must account for these relationships. Furthermore, Barbieri et al. (2022) explore regional technological capabilities and green opportunities in Europe, providing insights into how different regions can capitalize on their existing strengths to advance the green transition.

In the Italian context, the discourse on green industries is shaped by the country's unique industrial landscape and its role within the broader European framework. Studies by Di Tommaso et al. (2020, 2022, 2023) highlight the importance of a systemic approach to green transition, which integrates economic, social, and environmental dimensions. Italy's regional disparities, particularly between the industrial North and the less developed South, present both challenges and opportunities for the development of green industries.

The Italian experience underscores the need for tailored industrial policies that reflect regional specializations and varying capacities to adapt to the green transition. Ferrannini et al. (2021) emphasize the role of industrial policy in achieving sustainable human development in the post-Covid-19 era, arguing that targeted interventions are necessary to support regions in transitioning to green industries.

In conclusion, the literature on green industries presents a complex and evolving field that blends various definitions, methodologies, and case studies to illustrate the multifaceted nature of this sector. While significant progress has been made in understanding and promoting green industries, challenges remain in standardizing definitions, measuring impact, and ensuring that the benefits of the green transition are widely shared. This study builds on these foundations, applying a sector-based approach to analyze green and vulnerable industries across Italy's provinces, aiming to provide actionable insights for policymakers and contribute to the broader discourse on sustainable development.

6.3. Data and descriptive statistics

To understand the current landscape of green and vulnerable industries across Italy's provinces, it is essential to begin with a thorough examination of the data, including territorial references, time coverage, and sources. Additionally, descriptive statistics such as maps, figures, and tables provide a clear and comprehensive view of the spatial distribution and characteristics of these industries.

The analysis in this study is conducted at the provincial level, which allows for a detailed exploration of regional disparities and industrial specializations within Italy. Italy's 107 provinces represent distinct administrative divisions within the country's regions, each varying significantly in terms of economic structure, industrial capacity, and development levels. By focusing on these provinces, the study captures the heterogeneity across different areas, offering a nuanced understanding of how green industries are distributed and which regions are most vulnerable to economic shifts driven by the green transition. This provincial-level analysis is particularly important in Italy due to the well-documented economic differences between the industrial North and the less developed South, a dichotomy that has long been a focus of both economic and policy research.

The time coverage for the data used in this study centers on the year 2019, a critical period for analyzing trends and shifts in green and vulnerable industries within Italy. The year 2019 is selected because it represents a relatively stable economic environment before the global disruptions caused by the COVID-19 pandemic. This allows the study to provide a clear snapshot of the state of Italian industries without the distortions introduced by the pandemic. While the primary focus

is on data from 2019, the study also considers historical data where relevant to track the development of green industries over time and to place the findings within a broader temporal context. However, the emphasis remains on the most recent and comprehensive data available for the pre-pandemic period, ensuring that the analysis accurately reflects the state of the Italian economy at that time.

The data utilized in this study is drawn from multiple authoritative sources, ensuring its reliability and robustness. The primary dataset is the TEC-FRAMESBS, which provides detailed information on firms operating in Italy, including their export activities, industrial classifications, and geographic locations. This dataset is invaluable for identifying the export patterns of Italian provinces, a crucial aspect of understanding their specialization in green or vulnerable industries. Alternatives to TEC-FRAMESBS would be data from Eurostat, particularly the Environmental Goods and Services Sector (EGSS), which offers insights into industries directly involved in environmental protection and resource management. The EGSS data is instrumental in identifying sectors that can be classified as green based on their contributions to sustainability goals. Other significant sources include the International Energy Agency (IEA) for employment data related to the energy sector, which is critical for understanding the workforce implications of the green transition, and the U.S. Bureau of Labor Statistics (BLS) for methodological references on classifying green jobs. Nevertheless, as anticipated, our choice is to exploit the classification developed in Alessi & Battiston (2022) which allows for a fine-grained understanding of the "green" and "brown" content of the industries under analysis.

Indeed, among the various frameworks available for identifying and categorizing green industries, the taxonomy developed by Alessi and Battiston (2022) stands out for its methodological rigor and its ability to address the complexities of the green transition. Unlike other approaches, such as the U.S. Bureau of Labor Statistics' Green Jobs classification or Eurostat's Environmental Goods and Services Sector (EGSS), which primarily focus on either the products or the industries themselves, the Alessi & Battiston taxonomy provides a dual-coefficient system that evaluates both the alignment of industries with sustainability goals and their vulnerability to structural changes. The Taxonomy Alignment Coefficient (TAC) and Taxonomy Exposure Coefficient (TEC) offer a more dynamic and context-sensitive analysis, capturing the multifaceted nature of industries that may simultaneously contribute to and be threatened by the transition to a low-carbon economy. This level of granularity makes the Alessi & Battiston framework particularly suited to our study, as it allows for a more precise identification of green industries and a deeper understanding of the regional disparities in Italy's economic landscape. By choosing this taxonomy, we are able to move beyond simpler categorizations and gain insights that are critical for developing effective and region-specific policy responses.

Descriptive statistics play a crucial role in providing a detailed overview of the spatial distribution of green and vulnerable industries across Italy's provinces. The use of maps, figures, and tables enhances the understanding of the data, offering an intuitive grasp of the key findings. Maps, for example, are employed to visualize the geographic distribution of green and vulnerable industries. A color gradient is used to indicate the level of specialization in green sectors across different provinces. Provinces with a high concentration of green industries are marked in darker shades, while those with lower concentrations are in lighter shades. This visual representation reveals clusters of green industry specialization, particularly in regions like Lombardy, Emilia-

Romagna, and parts of Central and Southern Italy, where industrial activities align closely with environmental sustainability goals.

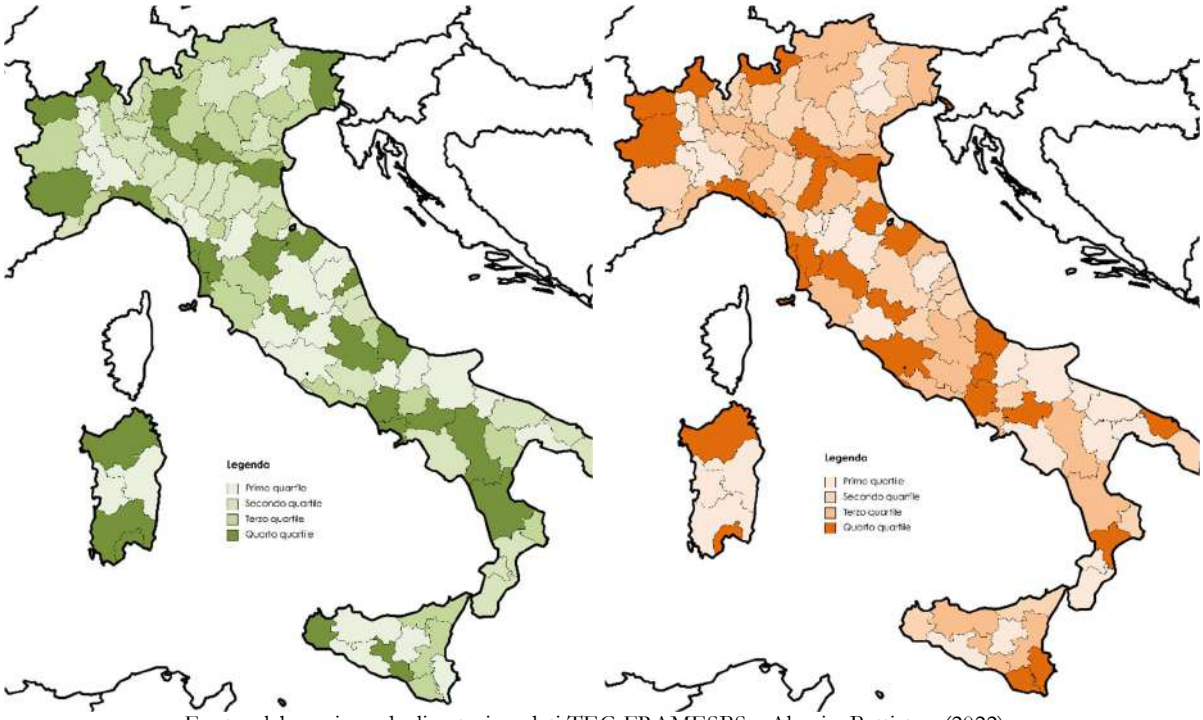
Similarly, another map highlights the distribution of vulnerable industries—those sectors at risk of decline due to the green transition. Again, a color gradient is used, with darker shades representing higher levels of specialization in vulnerable sectors. This map illustrates how certain provinces, such as Turin, Rome, and some coastal areas, are heavily dependent on industries like fossil fuels or other high-emission activities, which may face significant challenges in adapting to the green transition.

The two maps provided offer a visual representation of the distribution of green and vulnerable specializations across Italy's provinces, illustrating the varying degrees to which different regions are prepared for or at risk from the ongoing green transition. These maps are essential for understanding the regional disparities in how well different areas are aligned with the emerging green economy and how exposed they are to the challenges posed by reliance on industries that may not align with future sustainability goals.

The first map, shaded in different tones of green, appears to represent the level of specialization in green industries (SPECG) across Italy's provinces. The map is divided into quartiles, with darker shades of green indicating provinces that rank higher in terms of their green specialization. This suggests that these areas have a stronger concentration of industries aligned with environmental sustainability and the green economy. Notably, Northern Italy shows a significant concentration of darker green areas, particularly in regions such as Lombardy, Veneto, and Emilia-Romagna. These regions, with their advanced industrial bases and investments in green technologies, renewable energy, and sustainable practices, are better positioned to thrive in a low-carbon future. Additionally, some central provinces, particularly in Tuscany and parts of Umbria, also show strong green specialization, likely due to their involvement in advanced manufacturing and renewable energy sectors. In contrast, many southern provinces are shaded in lighter green, indicating lower levels of green specialization. This highlights a lag in the transition to sustainable practices in these regions, which could present economic challenges as the global shift towards sustainability accelerates.

Figure N – Green specialization

Figure N – Vulnerable specialization



Fonte: elaborazione degli autori su dati TEC-FRAMESBS e Alessi e Battiston (2022)

The second map, shaded in varying tones of orange, represents the level of specialization in vulnerable industries (SPECV). Darker shades indicate provinces with a higher concentration of industries that are at greater risk due to their reliance on fossil fuels, energy-intensive processes, or high emissions. The widespread distribution of darker orange areas across both Northern and Southern Italy indicates that vulnerability is not confined to any one part of the country. Even in regions with strong green specialization, such as parts of Lombardy and Piedmont, there are significant areas of vulnerability. This suggests that despite their progress in green industries, these regions still have substantial economic activities tied to traditional manufacturing sectors that have yet to fully transition to sustainable practices. In Southern Italy, the darker orange shading in many provinces indicates a higher degree of vulnerability, consistent with the observation that these regions have less diversified economies and are more dependent on industries that could face significant challenges in the transition to a green economy.

The juxtaposition of these two maps reveals the dual challenges that Italy faces in navigating the green transition. Northern regions, while leading in green specialization, also show significant pockets of vulnerability, indicating that even the most advanced areas must carefully balance the growth of green industries with the management of risks associated with their traditional economic activities. Southern Italy, on the other hand, faces a more complex and daunting challenge, with lower levels of green specialization and higher vulnerability, putting these regions at greater risk of economic decline if they do not accelerate their transition towards more sustainable practices. These maps underscore the urgent need for targeted interventions that support regions in their green transition, ensuring that no area is left behind. The clear visual disparity between green specialization and vulnerability highlights the importance of tailored regional policies that consider the unique industrial compositions of each province. Successfully

managing this dual challenge of fostering green growth while mitigating economic vulnerability will be crucial for Italy's overall success in adapting to the green economy.

Figures are used to depict trends and correlations within the data, providing a graphical representation of critical insights. For instance, a scatter plot correlates the specialization in green industries with the level of vulnerability in each province. This figure is particularly useful for identifying provinces that occupy precarious positions—those that are leaders in green industries but also heavily reliant on vulnerable sectors. Conversely, it also helps to highlight provinces that are well-positioned for the green transition, with high levels of green specialization and low vulnerability, as well as those at risk of economic decline due to low green specialization and high vulnerability. Another significant figure presents time series data, showing the growth of green industries over the past decade. This figure highlights how some provinces have successfully transitioned towards more sustainable industries, while others have lagged behind, offering a temporal context for understanding the evolution of different regions' industrial compositions leading up to 2019.

Tables complement these visual aids by providing a more detailed breakdown of the data, offering specific figures for each province. For example, one table lists the top 10 provinces in terms of green industry specialization, along with their corresponding levels of vulnerability. This allows for easy comparison between provinces and provides a clear ranking that can guide policy interventions. Another table presents the export values for green and vulnerable industries by province, detailing how much each province contributes to Italy's overall green exports and how much of its economy is at risk due to vulnerable sectors. These tables are crucial for understanding the economic impact of the green transition on different regions and for identifying which areas might require targeted support to mitigate potential disruptions.

Overall, the data and descriptive statistics presented in this study provide a comprehensive overview of the current state of green and vulnerable industries across Italy's provinces. By combining detailed territorial references, time coverage, and authoritative data sources with clear visual and statistical representations, this section offers a thorough understanding of the spatial distribution and economic significance of these industries. This robust foundation is essential for informing the development of targeted industrial policies that support the green transition while addressing the specific needs of Italy's diverse regions.

6.4. Methodology

The methodology employed in this study is designed to provide a rigorous and comprehensive analysis of the green and vulnerable industries across Italy's provinces. The approach integrates both quantitative and qualitative methods to ensure that the findings are robust, reliable, and relevant for informing policy decisions. This section explains the specific methods used and provides a justification for their selection, ensuring that the research objectives are met effectively.

The primary methodological approach in this study is quantitative, leveraging advanced statistical techniques to analyze large datasets and derive meaningful insights. The choice of a quantitative approach is driven by the need to objectively measure the extent of green and

vulnerable industry specialization across different provinces. By using quantitative methods, the study can systematically compare provinces, identify patterns, and establish correlations between different variables, such as the degree of green industry specialization and the level of economic vulnerability to the green transition.

Central to the methodology is the use of the TEC-FRAMESBS dataset, which provides detailed information on firms' export activities, industrial classifications, and geographic locations. This dataset is instrumental in calculating the indices of green and vulnerable industry specialization at the provincial level. The use of export data is particularly justified because exports are a strong indicator of a region's industrial strengths and its integration into global markets. Firms that are competitive enough to export typically reflect the broader industrial capabilities of their region, making export data a valuable proxy for understanding regional industrial specializations.

To quantify the degree of specialization in green and vulnerable industries, the study employs two key indices: the Taxonomy Alignment Coefficient (TAC) and the Taxonomy Exposure Coefficient (TEC). These indices, developed by Alessi and Battiston (2022), are used to assess the alignment of industries with sustainability goals (TAC) and their vulnerability to the green transition (TEC). The TAC measures the extent to which a sector's activities are aligned with the objectives of a low-carbon economy, such as through the production of renewable energy or the adoption of energy-efficient technologies. Conversely, the TEC measures the degree to which a sector is dependent on fossil fuels or other high-emission activities, making it vulnerable to future regulatory changes and market shifts aimed at reducing carbon emissions. These indices are calculated at the four-digit NACE classification level, which provides a high degree of granularity and allows for a detailed assessment of industry specializations. The four-digit NACE classification is chosen because it offers a precise categorization of economic activities, enabling the study to capture nuanced differences between sectors. This level of detail is crucial for accurately identifying which industries are green, which are vulnerable, and how these industries are distributed across Italy's provinces.

The calculation of the TAC and TEC indices involves several steps. First, the proportion of each industry's activities that can be classified as green or vulnerable is determined using sector-specific data on emissions, energy consumption, and other relevant environmental indicators. These proportions are then used to assign TAC and TEC scores to each industry within a province. The scores are weighted by the economic significance of each industry within the province, as measured by its contribution to provincial exports. This weighted approach ensures that the indices reflect not just the presence of green or vulnerable industries, but also their relative importance to the provincial economy. Below, we report an example for the Province of Roma that illustrates this step of the methodology.

Table 2 – Green/Vulnerable Export Basket – Province of Rome

ATECO	Sector Name	TAC	TEC	Export Percentage
0610	Crude Petroleum Extraction	0	1	0.10%
7711	Renting of Cars and Light Motor Vehicles	0.003	0.997	0.32%

Table 2 – Green/Vulnerable Export Basket – Province of Rome

ATECO	Sector Name	TAC	TEC	Export Percentage
6820	Renting and Operating of Own or Leased Real Estate	0.15	0.7	0.11%
5110	Passenger Air Transport	0	1	0.17%
5020	Sea and Coastal Freight Water Transport	0	1	0.15%
4671	Wholesale of Solid, Liquid, Gaseous Fuels and Related Products	0	1	9.51%
4511	Sale of Cars and Light Motor Vehicles	0	0.98	1.80%
4120	Construction of Residential and Non-residential Buildings	0.4	0	0.10%
3030	Manufacture of Aircraft, Spacecraft, and Related Devices	0	1	22.90%
1920	Manufacture of Refined Petroleum Products	0	1	3.63%
	Green specialization	0.00000459	Vulnerable specialization	0.00101

Source: Authors' calculations based on TEC-FRAMESBS data and Alessi & Battiston (2022). Note: The table includes only the top 10 sectors where TEC or TAC are non-zero.

This table provides a detailed snapshot of the export composition for the Province of Rome, focusing on sectors classified by their green (SPECG) and vulnerable (SPECV) specializations. The analysis employs the Taxonomy Alignment Coefficient (TAC) and Taxonomy Exposure Coefficient (TEC) to quantify the extent to which these sectors align with or are vulnerable to the green transition.

From the table, we observe that the manufacturing of aircraft, spacecraft, and related devices (ATECO 3030) dominates Rome's export profile, constituting 22.9% of total exports. This sector is entirely classified as vulnerable (TEC = 1) with no alignment to green objectives (TAC = 0), highlighting its significant exposure to the risks posed by the transition to a low-carbon economy. Similarly, the wholesale of fuels (ATECO 4671) and the manufacture of refined petroleum products (ATECO 1920) contribute 9.51% and 3.63% to exports, respectively, and are also fully vulnerable (TEC = 1) without any green specialization (TAC = 0). These industries are heavily reliant on fossil fuels, making them susceptible to declines as sustainability becomes increasingly prioritized.

Other notable sectors include the crude petroleum extraction (ATECO 0610) and the passenger air transport (ATECO 5110), both of which also show complete vulnerability with no green alignment. Even though these sectors represent smaller percentages of the total exports, their total TEC scores reinforce the idea that Rome's economy has substantial exposure to vulnerable sectors.

On the other hand, sectors with some degree of green specialization, such as the construction of residential and non-residential buildings (ATECO 4120) and renting and operating of real estate

(ATECO 6820), show relatively low TAC scores (0.4 and 0.15 respectively) and contribute minimally to the overall exports. These green-aligned sectors do not compensate for the high level of vulnerability found in the province's major export activities.

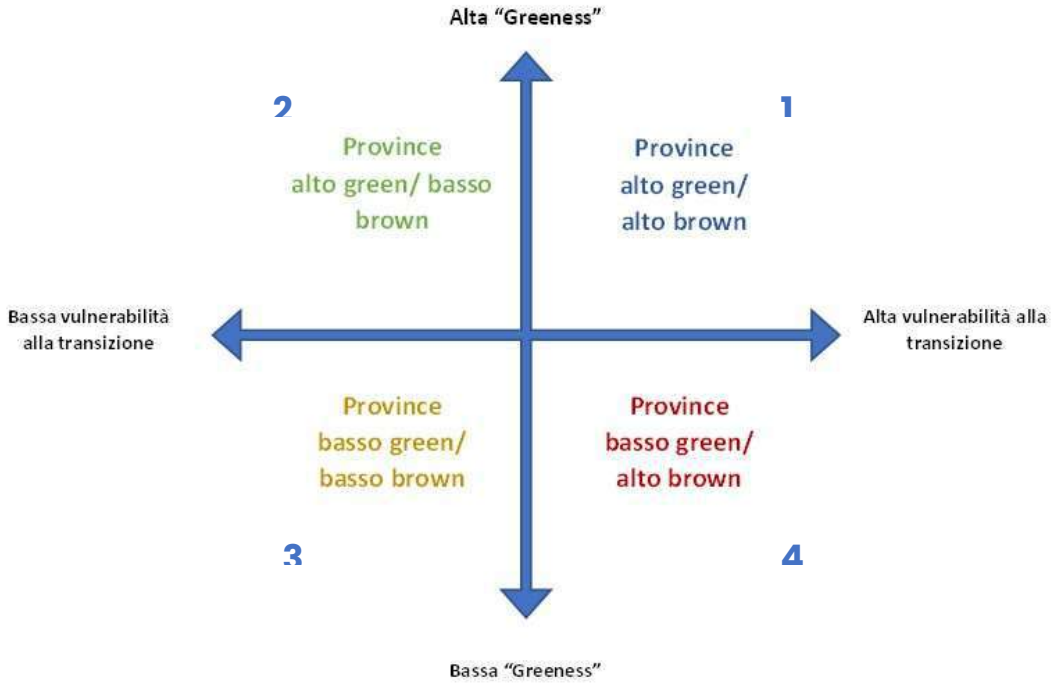
The overall SPECG score for Rome is extremely low (0.00000459), indicating that green industries constitute a negligible portion of the province's economic output. Conversely, the SPECV score is higher (0.00101), reflecting the significant presence of vulnerable sectors. This imbalance suggests that Rome's industrial structure is currently ill-prepared for the demands of the green transition, with a heavy reliance on sectors that may face economic decline as global policies and markets shift towards sustainability.

The results for Rome highlight the critical need for strategic economic diversification and the enhancement of green industries to mitigate potential risks associated with the province's current economic reliance on vulnerable sectors. This example illustrates how the methodology can be applied to provide a detailed provincial outlook, offering insights into both the strengths and vulnerabilities of different regions in the context of the green transition.

In addition to the quantitative analysis, the study also incorporates qualitative methods to contextualize the findings and provide deeper insights into the implications of the green transition for different regions. This qualitative component includes a review of policy documents, expert interviews, and case studies of specific provinces that exemplify the broader trends identified in the quantitative analysis. The qualitative analysis is justified because it allows the study to explore the underlying factors driving regional differences in green industry specialization and vulnerability. It also provides a more nuanced understanding of the challenges and opportunities that different provinces face in the green transition, which cannot be fully captured by quantitative data alone.

The selection of provinces for case studies is based on their positioning in the TAC-TEC matrix (see Figure below). Provinces that exhibit high levels of both green specialization and vulnerability, as well as those that are strong in green industries but low in vulnerability, are chosen for in-depth analysis. This ensures that the case studies reflect a range of experiences and provide insights into both the challenges and best practices associated with the green transition.

Figure N - TAC-TEC matrix



Source: own authors' elaboration

The methodology is also informed by the need to ensure the relevance and applicability of the findings to policy-making. By combining quantitative measures with qualitative insights, the study aims to provide a comprehensive understanding of the green transition that is grounded in empirical data but also sensitive to the specific contexts and needs of different regions. This approach is particularly important for informing industrial policy, as it allows for the identification of targeted interventions that can support regions in transitioning to a green economy while mitigating the risks associated with economic vulnerability.

In summary, the methodology used in this study is designed to provide a robust and comprehensive analysis of green and vulnerable industries across Italy's provinces. The use of advanced quantitative techniques, combined with qualitative contextual analysis, ensures that the findings are both empirically rigorous and relevant for policy-making. The selection of TAC and TEC indices, the focus on provincial-level data, and the integration of qualitative insights are all justified by the study's objectives of identifying regional strengths and vulnerabilities in the green transition and providing actionable recommendations for industrial policy.

6.5. Findings – Discussion

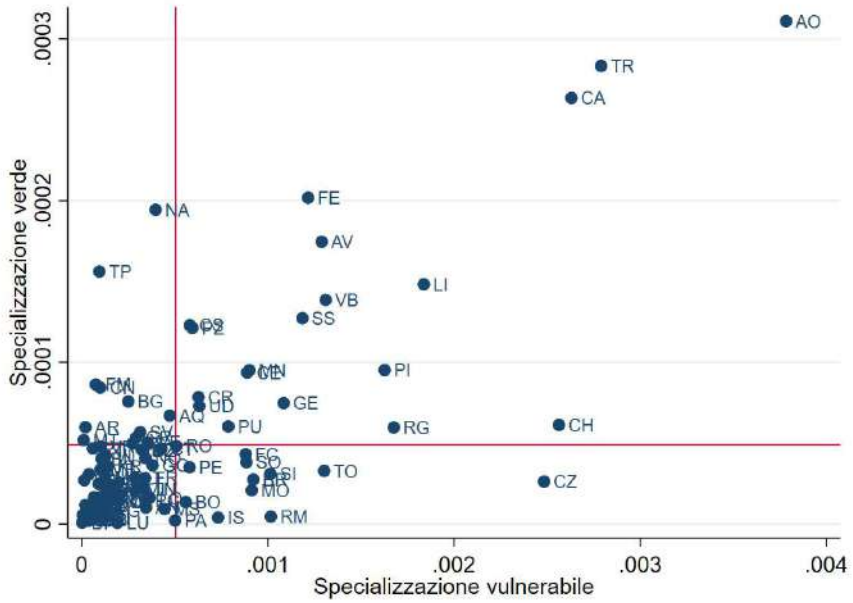
The analysis of green and vulnerable industries across Italy's provinces reveals a complex and uneven landscape that reflects the diverse economic structures and industrial capabilities of the country. By applying the Taxonomy Alignment Coefficient (TAC) and Taxonomy Exposure Coefficient (TEC), this study uncovers significant variations in how different regions are positioned

within the green transition, with some provinces showing strong potential for growth in sustainable industries while others are more heavily dependent on sectors that may face decline. A prominent finding is the marked geographic concentration of green industries in Northern Italy, particularly in provinces such as Lombardy, Emilia-Romagna, and Veneto. These regions exhibit high TAC scores, indicating a strong alignment with green economy objectives. The economic structure of these provinces is characterized by a significant presence of industries involved in renewable energy production, energy-efficient manufacturing, and other sectors that are pivotal to achieving a low-carbon economy. The high levels of specialization in green industries suggest that these provinces are not only prepared to adapt to the ongoing green transition but are also likely to be key drivers of economic growth in this emerging sector.

In contrast, several provinces, especially in Southern Italy and certain coastal areas, display high levels of vulnerability as indicated by their TEC scores. Provinces such as Rome, Naples, and others in the South are characterized by economies that rely heavily on traditional industries with significant carbon footprints, such as fossil fuel extraction, conventional manufacturing, and energy-intensive sectors. These provinces face a challenging economic landscape as the global shift towards sustainability may result in decreased demand for their primary industrial outputs. The high TEC scores in these regions reflect the potential economic risks associated with a delayed or unmanaged transition to greener industries, as these areas could experience declines in industrial output and employment if current trends continue.

The scatter plot provides a detailed visual representation of the relationship between green specialization (SPECG) and vulnerable specialization (SPECV) across various Italian provinces, each represented by a two-letter code. The x-axis measures vulnerable specialization, with higher values indicating a greater reliance on industries that may be at risk due to the green transition. The y-axis, on the other hand, measures green specialization, with higher values reflecting a stronger alignment with sustainable, low-carbon economy industries.

Figure N – Italian provinces scattered over the TEC-TAC matrix



What immediately stands out is the general clustering of provinces near the origin, indicating that many regions have low levels of both green and vulnerable specialization. This suggests that these provinces have a limited involvement in either green or high-risk industries, potentially reflecting a diversified economy or one with less defined industrial specializations. For instance, economically significant provinces such as Milan (MI), Bologna (BO), and Turin (TO) are located in this cluster. Despite their economic weight, these regions show relatively low specialization in both categories, which might indicate a balance in their industrial activities, avoiding heavy dependence on sectors that are either strongly green or particularly vulnerable.

One of the most striking observations is the outlier position of Aosta (AO), which exhibits the highest level of green specialization while maintaining very low vulnerable specialization. This unique positioning suggests that Aosta has a strong focus on sustainable industries with minimal reliance on sectors that are at risk in the green transition. Such a profile positions Aosta as a potential leader in Italy's move towards a green economy. Similarly, provinces like Terni (TR) and Cagliari (CA) also demonstrate relatively higher levels of green specialization, though they still maintain moderate levels of vulnerable specialization. This indicates that while these provinces are engaged in green industries, they have not completely mitigated their reliance on more vulnerable sectors.

On the other end of the spectrum, Catanzaro (CZ) emerges as a notable outlier with high vulnerable specialization and almost no green specialization. This positioning suggests that Catanzaro's economy is heavily dependent on industries that are likely to face significant challenges in the green transition, without the mitigating influence of green industries. Such a profile could make the province particularly susceptible to economic disruption as sustainability becomes an increasingly dominant factor in global markets.

The distribution along the x-axis indicates that most provinces have low to moderate levels of vulnerable specialization, with only a few exhibiting high levels. This suggests that while many

regions in Italy do not rely heavily on industries at risk, those that do are concentrated in specific areas, which could lead to regional economic challenges if these vulnerabilities are not addressed. Conversely, the y-axis distribution reveals that green specialization is generally low across most provinces, with only a few exceptions, like Aosta, showing significant engagement in green sectors (nevertheless, its low dimension, makes the emergence of the phenomenon much easier than larger regional economies). This underlines the need for a broader adoption of green industries across more regions to ensure economic resilience in the face of the green transition.

In summary, the scatter plot highlights the diverse economic landscapes across Italy's provinces, with some regions like Aosta being well-positioned for the green transition, while others like Catanzaro face significant challenges due to their reliance on vulnerable industries. The visualization underscores the importance of targeted strategies that take into account the specific industrial compositions of each province, whether that involves bolstering green industries or mitigating the risks associated with vulnerable sectors.

The study also identifies provinces that exhibit a dual specialization, meaning they have significant activity in both green and vulnerable industries. Turin is a prime example of this duality. On one hand, Turin is a major hub for automotive manufacturing, including the production of electric vehicles and green automotive technologies, which is reflected in its high TAC scores. On the other hand, the city still has a substantial reliance on traditional automotive manufacturing and related industries that are less aligned with green economy goals, leading to elevated TEC scores as well. This dual specialization creates a unique economic scenario where the region is simultaneously positioned to benefit from the green transition and at risk of economic challenges if traditional sectors fail to adapt.

The findings also highlight the persistent economic disparities between Northern and Southern Italy, which are exacerbated by the green transition. The Northern regions, with their well-established industrial bases, advanced infrastructure, and higher levels of innovation, are better equipped to integrate green technologies and capitalize on new economic opportunities. In contrast, Southern regions, with less developed industrial bases and infrastructure, are more susceptible to the risks posed by the transition away from carbon-intensive industries. This North-South divide in Italy's economic landscape is a critical factor in understanding the uneven distribution of green and vulnerable industries across the country.

Another important insight from the study is the relationship between export orientation and industrial specialization in green and vulnerable sectors. Provinces with a strong export orientation, particularly those in the North, tend to have higher TAC scores, reflecting their competitive advantage in green industries on a global scale. This export-driven green specialization suggests that these provinces are not only important players in the domestic economy but also crucial contributors to Italy's position in the global green economy. Conversely, provinces with lower export orientation and higher TEC scores are more likely to be inward-looking economies that may struggle to maintain competitiveness as international markets increasingly favor sustainable products and practices.

Table N - Specialization of the Top 10 and Bottom 10 Provinces by Export Value

Province	Export Value (in millions)	Green Specialization	Vulnerable Specialization
Top 10			
Milan	€71,720	Low	Low

Turin	€30,248		Low	High
Rome	€20,400		Low	High
Vicenza	€18,183		Low	Low
Bergamo	€15,443		High	Low
Florence	€15,199		Low	Low
Brescia	€15,122		High	Low
Bologna	€13,841		Low	High
Modena	€13,632		Low	High
Treviso	€12,756		Low	Low
Bottom 10				
Potenza		€ 74.23	High	High
Catanzaro		€ 60.96	Low	High
Cosenza		€ 54.18	High	High
Caltanissetta		€ 52.84	High	Low
Isernia		€ 33.07	Low	High
Oristano		€ 32.12	Low	Low
Nuoro		€ 21.52	Low	Low
Vibo Valentia		€ 20.16	Low	Low
Crotone		€ 14.78	Low	Low
Enna		€ 10.97	Low	Low

The table presents a clear comparison between the top 10 and bottom 10 Italian provinces based on their export values, alongside their respective levels of green specialization and vulnerable specialization. This offers insight into how different regions are positioned in relation to the green transition, particularly concerning their industrial focus and export activities.

Among the top 10 exporting provinces, Milan leads significantly with €71.7 billion in exports, yet it is characterized by both low green and vulnerable specialization. This suggests a balanced, diversified industrial base with neither a strong focus on green industries nor significant exposure to industries that may face challenges in the green transition. Milan's economic stability and diversification may provide it with resilience in adapting to future industrial shifts.

Turin and Rome are notable for their combination of high export values with low green specialization and high vulnerable specialization. This indicates a heavy reliance on industries that are at risk in the context of the green transition, such as traditional automotive and fossil fuel-related industries. These provinces may face economic challenges if they do not diversify and invest more in green sectors.

In contrast, Bergamo and Brescia stand out for their high green specialization and low vulnerable specialization, coupled with substantial export values. These provinces are well-positioned to benefit from the green transition, with a strong presence in industries that align with sustainability goals. Their ability to maintain low exposure to vulnerable industries while also achieving high export levels suggests a forward-looking industrial strategy that could serve as a model for other regions.

Vicenza, Florence, and Treviso also show low levels of both green and vulnerable specialization, similar to Milan. These provinces may have diversified industrial bases that are not heavily dependent on either green or at-risk industries, which could make their economies more adaptable to changes brought about by the green transition.

Among the bottom 10 exporting provinces, Potenza, Cosenza, and Caltanissetta are particularly interesting. Despite their relatively low export values, these provinces show high green specialization, indicating a potential focus on sustainable industries. However, both Potenza and

Cosenza also have high vulnerable specialization, suggesting that their economies are still partly reliant on at-risk industries. This duality could make their green transition more complex, as they balance the growth of green sectors with the decline of vulnerable ones.

In contrast, provinces like Catanzaro, Isernia, and Oristano are characterized by low green specialization and high vulnerable specialization, coupled with very low export values. These provinces may be at significant risk in the green transition, with economies that are both small and heavily dependent on industries that could decline. Without strategic interventions to diversify their industrial bases and invest in green sectors, these regions could face economic hardship.

Finally, Nuoro, Vibo Valentia, Crotone, and Enna show both low green and low vulnerable specialization, indicating minimal engagement in either category. With their low export values, these provinces may have limited industrial activity overall, making it crucial to consider how they can be integrated into broader economic strategies that promote sustainable development.

Overall, the table highlights the diverse economic landscapes across Italy's provinces, emphasizing the varying degrees of readiness for the green transition. While some provinces are clearly positioned to lead in the green economy, others face significant challenges due to their reliance on vulnerable industries. This comparison underscores the importance of tailored strategies that address the specific needs and opportunities of each region, ensuring that all provinces can navigate the green transition successfully.

Merging the findings of the study with historical considerations of Italian economic development brings to compelling territorial considerations. Northern provinces, which already had a solid industrial foundation, have more possibilities to accelerate growth in green industries, driven by investments in technology and infrastructure that support sustainability. This trend suggests a positive trajectory towards further economic resilience and growth in these regions. Meanwhile, the allocation of vulnerable industries is likely to be more static in their evolution, particularly in the South, where there has been less movement towards adopting green technologies and practices. This stagnation suggests that without significant shifts in industrial focus, these regions may face increasing economic difficulties as the green transition progresses.

Economically, the findings suggest that Italy's green transition is likely to be characterized by a divergence in regional economic outcomes. The provinces that are already aligned with green economic activities are expected to see continued economic growth and diversification, leveraging their existing industrial strengths to adapt to and lead in the green economy. In contrast, regions that are heavily invested in traditional, vulnerable industries may experience economic contraction or stagnation unless they can transition towards more sustainable industries. The concentration of green industries in the North and the vulnerability of the South highlights the need for a nuanced understanding of regional economic dynamics in the context of the green transition.

In summary, the findings of this study illustrate the uneven distribution of green and vulnerable industries across Italy's provinces, with significant implications for regional economic trajectories. The green transition is likely to reinforce existing economic strengths in some regions while posing serious challenges to others, particularly those reliant on industries that are less adaptable to the demands of a low-carbon economy. These insights provide a crucial foundation for

understanding the economic implications of the green transition across Italy and underscore the importance of ongoing analysis as the transition continues to unfold.

1.6. Policy implications and recommendations

he findings of this study underscore the critical importance of targeted and region-specific policy interventions to manage the green transition effectively across Italy's diverse economic landscape. As the green transition accelerates, it presents both opportunities and challenges that are unevenly distributed across the country. The policy implications drawn from this study highlight the need for differentiated strategies that address the unique circumstances of each region while fostering overall national economic resilience and sustainability.

One of the most significant policy implications is the necessity for a dual approach that both supports the expansion of green industries in already strong regions and mitigates the risks faced by provinces heavily reliant on vulnerable sectors. In Northern Italy, where provinces like Lombardy, Emilia-Romagna, and Veneto show high specialization in green industries, policies should focus on further enhancing these regions' competitive advantages. This could include increased investment in research and development (R&D) for green technologies, subsidies for green innovation, and incentives for businesses to expand their sustainable operations. Additionally, facilitating access to international markets for green products through trade agreements and export support would strengthen these regions' positions in the global green economy.

Conversely, in Southern Italy and other regions with high levels of vulnerability, policies must prioritize economic diversification and the transition away from industries that are likely to decline due to the global shift towards sustainability. This could involve the gradual phasing out of subsidies and support for high-emission industries, coupled with targeted investments in new, sustainable industries that can replace the economic activity currently dominated by vulnerable sectors. For example, developing renewable energy projects, such as solar and wind power, in the sunny and windy southern regions could create new economic opportunities and reduce dependency on fossil fuels.

For provinces that exhibit dual specialization in both green and vulnerable industries, such as Turin, a balanced policy approach is necessary. Here, the goal should be to manage the decline of vulnerable sectors in a way that minimizes economic disruption while simultaneously fostering the growth of green industries. This could be achieved through policies that support the retraining and upskilling of workers, enabling them to transition from declining industries to emerging green sectors. Moreover, targeted support for small and medium-sized enterprises (SMEs) in these regions could help them innovate and adapt to the changing economic environment.

The study also highlights the importance of addressing regional disparities through national-level coordination. While local and regional policies are crucial for addressing specific needs, a coherent national strategy is essential to ensure that all regions benefit from the green transition. This might involve redistributing resources and investments from wealthier, green-specialized regions to those lagging behind, thereby reducing the economic divide between the North and South. The development of national infrastructure projects, such as smart grids and efficient transportation networks, could also support the green transition across all regions, enhancing connectivity and enabling regions with lower green specialization to integrate into the broader green economy.

Furthermore, the findings suggest that policies should be adaptive and responsive to the dynamic nature of the green transition. As new technologies emerge and global market conditions evolve, policy frameworks must be flexible enough to accommodate these changes. This requires continuous monitoring of economic indicators related to green and vulnerable industries, as well as regular reviews and updates to policy strategies. By doing so, policymakers can ensure that interventions remain relevant and effective, enabling Italy to maintain its competitive edge in the green economy.

Another key recommendation is the need for stronger collaboration between public and private sectors. The green transition is a multifaceted challenge that requires the combined efforts of government, industry, and civil society. Public-private partnerships can play a vital role in driving innovation, scaling up green technologies, and ensuring that the benefits of the green transition are widely shared. For instance, governments can work with private companies to develop green industrial zones or innovation clusters that concentrate resources and expertise in specific areas, thereby accelerating the growth of green industries.

In addition, there is a need for comprehensive education and training programs that equip the workforce with the skills necessary for the green economy. As traditional industries decline, the demand for new skills in areas such as renewable energy, energy efficiency, and sustainable manufacturing will increase. Governments should invest in education systems and vocational training programs that align with the needs of the green economy, ensuring that workers are prepared to take advantage of new job opportunities. This will also help mitigate the social impacts of the green transition, particularly in regions where job losses in vulnerable industries could otherwise lead to economic hardship.

Finally, the study highlights the importance of fostering a culture of innovation and entrepreneurship in all regions, particularly in those currently lagging in green specialization. Encouraging the development of start-ups and new ventures in green technologies can stimulate economic growth and create new job opportunities. Policies that provide financial support, mentorship, and networking opportunities for entrepreneurs can help nurture a new generation of businesses that contribute to the green economy.

In conclusion, the policy implications and recommendations arising from this study emphasize the need for a strategic, multi-faceted approach to managing the green transition in Italy. By addressing the specific needs of different regions, fostering innovation, and ensuring that the benefits of the green economy are widely shared, Italy can navigate the challenges of the green transition and emerge as a leader in the global shift towards sustainability. The recommendations provided here offer a roadmap for policymakers as they seek to harness the opportunities of the green transition while mitigating its risks, ensuring a prosperous and sustainable future for all regions of the country.

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Technical Appendices

Table A1. List of Provinces by TEC-TAC matrix quadrant of belonging

Code	Name	Green	Brown	Code	Name	Green	Brown

BO	Bologna	Basso	Alto	BI	Biella	Basso	Basso
BR	Brindisi	Basso	Alto	BL	Belluno	Basso	Basso
CZ	Catanzaro	Basso	Alto	BN	Benevento	Basso	Basso
FC	Forlì-Cesena	Basso	Alto	BT	Barletta-Andria-Trani	Basso	Basso
IS	Isernia	Basso	Alto	BZ	Bolzano	Basso	Basso
MO	Modena	Basso	Alto	CB	Campobasso	Basso	Basso
PE	Pescara	Basso	Alto	CO	Como	Basso	Basso
RM	Roma	Basso	Alto	CT	Catania	Basso	Basso
RO	Rovigo	Basso	Alto	EN	Enna	Basso	Basso
SI	Siena	Basso	Alto	FG	Foggia	Basso	Basso
SO	Sondrio	Basso	Alto	FI	Firenze	Basso	Basso
SP	LaSpezia	Basso	Alto	FR	Frosinone	Basso	Basso
SR	Siracusa	Basso	Alto	GO	Gorizia	Basso	Basso
TO	Torino	Basso	Alto	IM	Imperia	Basso	Basso
TS	Trieste	Basso	Alto	KR	Crotone	Basso	Basso
AO	Valled'Aosta	Alto	Alto	LC	Lecco	Basso	Basso
AV	Avellino	Alto	Alto	LE	Lecce	Basso	Basso
CA	Cagliari	Alto	Alto	LO	Lodi	Basso	Basso
CE	Caserta	Alto	Alto	LT	Latina	Basso	Basso
CH	Chieti	Alto	Alto	LU	Lucca	Basso	Basso
CR	Cremona	Alto	Alto	MB	MonzaeBrianza	Basso	Basso
CS	Cosenza	Alto	Alto	MC	Macerata	Basso	Basso
FE	Ferrara	Alto	Alto	ME	Messina	Basso	Basso
GE	Genova	Alto	Alto	MI	Milano	Basso	Basso
LI	Livorno	Alto	Alto	MS	Massa-Carrara	Basso	Basso
MN	Mantova	Alto	Alto	NO	Novara	Basso	Basso
PI	Pisa	Alto	Alto	NU	Nuoro	Basso	Basso
PU	PesaroeUrbino	Alto	Alto	OR	Oristano	Basso	Basso
PZ	Potenza	Alto	Alto	PA	Palermo	Basso	Basso
RG	Ragusa	Alto	Alto	PC	Piacenza	Basso	Basso
SS	Sassari	Alto	Alto	PD	Padova	Basso	Basso
TR	Terni	Alto	Alto	PG	Perugia	Basso	Basso
UD	Udine	Alto	Alto	PN	Pordenone	Basso	Basso
VB	VerbanoCusioOssola	Alto	Alto	PO	Prato	Basso	Basso
AQ	L'Aquila	Alto	Basso	PR	Parma	Basso	Basso
AR	Arezzo	Alto	Basso	PT	Pistoia	Basso	Basso
BG	Bergamo	Alto	Basso	PV	Pavia	Basso	Basso
BS	Brescia	Alto	Basso	RA	Ravenna	Basso	Basso
CL	Caltanissetta	Alto	Basso	RC	ReggioCalabria	Basso	Basso
CN	Cuneo	Alto	Basso	RE	ReggioEmilia	Basso	Basso
FM	Fermo	Alto	Basso	RI	Rieti	Basso	Basso
GR	Grosseto	Alto	Basso	RN	Rimini	Basso	Basso
MT	Matera	Alto	Basso	SA	Salerno	Basso	Basso
NA	Napoli	Alto	Basso	TA	Taranto	Basso	Basso
SU	SudSardegna	Alto	Basso	TE	Teramo	Basso	Basso
SV	Savona	Alto	Basso	TN	Trento	Basso	Basso
TP	Trapani	Alto	Basso	TV	Treviso	Basso	Basso
VE	Venezia	Alto	Basso	VA	Varese	Basso	Basso
AG	Agrigento	Basso	Basso	VC	Vercelli	Basso	Basso
AL	Alessandria	Basso	Basso	VI	Vicenza	Basso	Basso
AN	Ancona	Basso	Basso	VR	Verona	Basso	Basso
AP	AscoliPiceno	Basso	Basso	VT	Viterbo	Basso	Basso

AT	Asti	Basso	Basso	VV	ViboValentia	Basso	Basso
BA	Bari	Basso	Basso				

Source: Authors' calculations based on TEC-FRAMESBS data and Alessi and Battiston (2022).

Table A2. List of Values by Province

Code	Name	Green specializ.	Vulnerable specializ.	Code	Name	Green specializ.	Vulnerable specializ.
AG	Agrigento	0.01	0.02	MO	Modena	0.02	0.91
AL	Alessandria	0.01	0.07	MS	Massa-Carrara	0.01	0.44
AN	Ancona	0.01	0.34	MT	Matera	0.05	0.01
AO	Valled'Aosta-Aosta/Aoste	0.31	3.78	NA	Napoli	0.19	0.40
AP	AscoliPiceno	0.02	0.17	NO	Novara	0.04	0.34
AQ	L'Aquila	0.07	0.47	NU	Nuoro	0.00	0.03
AR	Arezzo	0.06	0.02	OR	Oristano	0.01	0.04
AT	Asti	0.00	0.03	PA	Palermo	0.00	0.50
AV	Avellino	0.17	1.29	PC	Piacenza	0.01	0.34
BA	Bari	0.02	0.07	PD	Padova	0.02	0.10
BG	Bergamo	0.08	0.25	PE	Pescara	0.04	0.58
BI	Biella	0.00	0.00	PG	Perugia	0.01	0.13
BL	Belluno	0.00	0.02	PI	Pisa	0.10	1.63
BN	Benevento	0.04	0.11	PN	Pordenone	0.02	0.15
BO	Bologna	0.01	0.56	PO	Prato	0.03	0.01
BR	Brindisi	0.03	0.92	PR	Parma	0.01	0.12
BS	Brescia	0.05	0.27	PT	Pistoia	0.05	0.06
BT	Barletta-Andria-Trani	0.01	0.03	PU	PesaroeUrbino	0.06	0.79
BZ	Bolzano	0.05	0.33	PV	Pavia	0.02	0.13
CA	Cagliari	0.26	2.63	PZ	Potenza	0.12	0.59
CB	Campobasso	0.00	0.06	RA	Ravenna	0.02	0.20
CE	Caserta	0.09	0.89	RC	ReggioCalabria	0.01	0.07
CH	Chieti	0.06	2.56	RE	ReggioEmilia	0.02	0.17
CL	Caltanissetta	1.19	0.37	RG	Ragusa	0.06	1.68
CN	Cuneo	0.08	0.10	RI	Rieti	0.00	0.12
CO	Como	0.01	0.14	RM	Roma	0.00	1.01
CR	Cremona	0.08	0.63	RN	Rimini	0.01	0.04
CS	Cosenza	0.12	0.58	RO	Rovigo	0.05	0.51
CT	Catania	0.05	0.43	SA	Salerno	0.01	0.07
CZ	Catanzaro	0.03	2.48	SI	Siena	0.03	1.01
EN	Enna	0.00	0.02	SO	Sondrio	0.04	0.88
FC	Forlì-Cesena	0.04	0.88	SP	LaSpezia	0.03	4.48
FE	Ferrara	0.20	1.22	SR	Siracusa	0.00	10.70
FG	Foggia	0.01	0.03	SS	Sassari	0.13	1.18
FI	Firenze	0.00	0.04	SU	SudSardegna	0.51	0.02
FM	Fermo	0.09	0.08	SV	Savona	0.06	0.31
FR	Frosinone	0.03	0.34	TA	Taranto	0.01	0.06
GE	Genova	0.07	1.08	TE	Teramo	0.03	0.20
GO	Gorizia	0.04	0.38	TN	Trento	0.02	0.33
GR	Grosseto	0.05	0.29	TO	Torino	0.03	1.30
IM	Imperia	0.02	0.18	TP	Trapani	0.16	0.09
IS	Isernia	0.00	0.73	TR	Terni	0.28	2.79

KR	Crotone	0.04	0.14	TS	Trieste	0.00	4.41
LC	Lecco	0.05	0.32	TV	Treviso	0.03	0.04
LE	Lecce	0.02	0.09	UD	Udine	0.07	0.63
LI	Livorno	0.15	1.84	VA	Varese	0.01	0.19
LO	Lodi	0.02	0.36	VB	Verbano-Cusio-Ossola	0.14	1.31
LT	Latina	0.03	0.28	VC	Vercelli	0.01	0.03
LU	Lucca	0.00	0.19	VE	Venezia	0.05	0.35
MB	MonzaeBrianza	0.03	0.10	VI	Vicenza	0.04	0.13
MC	Macerata	0.01	0.04	VR	Verona	0.05	0.10
ME	Messina	0.03	0.12	VT	Viterbo	0.01	0.01
MI	Milano	0.02	0.29	VV	ViboValentia	0.01	0.02
MN	Mantova	0.10	0.90		**National average**	**0.06**	**0.67**

Source: Authors' calculations based on TEC-FRAMESBS data and Alessi and Battiston (2022). Note: To make the index values more readable despite their small magnitude, they have been multiplied by 1000.

Table A3. List of Values by Region

Region	Green specializ.	Vulnerable specializ.
Abruzzo	0.05	0.95
Basilicata	0.09	0.30
Calabria	0.04	0.66
Campania	0.10	0.55
Emilia-Romagna	0.04	0.49
Friuli-Venezia Giulia	0.03	1.39
Lazio	0.01	0.35
Liguria	0.05	1.51
Lombardia	0.04	0.37
Marche	0.04	0.28
Molise	0.00	0.40
Piemonte	0.04	0.40
Puglia	0.02	0.20
Sardegna	0.18	0.78
Sicilia	0.17	1.55
Toscana	0.05	0.55
Trentino-Alto Adige	0.03	0.33
Umbria	0.15	1.46
Valled'Aosta	0.31	3.78
Veneto	0.03	0.18
National average	**0.06**	**0.67**

Source: Authors' calculations based on TEC-FRAMESBS data and Alessi and Battiston (2022). Note: To make the index values more readable despite their small magnitude, they have been multiplied by 1000.

Table A4. Top Export Sector for the Top and Bottom 10 Provinces and Related Sectoral Alignment/Vulnerability Values

Province	ATECO Code	ATECO Name	TAC	TEC	Sector Weight on Total Exports
MI	1920	Manufacture of Refined Petroleum Products	0	1	7%

VV	2410	Iron and Steel Industry	0.05	0.5	0%
BS	2410	Iron and Steel Industry	0.05	0.5	7%
VI	2410	Iron and Steel Industry	0.05	0.5	4%
TV	2420	Manufacture of Tubes, Pipes, Hollow Profiles and Related Steel Fittings	0.05	0.5	1%
BG	2420	Manufacture of Tubes, Pipes, Hollow Profiles and Related Steel Fittings	0.05	0.5	5%
FI	2444	Production of Copper and Semi-finished Products	0.03	0	2%
MO	2910	Manufacture of Motor Vehicles	0.02	0.97	27%
BO	2910	Manufacture of Motor Vehicles	0.02	0.97	13%
TO	2910	Manufacture of Motor Vehicles	0.02	0.97	39%
CZ	3012	Building of Pleasure and Sporting Boats	0	1	13%
RM	3030	Manufacture of Aircraft, Spacecraft and Related Devices	0	1	23%
CL	3832	Recovery and Sorting of Materials	1	0	7%
IS	4211	Construction of Roads and Highways	0	0.98	3%
CS	4511	Sale of Cars and Light Motor Vehicles	0	0.98	4%
PZ	4511	Sale of Cars and Light Motor Vehicles	0	0.98	6%
EN	4531	Wholesale and Intermediation of Motor Vehicle Parts and Accessories	0	0.98	0%
OR	4671	Wholesale of Solid, Liquid, Gaseous Fuels and Related Products	0	1	0%
KR	4941	Road Freight Transport	0.002	0.998	1%
NU	4941	Road Freight Transport	0.002	0.998	0%

Source: Authors' calculations based on TEC-FRAMESBS data and Alessi and Battiston (2022).

7. The contribution of green Cohesion Policy funds to carbon abatement: a heterogeneity analysis across Italian municipalities

(Giovanni Bonaccorsi, Alessandro Buongiorno, Andrea Gilardi, Mario Intini, Valeria Maria Urbano, Andrea Flori, Angela Stefania Bergantino - UniBa and Polimi)

7.1. Introduction

Complete ex-post assessments on the impact of the EU Cohesion Policy suggest that the effectiveness of this regulatory framework was negatively affected by the wide set of targeted development axes, leading to fragmented spending across the different priorities with a lack of critical mass (Barca, 2009). Furthermore, the EU Cohesion Policy was characterized by insufficient consideration of the "logic of intervention", meaning that the regulation missed a clear implementation strategy to achieve the defined targets (CPMR, 2014, 2015).

As a consequence, in 2013 this policy framework was subject to significant and substantial regulatory changes, ensuring a stronger alignment between policy objectives and funds allocation and a greater thematic concentration focusing on environmental targets (Vironen et al., 2019). Consistently, the sustainability transition constituted one of the main pillars of the programming period 2014-2020 absorbing 161 billion euros corresponding to more than 30% of the total available budget. Indeed, the sustainability transition is commonly seen as a key option to combat climate change and comply with international targets established by the European Commission aiming to reduce greenhouse gas emissions to at least 55% below 1990 levels by 2030 and achieve carbon neutrality in 2050.

Despite such growing interest on the effects generated by environmental funds in terms of carbon abatement, extant literature has mainly focused on the analysis of the socio-economic impact of Cohesion Policy funds, considering the GDP per capita and employment as main outcome variables (see e.g., Gripaios et al. (2008), Mohl and Hagen (2010), Pienkowski and Berkowitz (2016), Dall'Erba and Fang (2017) and Scotti et al. (2022)). Moreover, the still limited set of studies discussing how public funds may contribute to reducing CO2 emissions has not adequately investigated how the effects of such programs of financial support targeting the environmental sector may vary depending on the local set of capacities, representing the stock of tangible and intangible assets that contribute to the local sustainable development. Indeed, there is a strong debate on the role of the local context in mediating the impact of EU Cohesion Policy funds (Fratesi et al., 2014, Fratesi and Perucca, 2016, 2018, 2019, Bachtrogler et al., 2020). If existing contributions show that public funds have a larger impact on firms growth in regions with lower income or limited endowments of territorial assets, we still lack evidence on how the local set of capacities may influence the outcome of financial support initiatives targeting carbon abatement.

Against this background, this paper aims to fill this gap by analysing the impact of green EU Cohesion Policy funds in terms of PM2.5 air concentration reduction in Italy over the time frame 2014-2020. Through the application of panel Spatial Durbin Models (SDM) we study the extent to which green funds generate both a direct and indirect effect in terms of PM2.5 reduction when we analyse the whole sample of Italian municipalities. Indeed, these programs of financial support may contribute to reducing emissions both in the municipality directly receiving them, but also in the neighbour areas. Moreover, we discuss potential heterogeneous dynamics across territories with different levels of territorial capital.

Overall, this report develops an insight on the effects generated by green Cohesion Policy funds in terms of PM2.5 reduction across territories with heterogeneous levels of territorial capital, supporting policy makers to further refine and improve this regulatory framework aiming to contribute to the sustainability transition.

The rest of the paper is organized as follows: Sections 2 and 3 illustrate the data and the methods we employ to investigate our research objective. Section 4 discusses our results, while the paper concludes by highlighting the main implications of our study.

7.2. Outline of literature background

Strategies for climate change mitigation and the EU Cohesion Policy are widely scrutinized topics, but they have rarely been jointly investigated (Nekvasil and Moldan, 2018). The limited availability of analyses focusing on their mutual relationship might be explained by the recent inclusion of climate change as a key priority area within the EU Cohesion Policy. Indeed, before the programming period 2014-2020, the environmental dimension did not represent a pillar of the policy (see Council Regulation (EC) No, 1083/2006 and Council Regulation (EU) No, 1303/2013).

Due to the impossibility of complying with international climate targets (e.g., Kyoto commitment, Paris Agreement) without a complete integration of the climate change dimension among critical priorities of the EU Cohesion Policy (Nilsson and Nilsson, 2013), the budget allocated by the EC to projects directly focusing on climate-related investments has significantly increased, moving from about 2% during the time window 2000-2006 to 8.4% and 16.3% during the most recent programming-periods 2007-2013 and 2014-2020, respectively.

EU funds may thus constitute critical instruments to re-direct economic capital from dirty incumbent technologies towards the development of clean innovation (Perez, 2010; Schmidt, 2014), contributing to overcoming financial barriers that typically constrain the sustainability transition (Leete et al., 2013; Iyer et al., 2015; Polzin et al., 2016). Indeed, they may alleviate firms' financial constraints, enabling research and development activities on new technologies targeting emissions reduction with a still risky return profile (Zhang et al., 2020; Alam et al., 2022). Furthermore, they show the commitment of relevant international institutions such as the EC in favor of the sustainability transition, thus limiting the uncertainty associated with firms' investments in low-carbon technologies (Polzin, 2017; Geddes and Schmidt, 2020). As the decarbonization process is mainly driven by technological innovation derived from renewable energy sources, electrification of the economy across different sectors (e.g., transportation), improved energy efficiency in buildings, industry, and household appliances, as well as secure

energy systems, EU Cohesion Policy funds may thus support the large investments required at firm level to foster the low-carbon economy (Fragkos et al., 2017; Jamasb and Llorca, 2019; Cambini et al., 2020; Castrejon-Campos et al., 2022; Llorca and Rodriguez-Alvarez, 2024).

Consistently with these expectations, some preliminary evidence suggests that EU Cohesion Policy funds may support the socio-technical transition towards green innovation. For instance, as discussed by Nekvasil and Moldan (2018), operational programs focused on clean energy production fostered the substitution of fossil fuels with renewable energy sources, reaching a value of 7700 MW per year, almost tripling the level observed at the end of the programming period 2007-2013. Furthermore, public and residential buildings, responsible for approximately 36% of CO2 emissions in the EU, experienced a decrease of primary energy consumption in public buildings by 5.2 TWh per year across all EU Cohesion Policy operational programs. These climate-related projects have translated into a progressively stronger contribution of the EU Cohesion Policy to the achievement of environmental targets since the overall reduction of GHG emissions associated with finalized projects under this regulatory framework raised from17.1 to 25.1 Mt of CO2, corresponding to about 0.5% of total EU emissions.

Although such data highlight that the EU Cohesion Policy stimulated carbon abatement at the aggregate level, heterogeneous results emerge when considering single countries. Indeed, convergence in terms of CO2 per capita was observed over the period 1990-2010 across EU countries, with territories experiencing higher starting levels of GHG emissions (e.g., Finland, Ireland, Belgium) associated with a stronger yearly carbon abatement rate (between -4.0% and -2.0%) (Duro and Padilla, 2013; Liobikiene and Mandravickaite, 2016). Conversely, the most problematic countries were Estonia, Austria, and Poland exhibiting a large initial emissions level and still subject to a growth in pollution (between 0.2% and 2.0%).

Such results may be driven by the different intensity of funds targeting the sustainability transition attracted by territories, with more peripheral regions in the North and South of Europe from a geographical, innovation, and socio-economic perspective receiving a larger amount of financial support. Conversely, when focusing on within-country disparities in terms of green funds attraction, peripheral areas tended to experience a lower level of low-carbon investments with respect to territories exhibiting a higher demographic density and level of economic development in terms of GDP and income per capita (Kozera et al., 2022; Penalosa and Castaldi, 2024).

Overall, the available studies tend to show that the EU Cohesion Policy may have a strong potential to drive the sustainability transition. However, we still lack robust studies clarifying the EU funds' impact on climate change-related targets. With our study, we build an original dataset linking EU green fund expenditures and PM2.5 levels at the municipal level over the most recently concluded programming period 2014-2020. Therefore, we fill this gap by showing how EU Cohesion Policy funds targeting the environmental sector contributed to carbon abatement across territories with a heterogeneous local context. Such empirical evidence might also be informative to increase the effectiveness of future programming periods (e.g., 2021-2027) to support the achievement of a low-carbon economy.

7.3. Data

7.3.1. Beneficiaries Identification

Since our research objective is to disentangle the impact of green funds, we first restrict our analysis of EU Cohesion Policy funds to the subset of projects explicitly targeting carbon abatement purposes. We thus build a comprehensive database on the set of projects financed by the EU Cohesion Policy in all Italian regions focused on the sustainability transition, relying on the Open Coesione data platform.[18]

In particular, we focus on the European Regional Development Fund (ERDF) and the European Social Fund (ESF), since with 199 and 84 billion € they represent two main funds within the EU Cohesion Policy framework over the time frame 2014-2020. Moreover, differently from other programs of financial support, such as the European Maritime and Fisheries Fund and the Fund for European Aid to the Most Deprived, the ERDF and the ESF are allocated to all Italian territories and not only to sub- specific areas, thus allowing us to compare the effects generated by these funds across different municipalities in Italy.

Based on the thematic code attributed to each project by the European Commission, in a first stage, we restrict our analysis to projects related to "low carbon economy and energy efficiency" (thematic objective 4). Based on the project description, we verify that such projects strictly relate to activities targeting emissions reduction, thus potentially having a direct impact on carbon abatement. Through this procedure, we initially select 5,736 projects.

Then with reference to these selected projects, based on the title and synthetic description of such projects, we identify a set of frequent keywords, allowing us to distinguish projects targeting the sustainability transition in terms of carbon abatement. We use such keywords to identify projects whose thematic objective is not classified in the thematic objective 4 by the European Commission (thus initially excluded from our selected sample), but that still are mainly contributing to emissions reduction.

Since projects out of thematic objective 4 might be focused on different dimensions with respect to carbon abatement, we expect that single keywords may not be able to correctly identify projects actually focusing on carbon emissions. Therefore, we select a very specific set of combination of keywords that must be found in the synthetic description of projects with thematic codes 1-3 and 5-11 in order to be selected as projects fostering carbon abatement. Through this procedure we select other 5,172 projects. In this way, we expect to provide a complete overview on the set of projects targeting the sustainability transition with a specific focus on CO2 emissions abatement.[19] In particular, our sample consists of 10,908 (5,736+5,172) projects and 4.1 billion euros of realized expenditures. From this sample, we exclude projects with a realized cost and public funds equal to zero. Indeed, such projects have not started yet to be implemented and do not seem to have received public funds (either from the EC or national government). Our final sample, thus consists of 10,468 projects.

Since our geographical unit of analysis is municipalities, we aggregate our data at the municipal level. Overall, our dataset covers 4,941 Italian municipalities receiving public funds from the

[18] Information related to projects implemented by each Italian region within the EU Cohesion Policy framework is available at the following link: https://opencoesione.gov.it/it/opendata/#!progetti_regione_section.

[19] Here, we report an shortlist of keywords combinations we use to select such projects: "energy efficiency", "energy saving", "pollution", "photovoltaic", "emission", "solar", "diesel", "methane", "bio-methane", "CO2 emission", "carbon abatement".

Cohesion Policy with a specific target on carbon abatement over the timeframe 2014- 2020. Figure 1 shows the distribution of green funds expenditures across Italian municipalities normalized by the total income of the underlying administrative unit. Consistently with the allocation logic of the ERDF and the ESF, mainly targeting less developed areas, we observe a higher level of expenditures in the South of Italy.

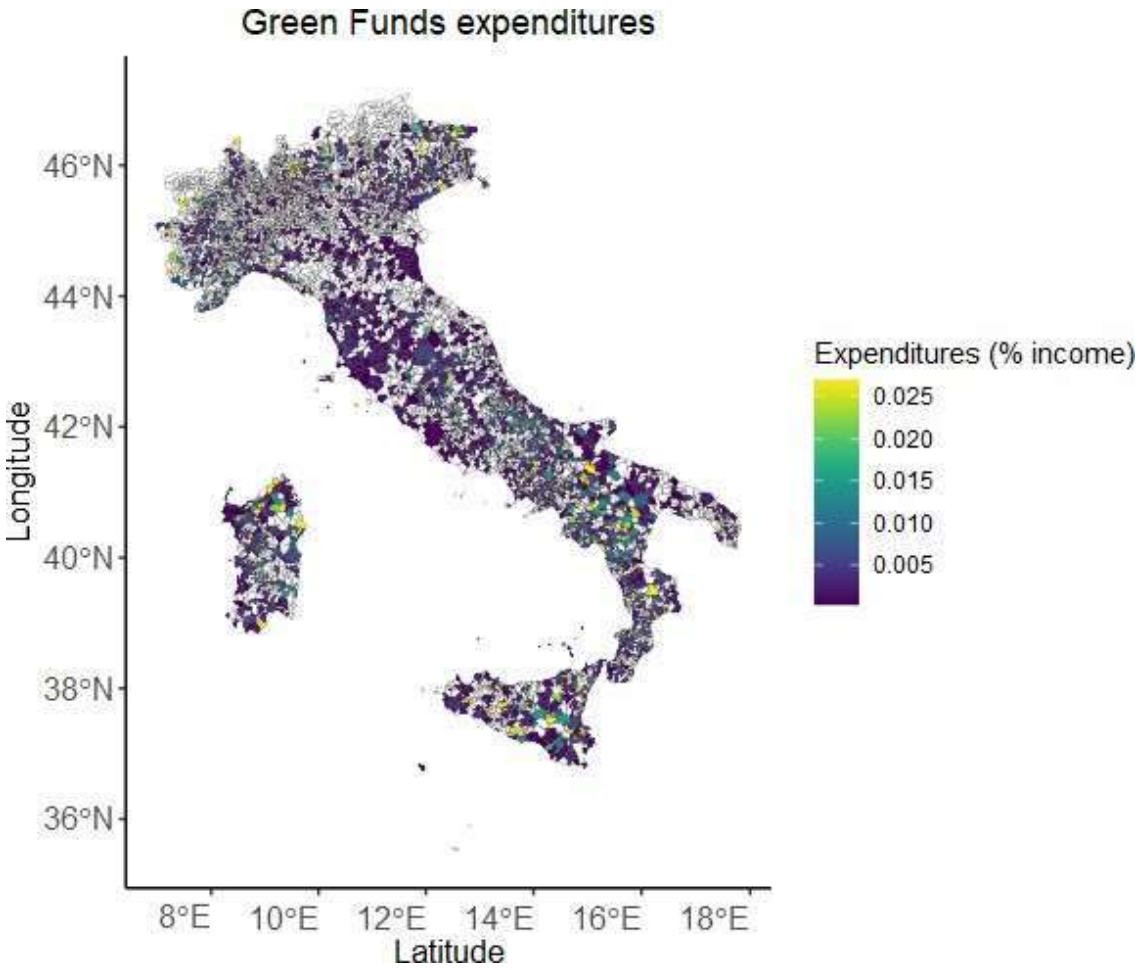

Figure 8: We show the distribution of green funds expenditures across Italian municipalities normalized by the total income of the underlying administrative unit.

7.3.2. Dependent Variable

We consider the level of PM2.5 emissions at the municipal level for the time frame 2014-2020 as our dependent variable. We focus on PM2.5 since it is a primary cause of death monitored by the European Environment Agency (EEA) and is a reference pollutant used by the European Commission to establish environmental targets (Tarın-Carrasco et al., 2021; Beloconi and Vounatsou, 2023).[20]

[20] Further information is available at the following links: https://www.eea.europa.eu/en/analysis/indi cators/health-impacts-of-exposure-to and https://environment.ec.europa.eu/topics/air/air-qua lity/eu-air-quality-standards_en.

National statistical offices do not provide information related to the air concentration of alternative pollutants with the spatial granularity and temporal frequency required by our analysis. Therefore, we build our dependent variable based on satellite data disclosed by the European Environmental Agency (EEA) covering the timeframe 2014-2020. In particular, we rely on air pollutant concentration grids (1km2 x 1km2) combining monitoring air quality data in a 'regression-interpolation-merging mapping' methodology. We compute the yearly level of PM2.5 in every Italian municipality as a weighted average of the pollutant concentration in each grid based on the portion of the overlapping area between the grid and the considered administrative unit.

Figure 2 shows the geographical distribution of PM2.5 levels across Italian municipalities in 2014. We observe a higher concentration of emissions in the North of Italy especially in Lombardy, Piedmont, Emilia-Romagna, and Veneto regions. PM2.5 levels tend to be lower in the Centre-South of Italy, with Sardinia constituting the cleaner region.

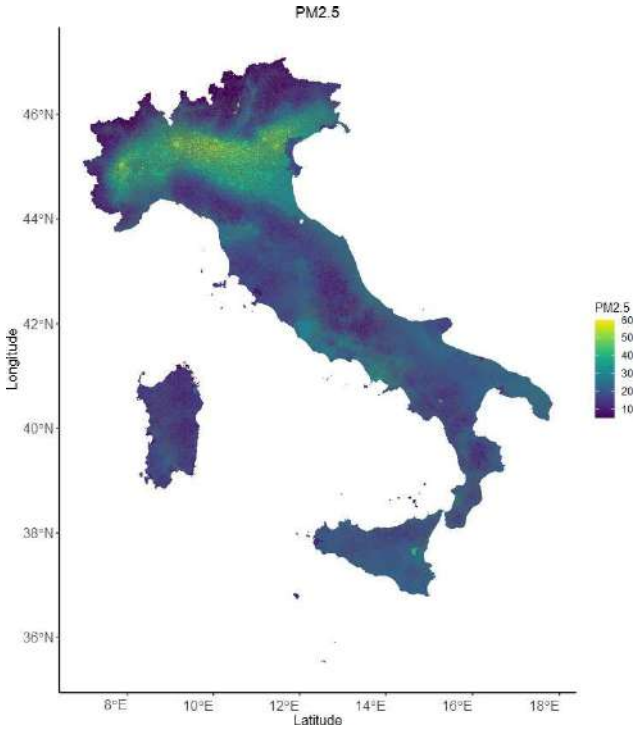

Figure 9: We show the geographical distribution of the level of PM2.5 across Italian municipalities.

7.4. Methodology

7.4.1. Cluster analysis

Our analysis aims to disentangle the impact of green EU Cohesion Policy funds across territories based on the local context. In order to distinguish the different characteristics of Italian municipalities, we rely on a cluster analysis. The selection of variables used in the cluster analysis takes as reference the "Territorial Capital" framework introduced by Camagni et al. (2009). However, we expand the set of variables previously used by Fratesi et al. (2014), Fratesi and Perucca (2016), Fratesi and Perucca (2018), Fratesi and Perucca (2019) and Bachtrogler et al. (2020) mainly focusing on private/public assets and hard/soft infrastructures to account for a complete set of social, economic, environmental and demographic variables.

In particular, in terms of economic variables we consider Income per capita, Bank branches, Bank deposits per capita and Bank loans per capita, and the Percentage of employees in the Manufacturing sector Manufacturing employees. We also include the percentage of Waste sorting, availability of Drinking water (expressed as thousands of cubic meters of water per inhabitant dispensed by the local municipality), and portion of Soil usage as proxies of urban ecology, quality of local environmental services, and of the level of anthropization of the area. We account for additional local services by including the Public mobility index and the number of Accommodation beds. We also plug the heterogeneity in housing and household assets through the Housing dispersion and Building expansion indices. Finally, the percentage of enrolled university students based on the municipality of residence University students and the portion of Active Population allow us to map the human capital of Italian administrative units.

We perform a hierarchical cluster analysis based on these variables using the Ward 2 linkage criterion method as a standard approach to perform such analysis. We then assess the stability of our results by comparing the output of different hierarchical clustering methods based on alternative agglomeration methods such as "Single", "Complete", "Average", "Mcquitty", "Median", "Centroid" (McQuitty, 1966; Hartigan, 1975). To select the optimal number of clusters we rely on the silhouette coefficient, allowing us to compare intra and inter-cluster distances, thus providing insight on the quality of the clustering method output. We define the silhouette as:

$$Silhouette = \frac{1}{N} s_i \quad (1)$$

where s_i is the silhouette of observation i and N is the sample size. In particular, s_i can be computed as:

$$s_i = \frac{b_i - a_i}{max(a_i; b_i)} \quad (2)$$

where a_i is the mean distance of observation i from all other units in the same cluster () and b_i is the minimum average distance of observation i from all units in other clusters.

In formula:

$$a_i = \frac{1}{N_{c_i} - 1} \sum_{j \in c_i, j \neq i} \left(d_{i,j}\right) \quad (3)$$

where N_{c_i} is the size of cluster c_i and $d_{i,j}$ is the euclidean distance between observation i and j.

We obtain the optimal results in terms of silhouette for a number of clusters equal to 3 (see the left panel in Figure 3). Figure 3 (right panel) reports the geographical distribution of municipalities across the three clusters. Figure 4 shows the distribution of the covariates used in the cluster analysis across the 3 groups. In particular, Cluster 1 mainly encompasses municipalities in the Centre-North of Italy, with a high economic capital. Cluster 2 tends to include areas with a high presence of accommodations in the Touristic sector. Finally, Cluster 3 accounts for municipalities

in the Centre-South of Italy, with a large portion of university enrolled students, a high usage of public mobility means of transport and a low level of services in terms of waste sorting. Table 1 reports the median values of all the covariates for the 3 clusters.

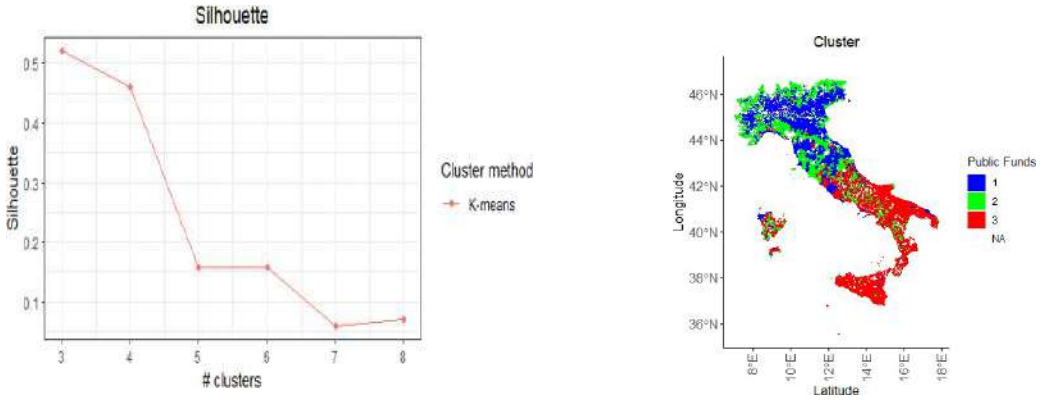

Figure 10: We show the output of our cluster analysis and the silhouette associated with alternative number of clusters.

Table 1: We show the median value of covariates for the 3 clusters.

Cluster	1	2	3
Income pc	0.382	0.298	0.188
Bank branches	0.055	0.056	0.042
Bank deposit	0.032	0.032	0.020
Bank loans	0.026	0.026	0.013
Manufacturing employees	0.369	0.132	0.118
University students	0.102	0.092	0.176
Drinkable water	0.081	0.087	0.072
Public mobility	0.191	0.202	0.246
Waste sorting	0.615	0.440	0.276
Soil usage	0.950	0.908	0.951
Accommodation capacity	0.002	0.009	0.002
Housing dispersion	0.926	0.864	0.938
Building expansion	0.172	0.057	0.062
Active population	0.613	0.546	0.577

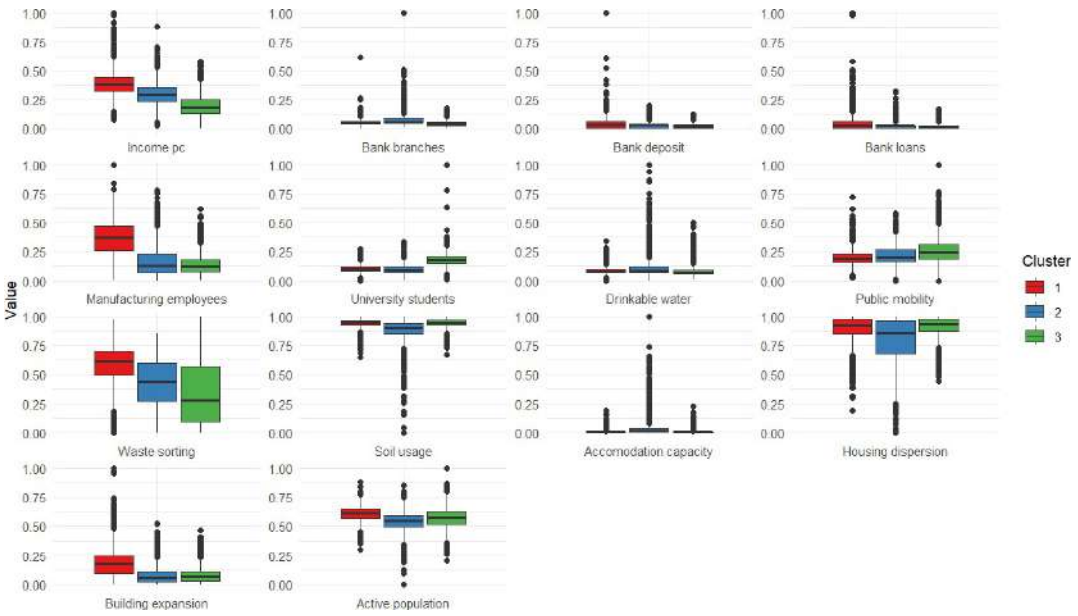

Figure 11: We show the distribution of the normalized covariates used in the cluster analysis across the 3 groups.

7.4.2. Spatial analysis

To investigate our research question, we implement a panel Spatial Durbin Model (SDM), based on the following equation:

$$Y_{i,t} = \lambda \sum_j w_{i,j} * Y_{i,t} + \beta_0 + \beta_1 * Environmental\ Funds_{i,t} + \beta_2 * \sum_j w_{i,j} * Environmental\ Funds_{i,t} + \gamma * X_{i,t} + \varepsilon_{i,t} \quad (4)$$

where $Y_{i,t}$ is our dependent variable computed as the percentage variation of PM2.5 concentration in municipality i in year t (see Section 1.3.2 for further details). We include the spatial autoregressive component $\sum_j w_{i,j} * Y_{i,t}$ to account for potential similar pollutant concentration dynamics in close municipalities. Moreover as explained in Section 1.3.1, $Environmental\ Funds_{i,t}$ is the expenditure of green funds allowing us to capture the direct contribution of such programs of financial support to the reduction of pollution in the municipality where projects are implemented (direct effect). The term $\sum_j w_{i,j} * Environmental\ Funds_{i,t}$ is rather responsible for spillover effects (indirect effect) since the expenditures of green funds in a municipality may also have an impact in terms of PM2.5 reduction in neighbour municipalities. Finally, $X_{i,t}$ is a vector of control variables including meteorological factors that could affect the pollutants concentration such as the wind speed, precipitation level, temperature and humidity (Zhou and Levy, 2007; Zhang et al., 2015; He et al., 2017). We test the robustness of our results through alternative specifications of the spatial matrix W.

First, we model traditional weight matrices based on the great circle distance between the centroids of different regions. Based on the application of the K-Nearest Neighbours (KNN) algorithm, we thus define this spatial matrix W as:

$$W = \begin{Bmatrix} w_{ij}^*(k) = 0 \; if \; i = j \\ w_{ij}^*(k) = 1 \; if \; d_{ij} \leq d_i(k) \; and \; w_{ij}(k) = \dfrac{w_{ij}^*(k)}{\sum_j w_{ij}^*(k)} \\ w_{ij}^* = 0 \; if \; d_{ij} > \; d_i(k) \end{Bmatrix}$$

where $d_i(k)$ is the cutoff threshold, representing the distance of the kth closest administrative unit to municipality i, such that each administrative unit has exactly k neighbours. We set k = 10 and then we perform robustness checks considering also alternative specifications (e.g., k = 10, 20, 30, 40, 50). Hence, $w_{ij}^*$is an element of the unstandardized weight matrix W, while $w_{i,j}$ is an element of the standardized weight matrix in which the sum of each element of a row equals to 1.

A preliminary investigation of the relevance of direct and indirect effects could be performed based on the estimates of the parameters λ, β_1, and β_2 derived from Equation 4. However, LeSage and Pace (2009) illustrate how a more valid inference on direct effects and spillovers may be obtained by analyzing the matrix of partial derivatives of the dependent variable (PM2.5 variation) with respect to our variable of interest (environmental funds). Indeed, this approach takes into account all the relevant parameters contributing to generating the direct and indirect effects in a more precise manner. In line with the terminology in Elhorst et al. (2014), we thus define direct, indirect and total effects based on our equation 1

7.5. Findings

7.5.1. Results across clusters

In this section, we analyse the impact of green EU Cohesion Policy funds across different clusters of municipalities displaying heterogeneous social, economic, environmental and demographic characteristics as shown in Section 1.4.1.

In particular, in Table 2 we separately estimate the panel-spatial models by restricting the sample to municipalities included in one single cluster. In Cluster 1, we observe a significant direct and indirect impact of funds targeting carbon abatement. In particular, these programs of financial support reduce by 1.1% the level of PM2.5 emissions in the municipality implementing the project and by 2.2% in the neighbour administrative areas. On the other hand, we only find statistically significant spillovers for municipalities in Cluster 2. However, notice how the magnitude of β_2 (0.012) is lower than in Cluster 1. Finally, we do not obtain relevant effects of green funds for municipalities located in Cluster 3.

Table 3: We show the estimates of a Spatial Durbin Models analysing the impact of funds targeting carbon abatement on the variation of pollutants intensity in terms of PM2.5 across clusters.

	Dependent variable: Variation of PM2.5 concentration		
	Cluster 1	*Cluster 2*	*Cluster 3*
Lambda	0.944***	0.922***	0.931***
	(0.003)	(0.005)	(0.004)
Environmental funds	-0.011**	-0.004	0.000
	(0.004)	(0.003)	(0.001)
Environmental funds spillovers	-0.016***	-0.012***	-0.003
	(0.005)	(0.004)	(0.002)
Temperature	0.000	0.000	-0.001
	(0.002)	(0.002)	(0.001)
Precipitation	-0.002*	-0.002	-0.001
	(0.001)	(0.002)	(0.001)
Wind speed	0.002	0.000	0.000
	(0.002)	(0.002)	(0.001)
Humidity	-0.003***	-0.002	-0.002*
	(0.001)	(0.002)	(0.001)
N	7,343	7,315	6,832
AIC	-12,775.62	-5,893.453	-14,235.75
BIC	-12,727.30	-5,845.17	-14,187.95

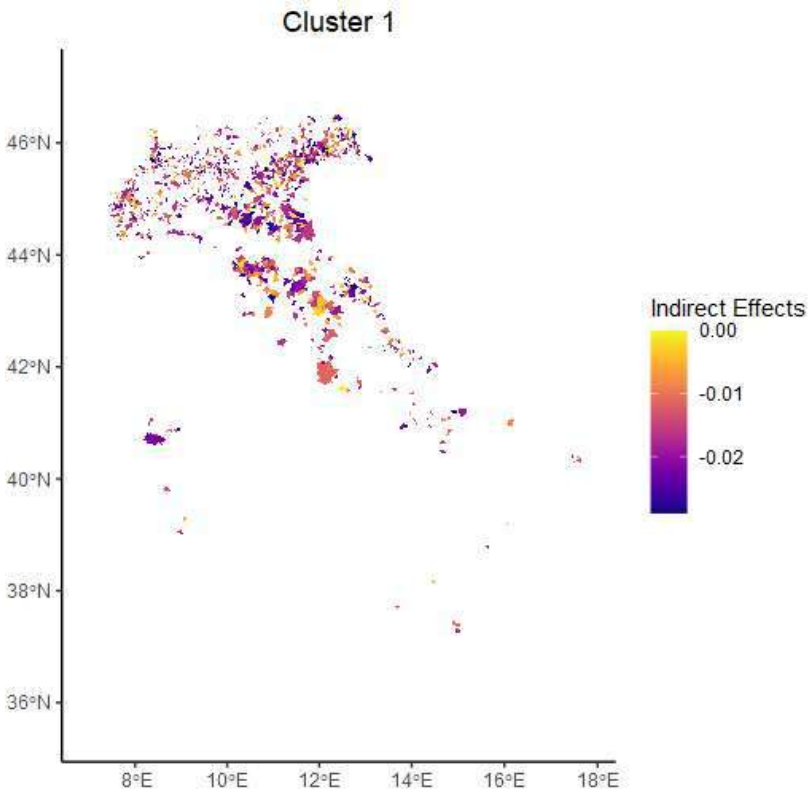

Figure 12: Geographical distribution of indirect effects in municipalities in Cluster 1.

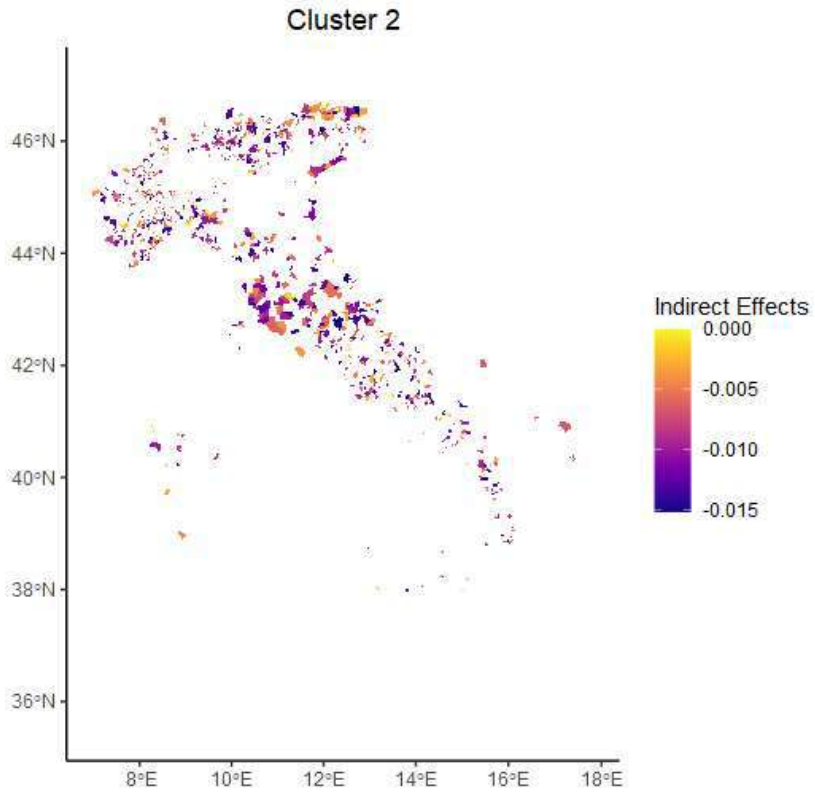

Figure 6: Geographical distribution of indirect effects in municipalities in Cluster 2.

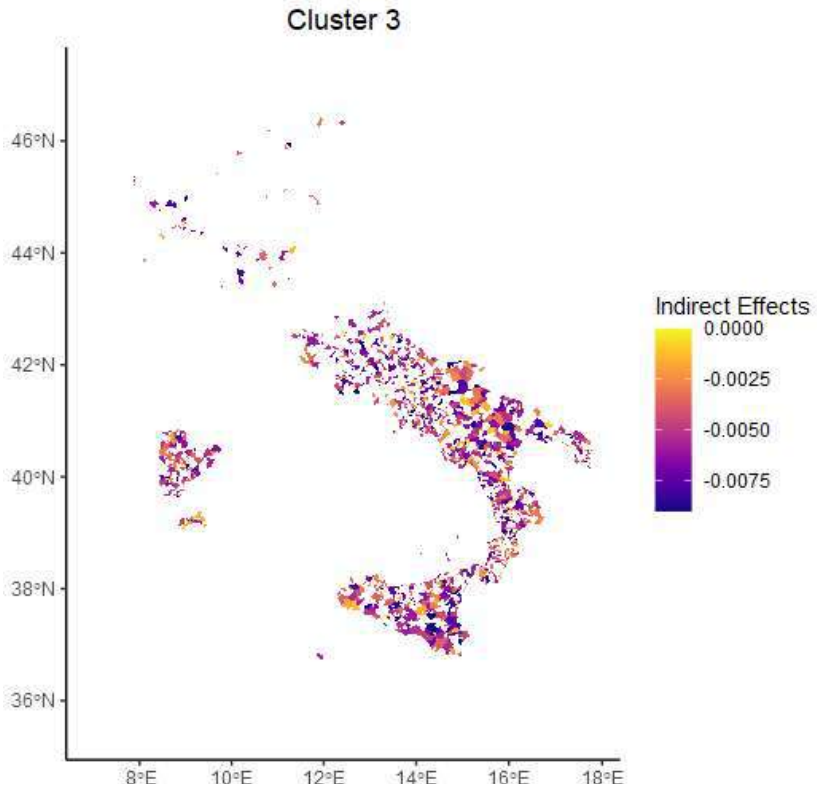

Figure 7: Geographical distribution of indirect effects in municipalities in Cluster 3.

In line with LeSage and Pace (2009), we also estimate indirect effects to assess the spillovers generated by the green EU funds. For Cluster 1, we find that a 1% growth of EU funds, expressed as a portion of local total income, generates a decrease in emissions by 1.6% in neighbouring municipalities. A similar impact in terms of spillovers is observed in municipalities of Cluster 2 where the green funds reduce PM2.5 levels by 0.9%. We confirm the absence of indirect effects in Cluster 3. Figure 2 highlights the geographical distribution of spillovers across municipalities.
We find that on average higher indirect effects are generated in municipalities of Cluster 1 with Provinces in the North of Italy (e.g., Imperia, La-Spezia, Trieste, Reggio Emilia, and Cremona) experiencing the highest spillovers (between -2.0% and -1.4%). Conversely, significantly lower indirect effects are generated in municipalities of Cluster 3 with values below -0.5%.

7.5.2. Spatial matrices robustness check

Our results might be driven by the definition of the concept of "neighbour" municipalities. In previous sections, neighbour municipalities were the 10 closest municipalities based on the distance between centroids of considered administrative units. For this reason, we check the robustness of our findings in case we rely on alternative definitions of our spatial weight matrix W . In particular, Table 5 shows a sensitivity analysis in case we use the KNN method with k = 20, 30, 40, 50 to identify neighbour municipalities.
Table 5 tends to confirm our previous findings. Indeed, in all cases we confirm that green funds allocated to Cluster 1 generate a significant reduction of PM2.5 levels in the administrative unit spending these financial resources and in the neighbour municipalities. We obtain only relevant spillovers for Cluster 2 municipalities and no significant effects in Cluster 3 areas. Notice how limited exceptions arise only in the case of a larger number of neighbour municipalities (e.g., k = 40 or k = 50).

Table 5: We show the estimates of a Spatial Durbin Models analysing the impact of funds targeting carbon abatement on the variation of pollutants intensity in terms of PM2.5. The model is estimated across alternative spatial matrices using different number of K-Nearest Neighbours.

	Dependent variable: Variation of PM2.5											
	Cluster 1				*Cluster 2*				*Cluster 3*			
	(k=20)	(k=30)	(k=40)	(k=50)	(k=20)	(k=30)	(k=40)	(k=50)	(k=20)	(k=30)	(k=40)	(k=50)
Lambda	0.961***	0.965***	0.967***	0.968***	0.942***	0.951***	0.959***	0.964***	0.950***	0.956***	0.962***	0.966***
	(0.004)	(0.004)	(0.004)	(0.005)	(0.006)	(0.006)	(0.006)	(0.006)	(0.004)	(0.005)	(0.005)	(0.005)
Environmental funds	-0.016***	-0.019***	-0.021***	-0.023***	-0.006	-0.006	-0.006	-0.006	-0.001	-0.001	-0.001	-0.001
	(0.005)	(0.005)	(0.006)	(0.006)	(0.005)	(0.005)	(0.004)	(0.004)	(0.001)	(0.001)	(0.001)	(0.001)
Environmental spillovers	-0.040***	-0.060***	-0.073***	-0.072***	-0.017**	-0.015*	-0.012	-0.005	-0.004	-0.006	-0.007	-0.009*
	(0.012)	(0.015)	(0.017)	(0.018)	(0.007)	(0.008)	(0.009)	(0.010)	(0.003)	(0.004)	(0.005)	(0.004)
Temperature	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-0.001	-0.001	-0.001	-0.001
	(0.002)	(0.002)	(0.002)	(0.002)	(0.003)	(0.003)	(0.003)	(0.003)	(0.001)	(0.001)	(0.001)	(0.001)
Precipitation	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.002	-0.002	-0.002	-0.003*	-0.002
	(0.001)	(0.001)	(0.001)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.001)	(0.002)	(0.002)	(0.002)
Wind.speed	0.002	0.002	0.002	0.002	0.001	0.001	0.001	0.001	-0.001	-0.001	-0.001	-0.001
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.003)	(0.003)	(0.003)	(0.001)	(0.001)	(0.001)	(0.001)
Humidity	-0.003**	-0.002	0.000	0.001	-0.003	-0.003	-0.003	-0.003	-0.003***	-0.004***	-0.005***	-0.005***
	(0.001)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.001)	(0.001)	(0.001)	(0.001)
N	7,343	7,343	7,343	7,343	7,315	7,315	7,315	7,315	6,832	6,832	6,832	6,832
AIC	12,445.17	12,535.17	12,645.17	12,745.17	5,863.21	5,901.28	5,953.23	5,981.86	14,351.69	14,472.35	14,593.41	14,701.38
BIC	12,387.23	12,481.18	12,594.16	12,695.51	5,812.28	5,856.18	5,901.94	5,934.79	14,301.61	14,421.81	14,519.83	14,642.91

7.6. Policy Implications

This study highlights how the relationship between funds with a carbon abatement objective and the reduction of the concentration of PM2.5 levels is heterogeneous with respect to the local territorial capital.

In particular, Cluster 1 municipalities, including territories with a high economic capital, we observe both a direct and indirect effect of these funds. This means that the spending of low-carbon economy funds is associated with a reduction in the concentration of PM2.5 in the municipalities where these projects are implemented. Furthermore, this expenditure also contributes to a reduction of pollutants in neighbour municipalities.

The municipalities of Cluster 2 tend to experience a direct effect that is not statistically significant, while the spillovers are significant. We show how these indirect effects might be generated by close Cluster 1 administrative units. Finally, a null relationship between green funds and PM2.5 variation is obtained with regard to the municipalities of Cluster 3.

The results are robust to a number of alternative definitions of clusters and spatial matrices. Although this paper does not aim to explain the mechanism of this heterogeneity in the effect of funds with respect to the local territorial capital, the different levels of institutional capacity and efficiency of the Cluster 1 municipalities in implementing effective projects may be the main determinants of the observed significant reduction of pollution in these areas.

Our study has relevant implications for different economic actors (e.g., regulators at the national and international levels) since we highlight the main determinants of a successful implementation of projects fostering the sustainability transition in Italian municipalities. This analysis may thus support policy makers in a proper comprehension of the key factors contributing to decreasing PM2.5 levels and to designing a more cost-effective allocation of the EU Cohesion policy budget. Furthermore, a precise knowledge of the impact of green EU funds on pollution reduction may help international institutions to better understand how to coordinate and integrate alternative policy packages aiming to achieve carbon abatement and comply with EU targets (Stojcic, 2021; Van den Bergh et al., 2021; Greco et al., 2022).

Furthermore, our results may affect the discussion on the geographical concentration of EU funds that may need to be located in areas with specific characteristics in order to generate relevant spillovers. In particular, Crescenzi (2009) critiques the allocation criterion of Cohesion Policy funds, as an insufficient territorial concentration of the expenditure may explain weak spillovers effects across territories (Canova, 2004; Dall'Erba, 2005; Bradley, 2006).

Finally, our findings enrich the literature discussing the key local characteristics that may contribute to increasing the effectiveness of EU funds such as the quality of institutions and government processes (Crescenzi and Giua, 2016; Allain-Dupre, 2020). Furthermore, as less developed regions will be allocated the largest portion of EU Cohesion Policy funds also in the next programming period (2021-2027), our analysis might be informative for policy makers aiming to distribute the available budget across territories based on robust empirical evidence.

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Executive summary *(Report Coordinator: Stefano Galavotti)*

The last few decades have seen the emergence of new and unprecedented challenges for communities, cities, and territories. Globalization and the digital revolution have dramatically changed the traditional paradigms of production, labor, and consumption. Migrations from poor to rich countries and population ageing in the latter have radically modified the composition of the societies. Technological progress has produced a great abatement in transportation costs, allowing people and goods to easily move worldwide. At the same time, climate change has started producing its dramatic effects on the environment, making it urgent a complete rethinking of our way of producing, consuming and living. These changes have left profound and diversified effects on the socio-economic conditions of Italian territories, casting doubts on the growth prospects of many communities.

For territories and cities to be able to face these challenges, two concepts have become crucial: sustainability and resilience. Sustainability refers to the capacity of a system, be it a natural or a socio-economic system, to maintain its internal balance between depletion and regeneration of resources, Resilience refers to the capacity of a system to resist and recover when hit an external shock. Clearly, these two concepts are strictly related and somewhat complementary. A sustainable system is less likely to be hit by a shock, and, when this happens, the effects of the shock are typically less profound. On the other hand, a resilient system, by possessing the resources to recover from a shock, is more sustainable in the long run.

When it comes to the sustainability and resilience of cities and territories, accessibility and mobility are factors of paramount importance. Accessibility refers to the capacity of a city or territory to guarantee that users can easily and effectively reach their destinations: citizens accessing to services, students/workers reaching their workplace, tourists reaching amenities, firms moving goods, etc. While accessibility is strictly related to the presence and quality of the infrastructures, it also depends on the way in which mobility is planned and managed by administrators. By making a territory accessible, an effective mobility system can contribute to an equilibrated economic life, favor social aggregation, reduce inequalities, controlling emission: in few words, it is crucial for guaranteeing a sustainable growth. Also, the mobility system should be such that accessibility is constantly guaranteed, even in response to unexpected or abnormal shocks, like disruptions, strikes, demonstrations, meteorological events, i.e. it should be resilient.

Starting from the consideration that mobility and accessibility are fundamental leverages for making cities and territories more sustainable and resilient, this report collects some research outputs that, although different in their methods and approaches, provide instruments that may be useful to design *"green and digital innovative solutions, policies and strategies to improve the accessibility, resilience, sustainability and attractivity of territories and cities"*, which is one of the goals of the Work Package N.2 (*Infrastructures and smart & sustainable mobility*) of the Spoke N.7 (*Territorial sustainability*) of GRINS Project.

More specifically, the contributions collected in this report:

- improve our knowledge on the connections between mobility, accessibility, sustainability and resilience;
- develop indicators to measure accessibility of territories and resilience of mobility systems;
- suggest methodologies and techniques that can be used to measure and interpret accessibility;
- make policy recommendations for transport and urban planners.

The various contributions, which all contain an in-depth review of the literature, range from theoretical and methodological studies to empirical analyses and case studies. Altogether, they show how data integration and rigorous analysis are necessary to obtain a deep understanding of the complex elements that jointly determine the functioning of a mobility system. The insights from this report may inform practitioners and policy makers on how to monitor mobility systems, intervene when the system is hit by a shock, plan investments and policies to improve the accessibility, resilience, sustainability and attractiveness of territories and cities,

This report contains 7 chapters.

Chapter 1 defines the concept of resilience of a mobility system as "*the ability of a transport system to resist external shocks, maintain its functions, and return to full service as quickly as possible.*" Through an in-depth recognition of the literature, it discusses the components that jointly characterize the resilience of a mobility system, namely robustness, redundancy, resourcefulness, and rapidity, as well as the factors that influence them. Finally, it presents one case study, e-scooters rental in Turin, showing how redundancy and thereby resilience can be positively affected by the integration between the standard public transportation system and forms of sharing mobility.

Clearly, urban planning is fundamental to achieve a successful integration between public transportation and shared mobility. This is the content of the **Chapter 2** which, beyond discussing the recent literature on shared mobility and integration with public transportation, concentrates on one solution to achieve this goal: mobility hubs. A mobility hub is "*a publicly accessible physical infrastructure providing a physical location for users to switch between (at least) two shared transportation modes.*" Given the limited empirical evidence on mobility hubs in Italy, the authors outline a survey to collect information focusing on both shared mobility services and the characteristics of mobility hubs and users (the survey is currently being administered).

The next three chapters move to the notion of accessibility and tackle the question of how correctly measuring it, a prerequisite for any policy to improve it. **Chapter 3** builds indicators of accessibility in terms of travel times and applies them a grid of one-by-one kilometer cells for the Italian territory. This analysis allows to have a map of accessibility in Italy that is completely detached from administrative boundaries. The results show the complex interaction between *first-nature* and *second-nature* geography in shaping the accessibility of the various territories.

Chapter 4 shows how the concept of accessibility can be used to measure the vulnerability of a mobility system, namely the amount of performance degradation experienced during the shock.

Specifically, vulnerability is measured as the percentage variation of an indicator of accessibility before a certain event that hits the system occurs. As the authors show, this measure can be used to simulate the effects of various scenarios of disruptions, which may help administrators and urban planners to identify the most critical arteries and thereby target interventions.

Chapter 5, using as a case study the health services in Rome, combines network analysis with different measures of spatial accessibility to comprehensively assess disparities in accessibility. The methodology adopted shows how integration of different data sources is fundamental to have a reliable picture of the complexities of mobility systems and accessibility.

The last two chapters have a more methodological flavor. **Chapter 6** proposes an original method for estimating dynamic Origin-Destination matrices. This method is applied to the railway transportation network in Milan, and integrates data from ticket sales and Automated Passenger Counting (APC) systems. The interesting feature of the methodology proposed is that it is based on data that are potentially available in real time, so that it can be used by operators to immediately detect anomalies in the system and respond quickly.

Chapter 7 employs an original statistical method to assess the environmental sustainability of urban infrastructure in terms of PM_{10} emissions. The methodology uses the data produced by the monitoring stations and, through principal component analysis and interpolations, yields as an outcome the probability that a certain municipality exceeds the PM_{10} threshold, providing a detailed map of areas with the highest risk of air pollution.

1. A summary of the empirical transport resilience literature and a review of a case study *(A.S. Bergantino, A. Gardelli)*

1.1 Introduction

Transport resilience refers to the ability of transport networks (both at an infrastructure and a service level) to resist external disruption, maintaining functions as much as possible and return to a full level of service in a short time. This summary, based on the paper published in Transport Reviews (Bergantino et al., 2024), reviews the relevant empirical literature on transport resilience, categorizing the various factors influencing resilience and identifying the spatial patterns commonly found across case studies. These factors and patterns are contextualized within a typical resilience assessment framework to provide insights for improvement and suggest future research directions for transport scholars. Although several reviews on transport resilience have been published in recent years, limited work has focused on classifying empirical findings or, more broadly, on understanding the role of real-world data in resilience assessments. The main innovation of this study lies in its review of the use of empirical data in transport resilience assessment, its classification of analytical results, and the insights and recommendations derived from this analysis. Under the GRINS topic, the review addresses the need for supporting resilience assessment metrics, particularly focusing on transport networks and their impact on the resilience of territories. To achieve this, the paper collects a set of 127 relevant transport resilience studies, subsetting it down to the 53 that utilize real-world data for analysis. The empirical findings are classified within the 4R framework supporting the resilience triangle (Bruneau et al., 2003; Tierney & Bruneau, 2007), which is the most widely adopted framework in the literature. The paper's key objective, based on this contextualization, is to test this standard framework over several case studies, offering insights for its improvement, and highlight topics worth of further investigation.

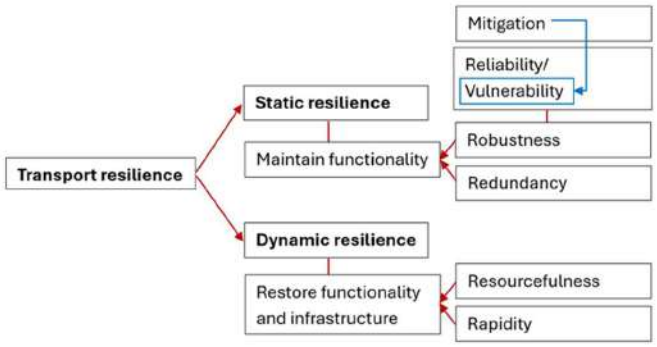
1.2 Outline of literature background

1.2.1 Methodology of the review

As anticipated, several review papers have explored the conceptualization of transport resilience, elaborating on its related attributes and the interconnections between them. The literature also overviews in detail assessment metrics. Below, a brief summary of the key insights on both the concepts and the metrics is presented. Transport resilience refers to the ability of a transport system to resist external shocks, maintain its functions, and return to full service as quickly as possible. At the moment of disruption, the concepts of robustness and redundancy are used to describe the extent to which service is maintained (robustness) and the availability of alternative

options to offset the disutility of the performance loss (redundancy). Once the disruption is over, the concepts of rapidity and resourcefulness define how quickly, and by what means (in terms of resources deployed), the system's performance returns to its normal operating state.
These four main attributes—robustness, redundancy, resourcefulness, and rapidity—are the 4 "R"s that form the 4R framework (Bruneau et al., 2003). They define resilience in different stages: static resilience, measured by robustness and redundancy during the disruption, and dynamic resilience, measured by resourcefulness and rapidity during recovery (see Figure 1.1). Several other concepts complement this framework. Vulnerability, the opposite of robustness, defines the amount of performance degradation experienced during the shock. Reliability measures the likelihood of successful functionality under various operational conditions. Mitigation strategies, aimed at strengthening critical infrastructure, focus on enhancing robustness and reducing the risk of performance degradation during future disruptions.

Figure 1.1. Resilience concepts interconnections based on Bergantino et al. (2024)



Regarding assessment metrics, there are generally two types: topological and performance based. Topological metrics assess resilience by examining the static structure of the network (nodes and edges), focusing on changes in network topology (i.e., the connections between nodes). Performance based metrics, on the other hand, include the dynamic aspects of the network, such as flows, speed, and time, providing a quantitative assessment of resilience by measuring lost performance rather than focusing exclusively on changes in connectivity.
A literature keyword search was conducted to identify the most relevant studies on transport resilience. From an initial general search on Scopus, combined with additional papers identified through snowballing, 127 studies were retrieved. After reviewing the abstracts, 53 papers that utilize real-world data were selected for further analysis. Of these, 38 papers use flow data, 30 use on travel time, 7 coordinate tracking, 5 transport costs and 2 use accident data. 17 papers study road networks, 11 railways, 10 metro services, 10 bicycles, 6 airways, 5 bus services, 5 multimodal networks, 2 walking and 1 waterway. These 53 papers were thoroughly reviewed and qualitatively assessed to summarize their main findings and methodologies.

1.2.2 Main insights

Several spatial patterns and influential factors of transport resilience are found across the set of reviewed papers. As regards the spatial patterns:

1. Central areas vs peripheral areas: central areas are vulnerable to disruptions due to dense passenger flows and infrastructure, but they often recover more quickly thanks to higher redundancy and prioritization in recovery. Conversely, peripheral areas tend to be less vulnerable due to lighter flows but lack of redundancy (few transport options)
2. High vs low accessibility: areas with lower accessibility are generally less vulnerable to disruptions due to lighter gravity, but tend to lack of redundancy, with few alternatives and main corridors that, If disconnected, heavily impacts performance.
3. Distance decay from alternative modes: when connecting alternative modes within a buffer, users disutility from disruption is partially offset. For example, when bike sharing services are located inside a 1km buffer from public transport stops, system resilience is increased.
4. Location of the hazard: When natural hazards like hurricanes hit, regions close to the coastline tend to be more impacted. However, there are countertrend, like local changes in demand and disruption spillovers.

As regards influential factors:

1. Redundancy: as expected, redundancy, both infrastructural and between modes, is associated with higher level of resilience. Infrastructural redundancy refers to the density of infrastructure and consequently all the different paths that can be taken to reach a destination. Between-modes redundancy refers to the quantity of different transport options to be taken by individuals.
2. Provision of real-time information: Effective communication from transport practitioners regarding real-time conditions is associated with higher level of resilience, allowing users to change behavior and find alternative solutions.
3. Institutional plans and management: Pre-, during and post-disruptions institutional actions help the transport system overcome the shock more smoothly. In particular, critical infrastructure identification, mitigation strategies and post-emergencies plans are found to be positive across case-studies.
4. Climate change and intensity of disruption: As expected, the stronger the disruption impact, the worse the drop in performance. As climate change is expected to exacerbate the impact of hazards, severity of disruptions effects are expected to rise.
5. Strengthening of the infrastructure: Improvements on the physical robustness of the infrastructure and on its connectivity (also in terms of integration and compatibility between types of infrastructure) mitigates performance degradation and increases redundancy.
6. Congestion: systematic congestions, also in terms of pre-existing bottlenecks, further strengthens the negative effects of disruptions.
7. Increase in socio-economic indicators: Increase in socio-economic indicators, like GDP growth, does not always automatically associate with increase in transport resilience. Side effects like increased pressure from urbanization can lead to offsets to transport resilience.

The papers found that both spatial pattern and influential factors fit into the 4R framework, meaning that all items identified have some type of effect on the 4 resilience attributes. It is worth noting that some have negative effects (e.g., congestion on rapidity), some have positive ones (e.g. central area on redundancy) and some have effects on more than one attribute (e.g. strengthening of infrastructure on robustness and redundancy). Because of this, multiple attribute resilience metrics should be preferred to single attribute ones. Table 1.1 below categorizes the effects of the identified items on the attributes of the 4R framework.

Table 1.1. Summary of positive and negative effects of the identified empirical factors

	Positive Effect	**Negative Effect**
Robustness	• Institutional plans and management • Strengthening of infrastructure	• Central area • High accessibility • Location of the hazard • Climate change and intensity of disruption • Congestion
Redundancy	• Central area • High accessibility • Distance decay from alternative modes • Institutional plans and management • Strengthening of infrastructure	
Resourcefulness	• Central area • Institutional plans and management	
Rapidity	• Central area • Institutional plans and management • Provision of real-time information	• Congestion

It is also possible to see from the table above that, if practitioners are interested in a specific attribute of resilience, they can leverage on specific factors. For example, policymakers willing to increase rapidity of recovery may consider tackling systematic congestion while making real-time information available during shocks.

1.2.3 Research gaps

Despite fitting the results into the 4R framework, we identified some issues related to its graphical representation. The first concern regards the definition of the pre-disruption level, which is difficult to ideally identify. In some cases, the pre-disruption reference value is set as the last observation before the shock, which might not be ideal as it could be affected by random operational fluctuations and may not represent the true 100% operational level. The same issue applies to the recovery target, that is often set as the pre-disruption level. Further investigation into these

methodological challenges is of utmost importance to improve the framework's real-world applicability. Long-term historical data, for example, could help setting a more ideal standard reference level for pre-disruption performance.

Furthermore, 4 relevant research strands have been identified to be further investigated. Specifically:

- How can disruptive events be categorized for empirical analysis?
- How do different types of disruptions impact various transport modes?
- Is there an association between long-term economic growth and growth in transport resilience?
- Multimodal networks remain underexplored, causing gaps in our understanding of resilience and disruption impacts within networks of networks.

We believe that the research on these underexplored topics will increase our knowledge on transport resilience while helping the adoption of resilience frameworks of assessment based on real data collection.

1.3 Case study: the contribution of e-scooter services to the resilience of urban transport [21]

1.3.1 Framework

The aim of this case study is to understand to what extent a greater supply of transport alternatives favors individuals during a disruption in an urban setting. A key concept central to this work is redundancy. Redundancy is the ability of a transport network to offer several alternatives that can support each other in the event of an external shock (Bergantino et al., 2024). How is the complementarity/substitution between modes evolving during such events? To answer this question, we take advantage of the natural experiment context of 7 local public transport (PT) strikes in Turin, Italy, between October 2021 and October 2022. During this time span, we observe the hourly number of e-scooters' rents and the length of the rents' trips. We aim to address two research questions:

1. Does e-scooter sharing offer redundancy to PT when the latter is disrupted?
2. Does a spatial pattern of proximity to disruption exist?

1.3.2 Data

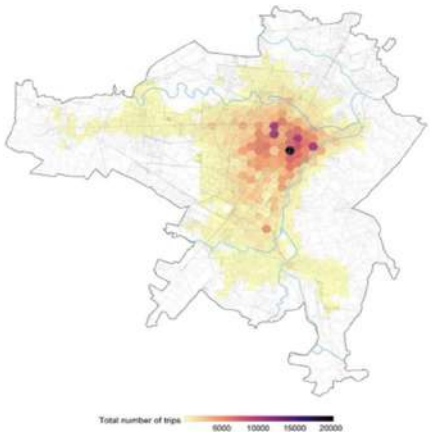
For this analysis, three main datasets[22] have been used. The following subsections will briefly discuss the three datasets.

[21] This chapter summarizes the content of the article: Bergantino, A. S., & Gardelli, A. (2024). The contribution of e-scooters services to urban transport resilience. Journal of Transport Geography, 118, 103869.

[22] Authors did not have the permission to share data openly but eventually and upon requests in an aggregate form.

Data of individual e-scooters Origin-Destination (OD) tracks aggregated at different levels, is used in the analysis. Figure 1.2 displays the concentration of starting trips inside a 500m × 500m grid.

Figure 1.2. Density of started trips on a 500m × 500m grid



In the same year window, 7 strike events are identified and double-checked both with the National Strike Authority and the local public transport operator, which provided us with the average participation of drivers to the strike (data available form the Authority).
Transit stop data is downloaded to investigate the spatial patterns. Relevant literature on the topic finds a distance decay pattern on the effect starting from the disruption site. Translated and applied to our case study, that would suggest that the closer the start of the trip is to a transit stop (disruption site), the stronger the effect of the disruption (strike) in terms of e-scooters trips counts and length increase.

1.3.3 Methodology

To answer the first research question, we observe the number of e-scooter trips and their lengths during a strike day, comparing them to a baseline scenario through econometric modeling. As regards the second research question, we include in the modeling an interaction term of proximity to transit stops to analyze if the strike effect on the e-scooter trips is larger in the vicinity of the disruption sites, i.e., the transit stops. Combining the two aspects, to study the effect the following negative binomial regression model is proposed:

$$E[trips_{it}] = exp(\beta_0 + \beta_1 \times strike_t + \beta_2 \times strike_t \times prox_{it} + \gamma \times X_{it})$$

where:

- $trips_{it}$ the hourly count of e-scooter trips for neighbourhood i,
- $strike_t$ is a dummy variable for the strike event at hour t,
- $prox_{it}$ is a dummy variable that controls proximity of transit stops via buffers,
- X_{it} is a vector of control variables, including weather, special events and fixed effects,
- γ is a vector of coefficients for the control variables.

As regards the length of trips, the following OLS model is proposed to study the effect of strike, interacted with proximity to transit stops:

$$triplength_{it} = \beta_0 + \beta_1 \times strike_t + \beta_2 \times strike_t \times prox_{it} + \gamma \times X_{it} + \varepsilon_{it}$$

1.3.4 Results

The results of the modeling show that there is a redundancy effect of e-scooters to PT, which is stronger when reaching proximity to the transit stops. During a strike event, on average the e-scooter trips are 89% more than during a regular day within a 50m buffer to transit stops, ceteris paribus. The average length of an e-scooter trip confirms a possible substitution pattern, considering that, during a strike day, the average length is around 9 transit stops. The analysis found temporal heterogeneity, as the effect is stronger closer to the weekends, while it is totally inhibited in the hour window 9am-12am. In terms of complementarity/substitutability, the redundancy effect is likely to be in between the two concepts. On the one hand, there is a substitution effect, as part of the undone PT rides is absorbed by the e-scooter rents. On the other hand, it may also be seen as a support to PT (and ideally a complement to it) when the latter is not able to perform to its operative regime. As regards the spatial pattern of proximity, which is in line with the relevant micromobility literature, such phenomenon may be explained through the so-called "announcement effect" (Adler & van Ommeren, 2016), which found that the effect of the strike is influential only when the strike is actually in place, while no effect is observed when the strike is announced but canceled. According to this evidence, it may be that the individuals are not aware of the strike, and part of them decide to look for the closest e-scooter while being at the transit stop. The analysis found a temporal heterogeneity as well. We hypothesize that the reason why the effect is stronger on the weekend and inhibited in the mornings might be because of the user class. Several evidence reports that the typical user class is young males, which use more the e-scooter on weekend days for recreational purposes while use them less during school hours.

To summarize, during disruption events, e-scooters support the PT by absorbing part of the undone transit trips, offering a viable alternative to perform them. The effect is spatially and temporally heterogeneous, being stronger reaching proximity to the transit stops (spatially), being stronger closer to the weekends and weaker in the week morning (temporal). The temporal heterogeneity, being possibly explained by the typical user class - young males - might mean heterogeneity in the redundancy effect as well. The analysis highlights the existence value of e-scooters, that only by being present offers an alternative mode to at least a part of the individuals. However, the benefit, and so this piece of resilience, is class-specific. For this reason, we recommend it to be only a piece in a bigger puzzle of policies to make urban transport network more resilient to all.

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2. Integrated Public and Shared Mobility in the City: A Review and Pathway towards the Evaluation of Mobility Hubs *(F. Carlet, A. Gardelli, R. Patuelli, A.S. Bergantino, M. Intini)*

2.1 Introduction

Sustainable and smart mobility is one of the eight thematic focuses of the European Commission that strives to achieve a climate-neutral society by 2050 (Ryghaug et al. 2023). Great attention is given, by researchers and practitioners alike, to new approaches aimed at diminishing the environmental and social impacts of motor vehicles in urban centers.

One of the most promising perspectives in this regard is the use of public transport systems in combination with shared mobility options to achieve a reduction of traffic congestion and pollution (Machado et al. 2018). Shared mobility plays an important role in reducing urban traffic congestion and travel commuting time, which in turn improves travelers' happiness and job effectiveness (Zhang and Kamargianni 2023). According to Winkler et al. 2023, modal shift policies promoting the use of public transport and micromobility modes have the potential to positively impact the urban space. In general, multimodal transportation schemes combining public transport and shared mobility options enhance connectivity and redundance, and reduce the burdens associated with heavy car use. Shared mobility hubs allow users to switch more easily between different modes of transport (public and shared), therefore decreasing the comparative attractiveness of private cars. In combination with other policy measures (e.g., vehicle electrification, congestion charges), widespread use of shared mobility modes can reduce the transportation sector emissions, thus helping with decarbonization and climate change targets (Fan and Harper 2022). A growing number of studies explore the role that urban transportation needs and socio-economic factors might play in creating mobility options appealing to the community of potential users (Ho and Tirachini 2024).

To harness the full potential of multimodal transportation systems, it is paramount to identify and study the factors affecting the users' decision to take part in shared mobility or to integrate it in their daily transport choices, as well as their preference of shared mobility device, and the role of mobility hubs in urban transportation schemes. This paper provides an overview of the literature on shared mobility, with its diverse modalities and shared mobility hubs in urban centers, as an alternative to individual transportation. Bringing forth an understanding of how this topic has been studied so far and a comprehensive synthesis of existing relevant studies, including user characteristics and indicators, our research takes a step further by leveraging these findings to design a research project aimed at examining transportation patterns and user preferences for shared mobility hubs. By building on previous research, we seek to explore the dynamic interplay between shared mobility services and the infrastructure of mobility hubs, focusing on how users

interact with these systems. This approach allows us to address gaps in current understanding and develop data-driven insights that can inform the future development of efficient, user-centered transportation networks.

2.2 Methodology

A comprehensive literature review was undertaken in academic and scientific databases, such as Web of Science, EBSCO Discovery Service (EDS), Scopus, Google Scholar, etc. including the most relevant published articles in the literature over the last two decades. We searched for relevant keywords, and then used forward and backward snowballing. The review aims to answer the following questions: what factors and aspects of shared mobility and mobility hubs have been analyzed so far? At which conditions are public transport and micromobility complementary? And when are they substitutes instead? What recommendations can be given for future research, and what are the future development trends?
It is important to point out that only scientific and grey literature in the English language was reviewed in this paper. Additionally, the section assessing hub-related literature only includes studies and reports on mobility hubs that comprise at least one shared mobility mode.

2.3 Outline of literature background

2.3.1 Shared mobility and integration with public transportation

Scholars argue that integrating public transit and micro mobility has become a critical matter which could support smart transportation and sustainable urbanization in many cities (Jin et al. 2022). Several studies present a conceptual analysis and review of policies and incentives in place to promote the integration of micromobility and public transport (Grosshuesch 2020; Kager, Bertolini, and Te Brömmelstroet 2016; Sagaris, Tiznado-Aitken, and Steiniger 2017). Public transit options combined with the accessibility of shared transportation is a promising solution for the first and last mile connection problem, making modal shifts more likely and contributing to the creation of more livable cities and equitable transportation schemes (Beale, Kapatsila, and Grisé 2023; Oeschger, Carroll, and Caulfield 2020). In this context, shared mobility can be studied as a complement to public transport (van Kuijk et al. 2022; Wu et al. 2022). Well planned multimodal transportation systems can provide efficient and comfortable transportation options that can compete with private motorized vehicles (Kager, Bertolini, and Te Brömmelstroet 2016). The relationship between public transport and shared mobility ridership is found to be dependent on the level of integration between the different modes of transportation (Oeschger, Carroll, and Caulfield 2020; Oeschger, Caulfield, and Carroll 2023). A higher level of integration, for example when shared mobility hubs and public transport stations are located close to each other, is found to promote ridership (Oeschger, Carroll, and Caulfield 2020; Oeschger, Caulfield, and Carroll 2023; Böcker et al. 2020). A study in New York City found that bike-sharing stations along a bus route were used more often than those unlinked to a bus route (Campbell and Brakewood 2017). Pricing

schemes and payment mechanisms are considered relevant to bolster use of multimodal transportation modes. Uniform ticketing systems, as well as integrated mobile phone apps, might improve integration by making transfers more efficient and improving user-friendliness (Böcker et al. 2020; Oeschger, Carroll, and Caulfield 2020; S. Shaheen and Chan 2016; Oeschger, Caulfield, and Carroll 2023; S.C. Shaheen, Nelson 2016).

Ma et al. 2019 found that the use of public transportation and shared e-bikes ridership are positively correlated. Free floating bicycle-sharing often integrates with and complements public transportation options (Wu et al. 2022). Modal integration between public transport and bike sharing is often associated with short trip duration and higher public transit service frequency (Kong, Jin, and Sui 2020). Yan et al. 2020 highlights the importance of land use and population density around public transport stations for the adoption of bicycle-sharing. The availability of a safe and convenient infrastructure for micromobility around public transport stations, as well as a safe environment to access the public transport stops, are some of the most relevant factors in determining the propensity of commuters to use micromobility options (Oeschger, Carroll, and Caulfield 2020). Dockless scooters are often used to connect to and from public transport modes (Aarhaug, Fearnley, and Johnsson 2023; Chicco and Diana 2022), increasing accessibility, with greater increments in the first mile than the last mile (Liu and Miller 2022). The presence of facilities and amenities such as bars, shops and restaurants are associated with e-scooter trip density, suggesting that the use of e-scooters happens for leisure trips (Chicco and Diana 2022; Christoforou, Psarrou Kalakoni, and Farhi 2023).

Shared mobility devices are also used in lieu of public transportation when the latter is not a practical option, thus often complementing public transport, and competing in other areas (Schwinger, Tanriverdi, and Jarke 2022; Ziedan et al. 2021). Aarhaug, Fearnley, and Johnsson 2023, found that for many e-scooter trips, using public transport alternatives would take at least twice as much time. A study by Moinse and L'Hostis 2024 revealed that in France, for example, users of micromobility devices are willing to travel 2 km or 10 more minutes during access or egress to avoid transfers on public transport. Shared e-scooters sometimes replace walking, cars, and public transport (Glavić et al. 2023). Studies based on survey data found that people use shared e-scooters in place of cars at significant rates, suggesting that in some locations, shared e-scooters could be an effective approach to decreasing reliance on cars (Wang et al. 2023). Shared e-mopeds proved to also be a practical option as individual modes for long-distance trips (van Kuijk et al. 2022).

2.3.2 Factors affecting choice and use of multimodal transport and shared modes

Several studies characterized users of shared mobility based on their socio-demographics, characteristics, common travel patterns and attitude towards sustainability and the environment. Preference for using integrated shared micromobility and public transport systems is correlated to young age, high educational attainment, high scooter ownership and low car ownership (Ghasri et al. 2024; Chi, Han, and Lee 2023). In general, age, gender, previous experience with

micromobility, weekday or weekend travel, and interest in micromobility are found to be significant factors that influence mode choice (Oeschger, Carroll, and Caulfield 2020; Oeschger, Caulfield, and Carroll 2023; van Kuijk et al. 2022; Montes et al. 2023). Users of shared mobility are usually concerned about environmental issues and care about sustainable transportation and the environment (Chi, Han, and Lee 2023).

Micro-mobility mode choice is greatly affected by distance, weather conditions, air quality, accessibility, elevation rise, and time of day (Reck, Martin, and Axhausen 2022; Hu et al. 2022). Trip distance, for example, is found to be significantly associated with users' mode options, indicating that bike-sharing schemes usually serves short distance transfer users, normally trips between 1 and 5 km (Bergantino, Intini, and Tangari 2021), while ride sourcing mainly serves long-distance transfer users (Bi, Ye, and Zhang 2021). The availability of transit facilities, parking lots, and the proximity to bus or metro stations had a substantial positive impact on the demand for free-floating bike-sharing (Hu et al. 2022). Docked bikes tend to be used mostly for short trips connecting to and from major public transit transfer stations (Lazarus et al. 2020). Thus, integrating bike sharing hubs with public transport station could increase the number of multimodal trips (Reck et al. 2021). E-scooters are found to be mostly used near universities, and in central business districts (Reck, Martin, and Axhausen 2022). The presence of facilities and amenities such as bars, shops and restaurants are associated with e-scooter trip density, suggesting that the use of e-scooters happens for leisure trips (Chicco and Diana 2022; Christoforou, Psarrou Kalakoni, and Farhi 2023).

Travel cost affects choice of transportation mode. Strategies such as membership plans and discounts may contribute to attracting car users to switch to multimodal transportation including shared modes and public transportation (Luo et al. 2023).

Mobility options of a mobility hub can be integrated into a MaaS service (Athanasopoulou et al. 2022). MaaS can facilitate trips by suggesting the most efficient combination of transportation modes to reach a destination, and by allowing users to make reservations or pay for different transportation modes all in one place (Hachette and L'Hostis 2024).

2.3.3 Definition and characteristics of shared mobility hubs

The concept of "mobility hub "started to emerge in the early 2000s, but has gained popularity in the last two decades, with a constantly increasing volume of literature worldwide on the topic (Hachette and L'Hostis 2024; Roukouni et al. 2023). Mobility hubs allow users to switch between different modes of transport (public and shared), therefore potentially leading to mode substitution or integration with public transport, disincentivizing the use of private transportation (Aydin, Seker, and Özkan 2022; Luo et al. 2023). A study on a pilot mobility hub in the city of Munich, for example, revealed that users of shared mobility services joined and/or used other mobility services more often because of the mobility hub (Miramontes et al. 2017). Several different definitions and characterizations of mobility hubs exist in the literature, based on different frameworks and variables, such as location, and the service they provide (Geurs et al. 2024; Hached, L'Hostis, and Gragera 2023). Most definitions focus on the mobility and transfer

components of hubs and include the presence of multiple modes and transfer between modes as requirements for mobility hubs. Researchers agree that a shared mobility hub can generally be described as a publicly accessible physical infrastructure providing a physical location for users to switch between (at least) two shared transportation modes (Geurs et al. 2024; Hached, L'Hostis, and Gragera 2023). A common element in the definitions of (shared) mobility hubs is the presence of shared mobility services such as shared bikes, scooters or cars (Miramontes et al. 2017; Shaheen et al. 2020).

Because the concept of shared mobility hubs is still relatively new and emerging, there is no consensus among researchers regarding the appropriate way of defining mobility hub typologies. Hubs classification can be based on different parameters, such as spatial scale (influence radius), size, target users, urban location, transportation function (entry, transfer, destination), and role in the transportation network (Roukouni et al. 2023). Regarding the urban context, for example, shared mobility hubs can be classified as follows: City Centre, Urban Transit Nodes, Emerging Urban Growth Centers, Historic Town Centers, Suburban Transit Nodes and Key Destinations (Aono 2019; Roukouni et al. 2023).

Availability of different shared vehicle types adds value to the shared hub by appealing to different groups of transport users and population segments (Bösehans et al. 2023). On site access or proximity to public transport is considered as an essential characteristic of a shared mobility hub (Miramontes et al. 2017).

Other features of shared mobility hubs as mentioned in the literature are the availability of amenities, such as shelters, wayfinding, lockers, activity centers, digital pillars with information and ticketing, and proximity to retail and service destinations (Geurs et al. 2024). Amenities, a sense of space and services provided can incentivize public and shared transport usage and affect the waiting and ticketing experience, as well as the users' perception of safety (Arnold et al. 2023). Together with transit stops and micromobility parking, ride hailing pickup and drop-off zones may also be present (Anderson et al. 2017; Shaheen and Cohen 2020).

2.3.4 Existing studies and data on shared mobility hubs and shared mobility hubs users

The concept of shared mobility hubs has recently risen to popularity among practitioners, policy makers, and researchers alike, driven by the spread of shared transport in all cities in Europe. Consequently, international scholarly literature on shared mobility hubs has been growing exponentially over the last decade (Roukouni et al. 2023). Several studies researched suitable locations for mobility hubs and best ways to determine such locations (e.g., Aquilué Junyent et al. 2024; Xanthopoulos et al. 2024; Aydin, Seker, and Özkan 2022), while others focused on the characteristics of mobility hubs users (Bösehans et al. 2023), and their needs (Tran and Draeger 2021).

An increasing number of EU-funded projects, such as SmartHubs (EIT) and SmartHubs (ERANET-JPI Urban Europe) focused on this topic. The latter project's team, for example, conducted living labs in Brussels, Munich, Rotterdam, Vienna and The Hague from 2021 to 2024 to investigate

various dimensions of mobility hubs and formulate policy recommendations. The study involved a large-scale survey and choice experiment collecting information about user's profiles, usage patterns, and preferences for attributes of the hubs.

Research on shared mobility has also been conducted at the Italian level, with several studies focusing on various aspects of this evolving transportation model. These studies have explored topics such as user attitude towards shared mobility in general, and perception of shared scooters (Campisi et al. 2024), the impact of shared mobility services on urban sustainability, and the integration of shared mobility into urban transportation systems (Candiani et al. 2024). However, most of this research has been limited in scope, often focusing on specific cities or services. Several research studies on shared mobility and mobility hubs carried out in Italian cities investigated shared mobility ridership and coverage using a spatial approach (e.g. Chicco and Diana 2022; Giuffrida et al. 2021). Yet, existing studies have not yet fully examined the broader dynamics of shared mobility in combination with mobility hubs and user characteristics on a national scale, particularly using both revealed preference (RP) and stated preference (SP) data, leaving room for further exploration and deeper insights. While individual aspects of shared mobility and mobility hubs have been explored, a gap remains in the understanding of how these factors interact across diverse user groups and geographic regions. Integrating RP and SP data would provide a more comprehensive picture of actual behavior and potential future choices, offering insights that are critical for formulating effective transportation policies and infrastructure planning at the national level.

2.4 Findings and discussion

Our research highlights that, while shared mobility and mobility hubs have been widely studied at the international level, there is a significant gap in the Italian context. To date, no study in Italy has focused specifically on the intersection of shared mobility, mobility hubs, and user characteristics at the national level. International research has explored the role of these services in urban mobility systems, but a comprehensive analysis that integrates these elements and examines how they apply to the Italian landscape is missing.

Based on the literature review on shared mobility, the research teams of the universities of Bologna and Bari are currently developing a detailed survey focusing on both shared mobility services and the characteristics of mobility hubs and users. This survey, combining both RP and SP data, aims to explore user preferences, behaviors, and perceptions of shared mobility options, as well as the design, accessibility, and functionality of mobility hubs. It will be distributed across nine major Italian cities, enabling us to capture regional differences and gather insights on how these factors influence the adoption and effectiveness of shared mobility solutions. The results will contribute to a deeper understanding of how mobility hubs can enhance shared mobility systems in urban settings.

The first part of the questionnaire asks about demographic and socioeconomic details, questions regarding mobility and travel habits, and on the quality of the transportation services used. The RP part of the survey includes questions regarding both the interviewees' actual commute trip,

and their second-best commute mode choice. The data to be collected is aimed at reconstructing the users' profile, and will provide information regarding mobility patterns (e.g., change at station, transfer time, type of intramodality used) allowing to study transport behavior, mode preferences and mode substitutability. The second part of the questionnaire includes questions on SP, and scenarios developed with hypothetical mobility hub options. Inputs from the RP section will be used to customize the stated choice experiments. This part will elicit preferences for different mobility hub alternatives declared by users in a hypothetical context, uncovering information about the mobility hubs characteristics that are relevant to travelers, such as preferred amenities and means of transportation offered.

The proposed research is innovative in that it addresses a gap in the existing body of knowledge by focusing on shared mobility and mobility hubs across major cities in Italy. While previous studies have explored aspects of shared mobility on a regional or city-specific level, there has not yet been a comprehensive study conducted at the national scale in Italy. This research is unique in its scope, as it seeks to capture data from nine major cities, providing a broader understanding of the dynamics, challenges, and opportunities associated with shared mobility and mobility hubs throughout the country. This national-level approach will offer valuable insights that can inform both local and national transportation policies.

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3. Indicators of accessibility and travel times *(V. Licio, A.M. Pinna)*

3.1 Introduction

Over the last decade, both economic and transportation literature have shown a growing interest in the ease with which people can reach desired destinations, and the time they spend in reaching these locations.

Accessibility is typically quantified through a variety of indices that reflect the proximity of goods, services, and employment opportunities to individuals or firms. It encompasses different meanings, depending on whether the focus is on access to public services, employment, recreational and cultural activities, public transport, transport infrastructure, high-speed services, or information and communication technologies. Accessibility is closely tied to concepts like proximity (referring to reduced distance, where distance measurement goes beyond basic geometry), mobility (the ability to move using transportation systems), and connectivity (the links within a network).

Travel times are the other side of the coin. They are a proxy of transport costs and an important feature of market potential (Matas et al., 2018), reflecting time costs and the flows of people, goods, and information. Since the eighteenth century, technological advancements have led to reduced costs and faster speeds, resulting in greater volumes and more intricate patterns of flows. These developments have significantly influenced urban mobility patterns, the spatial distribution of activities, and location choices.

The discussion of accessibility and travel times is not always straightforward, as both concepts encompass a wide range of dimensions and intersect with various fields. In this research, we try to keep things as simple as possible, focusing on selected measures of accessibility and travel times. Without the use of engines, traveling across a territory is purely a matter of topography, what in the economic literature is called *first-nature* geography. In this sense, walking travel times offer a representation of the physical landscape. The endowment and quality of transport infrastructure, instead, provide a different perspective on travel times, also reflecting the *second-nature* geography of an area. This distinction implies that when we focus on a specific form of mobility, such as motorized travel times, we exclude other factors related to the movement of people and goods, such as delays, waiting times for public transportation, and intermodal mobility.

We aim to provide a clear overview of both travel times and accessibility in Italy at different territorial units, taking advantage of the availability of newly detailed data. We also aim to understand whether this granular information offers a more accurate representation compared to data aggregated at administrative levels.

Adopting a grid cell perspective introduces a novel approach to country-level analyses. Typically, accessibility and travel time assessments are conducted using smaller administrative divisions, such as municipalities (LAU) or NUTS 3 regions, and are shaped by governance frameworks.

However, important details can be obscured by the aggregation required at these levels, potentially leading to biased results. A grid cell approach allows for capturing significant internal variability within municipalities, often overlooked by more aggregated data, and provides more balanced findings that account for both geographical and human-driven factors.

In recent years, advancements in geospatial techniques and models, the use of geocoded data on transportation infrastructure, and the availability of satellite data on topographical, geographical, and demographic features have significantly elevated the importance of travel times and costs, as well as market access, in the assessment of socio-economic development and in improving access to public and private services. In this research, we compute and investigate travel times and accessibility for Italy using different indicators. We want to take advantage of this very granular decomposition of the Italian territory, completely detached from administrative boundaries, measuring travel times *within* grid cells of one-by-one kilometer, and computing accessibility to cities and ports at the same territorial level. We examine these measures relating them to geography, main transport infrastructure endowment, and urbanization. We also expand our view and analyze the same indicators for the Italian municipalities (LAU) and for NUTS 3 regions, providing a perspective more linked to institutional considerations.

The results show a large variability across Italy. Favorable geography is a key factor in determining lower travel times and higher accessibility. However, our findings suggest that *second-nature* geography plays a crucial role in traveling using the motorized transport infrastructure and, in turn, in accessing cities and ports. Although more disadvantaged topography in some areas of northern Italy, accessibility and time costs are not as negatively impacted. This contrasts with the South and the Islands, where more favorable geography, like the proximity to the sea, is not supported by an adequate infrastructure, resulting in less efficient access.

3.2 Outline of literature background

Although interest in accessibility and travel times has gained renewed emphasis in recent years, particularly in economic literature, the importance of measuring and accounting for ease of access to various locations within reduced travel times is a well-established concept in transportation and land-use planning literature. Early studies, such as those by Harris (1954) and Hansen (1959), demonstrate that areas with good accessibility are more likely to be developed and at higher densities compared to remote locations, making the latter less attractive. The freedom of individuals to choose whether to engage in different activities (Burns, 1979), facilitated by a specific transport system (Dalvi and Martin, 1976), and the advantages offered by integrated transportation and land-use systems (Ben-Akiva and Lerman, 1979), are just a few of perspectives used to analyze accessibility. Other research concentrated specifically on the measurement of accessibility itself. Geurs and van Wee (2004) offer a comprehensive review of accessibility measures, according to various factors and components. Ingram (1971) uses the concept of relative accessibility, i.e. the extent to which two locations or points on the same surface are connected. Similarly, indexes based on the number of opportunities that can be accessed within

a specified travel time, distance, or cost— along with the time or cost required to reach a fixed number of opportunities— have been developed starting from Wickstrom (1971) and Wachs and Kumagai (1973). Since then, a large number of studies have contributed to the understanding and analysis of a topic that is both complex and ever-relevant.

Research belonging to the urban economic literature focused mainly on accessibility and travel times at the regional level, examining how and whether transportation systems optimize resources and achieve intended goals, such as improving mobility, reducing travel time, and enhancing connectivity.

Analyses at the subregional level were not so common until recent times. In 2008, the Joint Research Center released the first global map of travel times to major cities. The accessibility map, along with corresponding raster data at a resolution of 30 arc-seconds, was developed by Nelson (2008) in collaboration with the World Bank's Development Research Group. Travel times to cities with a population of at least 50,000 inhabitants, referring to 2000, were quantified considering geographical frictions, national borders, and the type and quality of transport infrastructure. This pioneering work was later followed by an updated map and data by Weiss et al. (2018), who computed travel times to cities for 2015 at a spatial resolution of approximately one-by-one kilometer. In 2020, Weiss and coauthors produced a global map of travel times to healthcare facilities. The map is combined with walking-only and motorized friction surfaces that compute and provide the geographical barriers and infrastructural facilities that make the movement within the grid cell easier or costlier. Similar to these works, the contribution by Christodoulou et al. (2020) accounted for urban accessibility and congestion, constructing a dataset for European cities with populations of at least 250,000 people. Their findings indicate that congestion is negatively correlated with access to cities, and that accessibility serves as a good proxy for congestion and traffic.

Research on commuting has long attracted the interest of scholars from various fields. In economics, the primary goal is to save costs. For policymakers, understanding how individuals react to increased travel times and costs or switch to other transport modes due to congestion is fundamental for adopting the correct strategies to avoid costs in commuting. Additionally, understanding commuting goes beyond the central need to find policies aimed at reducing costs. Inequality is one of the dimensions that commuting involves: differences in accessibility and travel times exacerbate disparities in societies, making the cost of travel and access to services an extra burden for individuals. Jacob et al (2019) show how the increase in commuting times reduces female well-being, but does not affect men. Differences relate also to race. Bunten et al. (2024) provide evidence of significant differences between Black and White workers' commute times: although during the last 40 years the gap has narrowed, in large cities the time to reach the workplace is higher for Black people. Recently, city-level and census data have been used to assess the burden of commuting. Devin et al. (2024) exploit ZIP-code-level data on residential and workplace locations to measure differences in commuting between Black and White workers. Fuchs et al (2024) explore the gender commuting gap using geocoded administrative data about the residence and workplace for each worker.

The availability of newly collected and constructed geocoded data has made possible a further improvement of research at the subregional level. Smartphones' circulation and apps for mobile phones created novel sources of data for recent empirical research. In the seminal work by González et al. (2008), the authors use geocoded data from mobile phones to analyze human mobility patterns, demonstrating the utility of mobile-generated data for fine-grained geographic research. Akbar et al. (2023) and Couture et al. (2018) rely on the Google Maps route-finding feature to estimate car travel times at different hours of the day in the US and India. Miyauchi et al. (2021) and Kreindler (2024) use smartphone GPS records to measure urban traffic in Japan and Bangalore, respectively.

3.3 Data and descriptive statistics

We make use of geocoded data in raster (geotiff) format (1x1 km, 30 arc-second cells) for the entire Earth's surface to implement a *within* territories analysis in Italy.

The raster data derives from six different global accessibility maps generated using a GIS (Geographic Information System) model by Weiss, Nelson, Vargas-Ruiz et al. (2020) and by Weiss, Nelson, Gibson et al. (2018).

Our first source of data is represented by a global walking-only friction surface, as in the paper by Weiss, Nelson, Vargas-Ruiz et al. (2020). The authors compute the time to walk across a pixel of one-by-one kilometer, providing speeds in minutes per meter. The friction surface considers the geography of each pixel and the endowment in terms of transportation infrastructure in 2019. They assume a walking speed of 5 km per hour if the grid cell is endowed with roads, and a swimming speed of 1 km per hour to cross a territory with water bodies.

The second source of data is represented by a global friction surface including land-based travel speed, expressed in minutes per meter, with access to motorized transport. Weiss, Nelson, Vargas-Ruiz et al. (2020) compute all travel times to cross each cell of the Globe using roads and/or other motorized transport infrastructure in 2019. The global friction surface accounts for the geographical features (landscape characteristics, land cover types, elevation, slope, waterways and bodies of water), transport infrastructure (roads, railways, navigable rivers), and countries' borders.[23]

Our third source of data is a raster file linked to a paper by Weiss, Nelson, Gibson et al. (2018) and consists of travel times (in minutes) needed to access the nearest city of at least 50,000 inhabitants from each pixel of the Earth's surface using the motorized transport infrastructure in 2015. Travel times have been computed after constructing a friction surface, representing the cost in terms of time associated with moving through different geographies and transport infrastructure endowments. The difference between the friction surface used in Weiss, Nelson, Vargas-Ruiz et al. (2020) and the one constructed by Weiss, Nelson, Gibson et al. (2018) lies in the

[23] We downloaded the data about the "Global Walking Only Friction Surface" and "Global Motorized Friction Surface" linked to research paper by Weiss, Nelson, Vargas-Ruiz et al. (2020) from the Malaria Atlas Project (MAP, https://data.malariaatlas.org/maps).

accuracy of the number of roads and road speeds for developing countries included: the former is more detailed, updating the friction surface used for travel times to cities in 2015. Both raster data use OpenStreetMap and Google Roads to extract information about roads and railways and their speed. The fastest road in each cell determines the speed at which that specific pixel can be traversed. Unlike roads, railways are not differentiated by type, and a uniform speed is assigned for movement.

The fourth source of data is represented by three global accessibility maps to ports. Weiss, Nelson, Gibson et al. (2018) compute travel times (in minutes) using the motorized transport infrastructure to the nearest large, medium and of any size port in 2015.[24] Information about ports has been sourced from "World Port Index 26th edition" by NGA (2017).[25]

The analysis *within* grid cells is completed by other four main sources of data about geography, urbanization, and transport infrastructure. Nunn and Puga (2012) provide the data about the ruggedness of the territory. Elevation has been computed using the information from Jarvis et al. (2008). Data about the population at the grid cell level has been sourced from Istat. The information about motorways, railways and primary roads in 2019 comes from OpenStreetMap.

3.4 Methodology

Our analysis aims to understand and describe accessibility and travel *within* territories. We focus on territorial units of one-by-one kilometer, creating a grid composed of 306,929 equally-sized areas completely detached from administrative and institutional boundaries. To ensure that our research is comparable and can be integrated with other analyses, we use the grid cell shape file by Eurostat.[26] We also analyze the same indicators for the Italian municipalities (LAU) and NUTS 3 regions, providing a perspective more linked to institutional considerations.

Starting from the raster image files constructed by Weiss, Nelson, Vargas-Ruiz et al. (2020) and by Weiss, Nelson, Gibson et al. (2018), we use a GIS methodology based on the zonal statistics of the raster analysis in QGIS[27] to compute territorial averages for all Italian grid cells, municipalities and provinces (NUTS 3) and provide accessibility and travel times as minutes per one kilometer.

Raster files data is stored in TIFF format (Tagged Image File Format), which requires GIS tools to extract meaningful information and convert the pixel-based data into usable, quantitative insights. Each pixel within a raster file contains specific information, allowing researchers to analyze and manipulate the data at various scales, depending on the requirements of their study. This flexibility is particularly advantageous when researchers aim to perform geographical analyses that differ from those initially intended by the data's original authors. Raster files can

[24] The authors also compute travel times to small and very small ports. We don't take into account these data in our analysis.

[25] Data about travel times to cities and ports have been downloaded from https://figshare.com/articles/dataset/Travel_time_to_cities_and_ports_in_the_year_2015/7638134.

[26] https://ec.europa.eu/eurostat/web/gisco/geodata/grids.

[27] The same elaboration can be performed using ArcGIS.

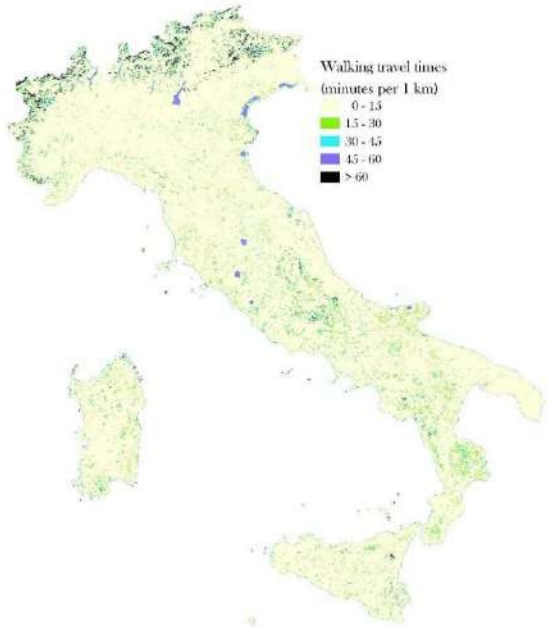
also be overlaid with an unlimited number of shape files, enabling the integration of different geographical boundaries and layers to suit the specific research objectives.
In this study, we start with the raster files from Weiss, Nelson, Vargas-Ruiz et al. (2020) and Weiss, Nelson, Gibson et al. (2018), and we combine them with a detailed polygonal shape file of grid cells of one kilometer by one kilometer sourced from Eurostat. This high-resolution enables us to extract and compute averages with a high degree of precision, move beyond traditional administrative boundaries, such as municipalities, and perform a more refined geographical analysis.
A key advantage of using raster data combined by with a grid cell decomposition lies in the ability to conduct a novel spatial research for Italy, independent of administrative divisions or governance-driven considerations. Administrative-level statistics, such as those at the municipal level, often mask important variations. This is particularly true in geographically diverse regions, where mountainous or rural areas may face significantly longer travel times compared to urban centers, despite being part of the same administrative unit. Even in regions that appear homogenous, with generally high population density and well-developed transport infrastructure, there may still be pockets of reduced accessibility that are overlooked by more aggregated data. By adopting a grid-based analysis, we can identify and address such disparities with much greater accuracy. This approach is especially valuable for identifying rural or underserved areas that may require targeted interventions, such as infrastructure improvements. Ultimately, grid-level analysis can lead to transport policies that are more closely aligned with local needs, promoting transport equity and ensuring that policy decisions are made with a nuanced understanding of accessibility at a finer geographic scale. This method allows policymakers to respond more effectively to the specific challenges faced by different regions, fostering more inclusive and balanced development across both urban and rural landscapes.
Due to the large number of observations, we represent our computations using maps. Results are discussed in the following section.

3.5 Findings and discussion

On average, in Italy, the time to walk one kilometer is about 15 minutes. However, there exists a large variability across the territory: walking travel times range from a minimum value of 12 minutes, that is predominant in many areas of the peninsula, to a maximum value of 1143 minutes (about 19 hours) in the province of Verbano-Cusio-Ossola, in northwestern Italy. Is geography the key factor determining this variability? Italian geography is quite diverse; it ranges from towering mountains to vast plains and long coastlines. The Alps in the North separate Italy from France, Switzerland, Austria, and Slovenia. The Apennines, instead, running down the length of the peninsula, divide Italy into its western and eastern parts. 35% of the territory is mountainous, 42% hilly, and 23% flat. The coastline consists of more than 7,600 km and two NUTS 2 regions are large islands in the Mediterranean Sea, Sicily and Sardinia. In these terms, Italian geography can be considered neither advantageous nor easy.

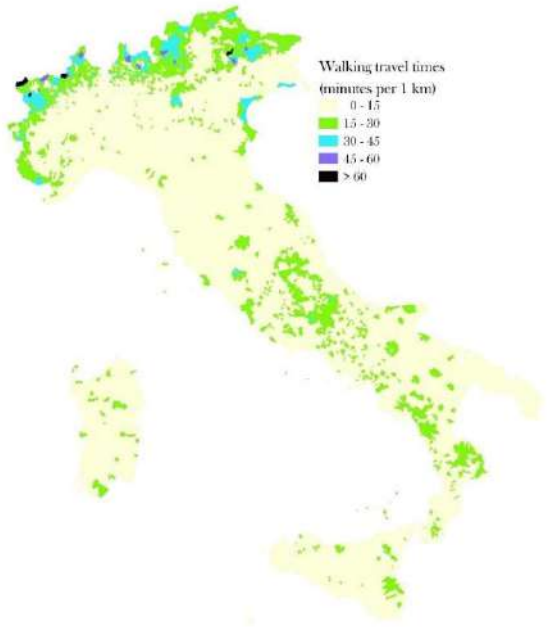
Figure 3.1 provides a clear picture of the time needed to cross one kilometer inside an area of one square kilometer. Most grid cells lie in the first category: 12 minutes is the predominant walking travel time in Italy, covering 87.7% of the peninsula. Mountainous areas are those registering the highest times to walk 1 km: in 3,486 cells (1.1% of Italy) more than 1 hour is needed to travel 1 km. Elevation and ruggedness are good proxies of walking travel times; water bodies, instead, act as obstacles slowing down movement. Differences across grid cells become clearer in Figure 3.2, where walking travel times are averaged at the LAU level. Green spots are widespread in many regions. Municipalities, where more than 30 minutes are needed to travel one kilometer, are, instead, concentrated in northern Italy. However, the overall picture is favorable. Despite vast differences between flatter and rougher areas, almost 90% of the Italian territory shares the same pedestrian time estimates, suggesting the importance of geography, but the relative effect it has.

Figure 3.1. Walking travel times in 2019 (minutes per km), grid cells



Source: own elaboration on Weiss, Nelson, Vargas-Ruiz et al. (2020) data

Figure 3.2. Walking travel times in 2019 (minutes per km), municipalities



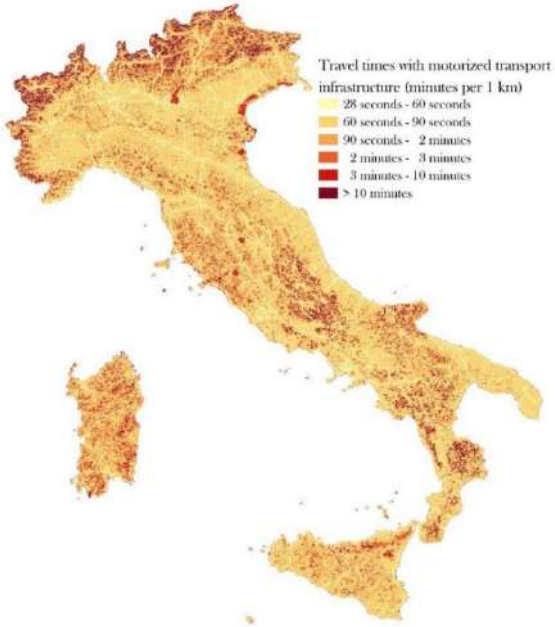
Source: *own elaboration on Weiss, Nelson, Vargas-Ruiz et al. (2020) data*

Incorporating the motorized transport network, and thus the possibility of using vehicles, introduces an extra element to the analysis. On average, in Italy, the minutes required to cross 1 km of territory using motorized means of transport are 3.7. This means more than 3 and a half minutes. However, as for pedestrian travel durations, there is a huge variability across the territory: travel times range from a minimum value of 0.46 minutes (about 28 seconds) to a maximum of 1143 minutes (about 19 hours), where the main factors determining this variability are the geographical features of the land and the land transport infrastructure. In this case, geography affects, on the one hand, the time of travel and, on the other hand, it affects the construction of the motorized network. The Italian motorway system is extensive, with over 6,700 km of highways, and a high-speed rail network. In terms of grid cells of one-by-one kilometer, 9,451 and 22,894 out of 306,929 cells are crossed by the motorways and railways, representing 3% and 7.5% of the total number of cells, respectively. Grid cells crossed by a primary road are 32,994, representing 10.7% of all grid cells.

Figure 3.3 shows the time needed to travel one kilometer with the transport infrastructure *within* a grid cell of one-by-one kilometer in 2019. About 5% of the Italian territory (16,501 grid cells) lies in the first category: less than one minute is used to travel one kilometer. However, unlike walking travel times for which geography was important, but didn't completely rule pedestrian journey durations, for motorized travel times, there seems to exist greater importance linked to geographical features. Moreover, differences between more and less developed areas as well as the presence and placement of the main transport infrastructure (the *second-nature* geography) seem to be key factors in making travel times higher. It immediately emerges how

the island of Sardinia consists of several dark areas, suggesting that there is indeed challenging geography, but also an infrastructure deficit. This scenario is confirmed, focusing also on municipalities. Figure 3.4 maps travel times involving the use of motorized transport infrastructure at the LAU level. What becomes clearer is the difference between northern and southern Italy. If in the North the correlation between ruggedness, elevation, and travel times with the motorized infrastructure is 0.34 and 0.37, respectively; in the South, these correlations are 0.25 and 0.27,[28] suggesting that geography plays a larger role in northern Italy, and that longer travel times in the South or central Italy may be less due to disadvantageous geography. Table 1.1 in the Appendix averages travel times at the NUTS 3 level. The first 14 ranks, except for L'Aquila at the foothills of the Gran Sasso in the South, are all northern provinces in the Alpine region. Following these are the provinces of Cosenza (rank 15) and Crotone (rank 17) in Calabria, despite their average elevation being lower and their geography being less challenging compared to the mountainous NUTS 3 regions at the top positions.

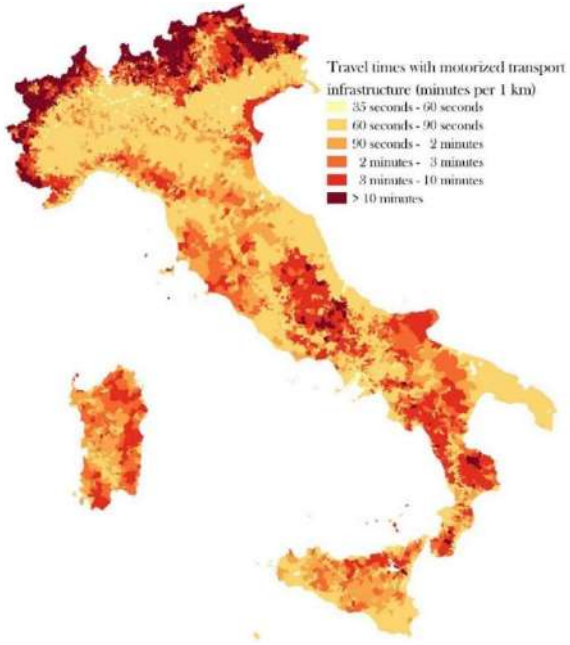
Figure 3.3. Travel times with motorized transport infrastructure in 2019 (minutes per km), grid cells



Source: own elaboration on Weiss, Nelson, Vargas-Ruiz et al. (2020) data

[28] In the Center they are 0.26 for ruggedness and 0.25 for elevation.

Figure 3.4. Travel times with motorized transport infrastructure in 2019 (minutes per km), municipalities



Source: own elaboration on Weiss, Nelson, Vargas-Ruiz et al. (2020) data

We add a further piece of information to the puzzle of travel times in Italy, considering travel times to cities of at least 50,000 inhabitants in 2015. This measure, compared to the previous ones, is less tied to geographical considerations and can be considered a measure of accessibility and market potential. Moreover, it allows for an assessment of accessibility to a broad range of services, such as schools, universities, hospitals and healthcare facilities, public offices, financial institutions, sports, and recreational centers.

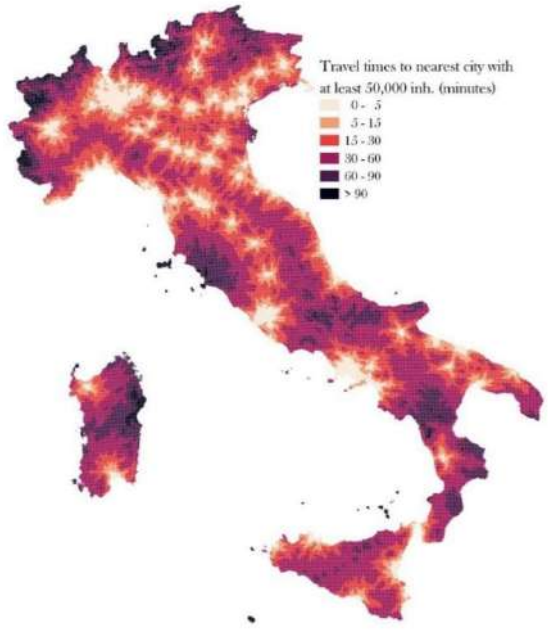
On average, in Italy, more than 35 minutes are needed to reach a large urban center, with peaks of 633 minutes (more than 10 and a half hours) in some areas. This large variability is represented in Figure 3.5. In lighter grid cells, the maximum time to reach a city is 5 minutes. Darker areas range from a minimum time of 60 minutes to more than 10 and a half hours.[29] Northern Italy, again, and coastal areas present higher accessibility to cities, while some areas lack a large city as a provider of services and facilities.[30] According to the 2021 census, 140 cities in Italy are populated by more than 50,000 inhabitants; they were 141 in 2011. 35% of these urban centers are in the North, 33% in the South, 20% in the Center, and 13% in the Islands. Indeed, on average, the NUTS 1 area registering

[29] Since the measure pertains to geospatial data, the actual degree of urbanization in some populated areas does not perfectly align with census data. As a result, the population of urban centers with more than 50,000 inhabitants is underestimated in some cases: we are aware of this issue.

[30] Despite some urban centers exceed 50,000 inhabitants, the source data does not classify them as large cities. This underestimation in the source data does not compromise the analysis but rather strengthens it by considering only the largest cities as providers of public and private services, which are known to offer a broader and more diverse range of activities and opportunities.

the shortest travel times to the nearest urban center is the North-East, with 28 minutes. In the North-West, instead, 36 minutes are needed. Central Italy registers an average travel time of 34 minutes; in the South and in the Islands, instead, the required minutes to reach a city with at least 50,000 people are 38 and 42, respectively. However, if we consider as a large urban center a city with at least 100,000 inhabitants, travel times increase and the number of municipalities drops to 46: 50% are in the North, 20% in the South, 17% in the Center, and 13 in the Islands. Table 3.1 in the Appendix lists travel times to urban centers for the 107 Italian NUTS 3 regions, ranked in descending order.

Figure 3.5. Travel times to the nearest city with at least 50,000 inhabitants in 2015 (minutes), grid cells



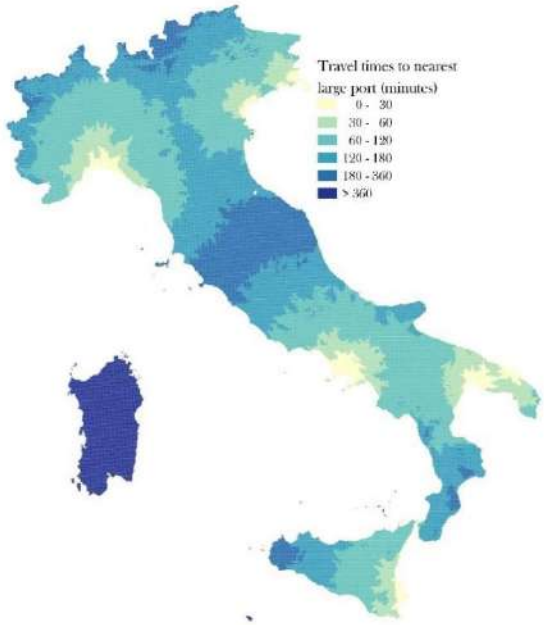
Source: own elaboration on Weiss, Nelson, Gibson et al. (2018)

Travel times to ports are our last measure under scrutiny. According to Assoporti,[31] Italy has a total of 62 ports of national interest. On the one hand, ports serve as critical nodes in global trade by enabling the movement of goods across countries and acting as hubs for logistics and supply chains. On the other hand, ports contribute to regional connectivity by improving access to markets and integrating rural and urban areas into the global economy. We compute travel times at the grid level to large, medium, and all categories of ports in Italy. Whether a port can be defined as large, medium, small, or very small depends on the definition provided by NGA (2017) in the "World Port Index". The index consists of different factors, including area, facilities, and wharf space, and considers 79 Italian ports. According to the index, Italy has 12 large ports: Genova and La Spezia in the North-West; Venezia and Trieste in the North-East; Civitavecchia and Livorno in

[31] Assoporti is the Association of Italian Ports.

central Italy; Brindisi, Gioia Tauro, Napoli, and Taranto in the South; Messina and Siracusa in Sicily. In Sardinia, the second island of the country, there are no large ports; Cagliari is categorized as a medium port. This important result is apparent in Figure 3.6, which shows travel times to the nearest large port in 2015. Sardinia, much of central Italy, certain areas in Sicily, and Calabria in the South experience high travel times to ports, comparable to those of landlocked regions in the North.

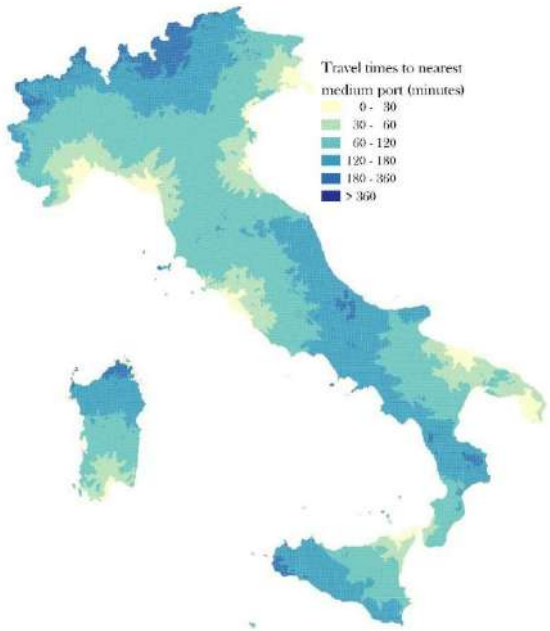
Figure 3.6. Travel times to the nearest large port in 2015 (minutes), grid cells



Source: own elaboration on Weiss, Nelson, Gibson et al. (2018)

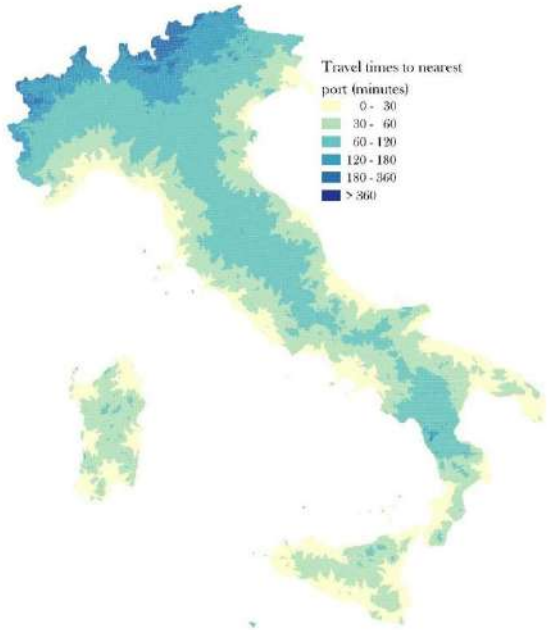
Considering medium-sized ports provides a more favorable picture for some regions. Italy has 10 medium ports: Rada di Vado in the North-West; Monfalcone in the North-East; Porto Corsini in the Center; Bari and Gallipoli in the South; Augusta, Catania, and Milazzo in Sicily; Cagliari and Sarroch in Sardinia. Figure 3.7 shows that now grid cells in northern Italy are those experiencing the highest travel times to reach a port. However, many southern territories and very large areas in the two islands still have travel times similar to those of northern areas, suggesting that being close to the coast does not mean having access to maritime facilities. This is an important result that highlights how the favorable geography of South Italy, in terms of access to the sea, is not supported by adequate access to infrastructure. Figure 3.8, which includes all types of ports, reconnects Italy's physical geography to the *second-nature* geography: grid cells closer to the coast are those closer to the maritime infrastructure.

Figure 3.7. Travel times to the nearest medium port in 2015 (minutes), grid cells



Source: own elaboration on Weiss, Nelson, Gibson et al. (2018)

Figure 3.8. Travel times to the nearest port of any size in 2015 (minutes), grid cells



Source: own elaboration on Weiss, Nelson, Gibson et al. (2018)

3.6 Policy implications and recommendations

The stark differences in travel times between northern and southern Italy, and in specific regions, point to infrastructure deficits. In some areas, rugged geography has hindered infrastructure development, but even flatter regions may face long travel times due to underdeveloped transport networks. In terms of policy, while natural geography cannot be changed, infrastructure can be developed to overcome geographical limitations. In this sense, solutions must be calibrated with the specific issues raised by different areas of the country. For example, where ruggedness and elevation significantly impact travel times, innovative engineering solutions are mostly required. Regions that lag well behind and experience high travel times, despite the less impacting geography, need clear strengthening interventions. The correlations between geography, infrastructure, and travel times identified in this paper can be used to inform infrastructure planning and prioritize areas that will benefit most.

Starting from the bigger picture - the national level - with only a small percentage of grid cells crossed by motorways (3%), railways (7.5%), and primary roads (10.7%), the analysis shows that there is an urgent and undeferrable need to expand the network. Severely underserved areas are concentrated mainly in the South and Sardinia. In this part of the country, motorized travel times to major cities and ports suggest a need for targeted infrastructure development, even when coastal municipalities are considered. Despite their proximity to the sea, southern regions lack effective port access, particularly to large ports, a condition that hinders economic development, market integration, and access to services. For this reason, infrastructure development must be intended as a tool to reduce economic disparities within Italy. The same infrastructure projects can create employment opportunities, stimulating local economies.

The fine-grid descriptive analysis suggests a final important consideration. Coordination among national, regional, and local governments is essential to ensure infrastructure development strategies. The real potential for creating cohesive conditions is met when local geographical and economic conditions are considered. In some instances, also investing in secondary roads and local transport networks or modernizing existing infrastructure to complement the major one can assure an improvement in overall accessibility.

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3.8 Appendix

Table 3.3.1. Travel times with motorized transport infrastructure in 2019 (minutes per km) and travel times to nearest city with at least 50,000 inh. in 2015(minutes), NUTS 3 regions

Rank	NUTS 3 region	Motorized travel times	Rank	NUTS 3 region	Travel times to nearest city
1	Aosta	26.04	1	Aosta	83.08
2	Sondrio	21.46	2	Sondrio	78.95
3	Verbano-Cusio-Ossola	19.62	3	Grosseto	73.20
4	Belluno	13.35	4	Nuoro	72.67
5	Bolzano	11.79	5	Verbano-Cusio-Ossola	68.52
6	Pordenone	9.63	6	Crotone	61.60
7	Trento	7.80	7	Campobasso	58.93
8	Torino	7.68	8	Oristano	58.40
9	L'Aquila	6.08	9	Vibo Valentia	56.28
10	Udine	5.16	10	Livorno	55.67
11	Bergamo	5.00	11	Potenza	55.45
12	Cuneo	4.78	12	L'Aquila	54.86
13	Vercelli	4.63	13	Isernia	54.73
14	Brescia	4.62	14	Belluno	54.54
15	Cosenza	4.50	15	Cuneo	51.53
16	Como	4.19	16	Agrigento	51.39
17	Crotone	3.96	17	Catanzaro	50.76
18	Rieti	3.89	18	Frosinone	50.35
19	Frosinone	3.73	19	Bolzano	47.43
20	Pescara	3.48	20	Viterbo	46.40
21	Ascoli Piceno	3.38	21	Macerata	45.08
22	Teramo	3.35	22	Mesina	45.05
23	Isernia	3.34	23	Cosenza	44.29
24	Massa Carrara	3.18	24	Lecce	43.34
25	Lecco	3.13	25	Sassari	42.76
26	Biella	3.11	26	Matera	41.40
27	Matera	3.05	27	Siena	40.56
28	Foggia	2.96	28	Biella	39.79
29	Salerno	2.90	29	Reggio di Calabria	39.71
30	Potenza	2.88	30	Latina	39.70
31	Imperia	2.83	31	Enna	39.63
32	Reggio di Calabria	2.81	32	Sud Sardegna	38.61
33	Catania	2.79	33	Chieti	37.75
34	Catanzaro	2.72	34	Torino	36.68
35	Mesina	2.71	35	Ragusa	36.09
36	Lucca	2.71	36	Trapani	35.90
37	Rovigo	2.63	37	Rieti	34.63
38	Nuoro	2.62	38	Foggia	34.51
39	Venezia	2.59	39	Vercelli	34.42
40	Cagliari	2.51	40	Rovigo	34.27
41	Gorizia	2.49	41	Trento	32.99
42	Sud Sardegna	2.49	42	Fermo	32.54
43	Ferrara	2.44	43	Caltanissetta	31.92
44	Sassari	2.40	44	Parma	31.29
45	Chieti	2.39	45	Palermo	30.96
46	Grosseto	2.34	46	Benevento	30.59
47	Livorno	2.24	47	Alessandria	30.57
48	Palermo	2.20	48	Salerno	30.36
49	Latina	2.18	49	Asti	30.16
50	Perugia	2.17	50	Udine	29.80
51	Viterbo	2.15	51	Teramo	29.63
52	Barletta-Andria-Trani	2.13	52	Brescia	28.95
53	Roma	2.06	53	Ancona	28.67
54	Caserta	2.00	54	Pesaro e Urbino	28.52
55	Terni	1.92	55	Pisa	27.95
56	Caltanissetta	1.91	56	Ascoli Piceno	27.38

57	Pisa	1.91	57	Perugia	27.36
58	Oristano	1.88	58	Pordenone	27.19
59	Macerata	1.87	59	Siracusa	26.23
60	Siena	1.87	60	Pavia	25.89
61	Avellino	1.86	61	Mantova	25.16
62	Benevento	1.85	62	Piacenza	25.11
63	Verona	1.84	63	Avellino	24.01
64	Enna	1.84	64	Catania	23.94
65	Campobasso	1.81	65	Pescara	23.15
66	Savona	1.78	66	Bergamo	22.97
67	Genova	1.77	67	Terni	22.89
68	Arezzo	1.77	68	Caserta	22.65
69	Pistoia	1.76	69	Arezzo	22.53
70	La Spezia	1.68	70	Gorizia	22.51
71	Vicenza	1.67	71	Forlì-Cesena	21.82
72	Agrigento	1.67	72	Modena	21.72
73	Forlì-Cesena	1.66	73	Taranto	20.99
74	Vibo Valentia	1.65	74	Massa Carrara	20.96
75	Piacenza	1.64	75	Ferrara	20.77
76	Ravenna	1.61	76	Brindisi	20.24
77	Bari	1.60	77	Imperia	20.19
78	Parma	1.59	78	Reggio nell'Emilia	19.40
79	Siracusa	1.59	79	Cagliari	19.20
80	Varese	1.58	80	Como	19.06
81	Firenze	1.57	81	Venezia	18.96
82	Prato	1.54	82	Lucca	18.76
83	Trapani	1.50	83	Firenze	18.65
84	Novara	1.49	84	Vicenza	18.58
85	Pesaro e Urbino	1.49	85	Bari	18.36
86	Alessandria	1.48	86	Verona	18.23
87	Cremona	1.47	87	Barletta-Andria-Trani	18.02
88	Reggio nell'Emilia	1.45	88	Savona	17.67
89	Mantova	1.44	89	Bologna	17.35
90	Modena	1.40	90	Cremona	16.90
91	Bologna	1.40	91	Genova	16.74
92	Treviso	1.39	92	Roma	16.41
93	Fermo	1.38	93	Rimini	16.04
94	Taranto	1.38	94	Ravenna	15.99
95	Pavia	1.37	95	La Spezia	15.82
96	Ragusa	1.33	96	Treviso	15.02
97	Rimini	1.32	97	Lecco	14.27
98	Lodi	1.31	98	Padova	13.78
99	Padova	1.30	99	Lodi	13.76
100	Trieste	1.29	100	Pistoia	12.71
101	Ancona	1.28	101	Novara	12.57
102	Brindisi	1.25	102	Prato	9.26
103	Lecce	1.24	103	Varese	8.47
104	Napoli	1.24	104	Trieste	4.57
105	Asti	1.23	105	Napoli	3.92
106	Milano	1.16	106	Milano	3.12
107	Monza e della Brianza	1.11	107	Monza e della Brianza	0.91

Source: own elaboration on Weiss, Nelson, Vargas-Ruiz et al. (2020) and Weiss, Nelson, Gibson et al. (2018) data

Table 3.3.2. Travel times to ports in 2015 (minutes), NUTS 3 regions

Rank	NUTS 3 region	Travel times to large ports	Rank	NUTS 3 region	Travel times to medium ports	Rank	NUTS 3 region	Travel times to any port
1	Sud Sardegna	682.41	1	Sondrio	215.94	1	Sondrio	197.58
2	Cagliari	664.42	2	Aosta	172.81	2	Aosta	169.42

3	Nuoro	641.83
4	Oristano	635.89
5	Sassari	561.88
6	Ancona	213.32
7	Macerata	212.11
8	Perugia	204.02
9	Sondrio	198.53
10	Pesaro e Urbino	194.41
11	Fermo	193.16
12	Viterbo	191.25
13	Grosseto	189.43
14	Terni	187.29
15	Arezzo	186.43
16	Trapani	181.24
17	Siena	180.57
18	Ascoli Piceno	178.20
19	Aosta	171.76
20	Bolzano	168.95
21	Verbano-Cusio-Ossola	164.81
22	Catanzaro	164.55
23	Rimini	157.56
24	Teramo	156.77
25	Forlì-Cesena	155.82
26	Vibo Valentia	155.38
27	Rieti	152.57
28	Firenze	150.76
29	Crotone	148.04
30	Brescia	142.28
31	Reggio di Calabria	140.59
32	Palermo	139.10
33	Prato	137.27
34	Bergamo	136.75
35	Roma	136.67
36	Trento	136.54
37	Agrigento	134.97
38	Bologna	134.05
39	Como	130.75
40	Ravenna	130.56
41	Torino	129.29
42	Pescara	128.54
43	Modena	127.26
44	Pisa	124.66
45	Lecco	124.27
46	Mantova	124.16
47	Pistoia	120.94
48	Cosenza	119.53
49	L'Aquila	119.02
50	Livorno	117.58
51	Varese	113.65
52	Reggio nell'Emilia	113.18
53	Verona	112.39
54	Biella	112.06
55	Foggia	111.18
56	Belluno	110.85
57	Chieti	109.15
58	Ferrara	105.17
59	Vercelli	104.81
60	Cremona	103.85
61	Parma	101.07
62	Cuneo	99.99
63	Caltanissetta	99.98
64	Monza e della Brianza	98.11
65	Novara	96.60
66	Lucca	95.94
67	Potenza	95.28
68	Barletta-Andria-Trani	94.06
69	Campobasso	93.02

3	Verbano-Cusio-Ossola	170.83
4	Bolzano	169.48
5	Chieti	169.23
6	Isernia	163.71
7	Trento	162.98
8	Crotone	158.62
9	Caserta	155.54
10	Pescara	155.31
11	Bergamo	154.70
12	Trapani	153.58
13	Como	149.52
14	Fermo	149.32
15	Agrigento	149.20
16	Brescia	148.81
17	Campobasso	147.70
18	Sassari	145.72
19	Cosenza	143.50
20	Lecco	143.03
21	Teramo	142.62
22	Ascoli Piceno	141.70
23	Benevento	139.74
24	Napoli	137.69
25	Macerata	134.50
26	Salerno	132.68
27	L'Aquila	130.44
28	Caltanissetta	128.01
29	Varese	126.95
30	Verona	126.53
31	Palermo	125.17
32	Ragusa	123.85
33	Vicenza	122.42
34	Avellino	120.05
35	Biella	117.98
36	Catanzaro	117.38
37	Ancona	117.36
38	Monza e della Brianza	116.92
39	Frosinone	116.41
40	Torino	114.82
41	Belluno	113.73
42	Nuoro	112.17
43	Vercelli	110.44
44	Cremona	107.60
45	Lodi	107.01
46	Foggia	104.84
47	Milano	104.69
48	Novara	103.47
49	Perugia	103.29
50	Mantova	102.19
51	Potenza	101.26
52	Siracusa	101.12
53	Arezzo	101.05
54	Enna	100.94
55	Siena	98.86
56	Rieti	96.57
57	Pesaro e Urbino	95.43
58	Latina	95.14
59	Padova	94.21
60	Piacenza	90.65
61	Oristano	89.47
62	Prato	87.78
63	Firenze	86.79
64	Pavia	85.24
65	Vibo Valentia	85.19
66	Modena	83.12
67	Treviso	81.71
68	Catania	80.47
69	Livorno	79.26

3	Verbano-Cusio-Ossola	164.81
4	Bolzano	163.13
5	Brescia	138.68
6	Bergamo	136.75
7	Como	130.75
8	Trento	129.65
9	Lecco	124.27
10	Torino	114.20
11	Varese	113.65
12	Biella	112.05
13	Belluno	106.70
14	Vercelli	104.61
15	Cremona	98.29
16	Monza e della Brianza	98.11
17	Mantova	97.55
18	Novara	96.60
19	Verona	96.00
20	Arezzo	90.87
21	Lodi	86.48
22	Milano	86.41
23	Perugia	86.13
24	Modena	79.36
25	Vicenza	77.81
26	Potenza	74.63
27	Cosenza	74.39
28	Bologna	73.64
29	Rieti	73.18
30	Pordenone	71.49
31	Piacenza	71.11
32	Terni	69.01
33	Siena	68.96
34	Cuneo	67.82
35	L'Aquila	67.79
36	Pavia	67.49
37	Prato	66.03
38	Firenze	65.43
39	Parma	65.43
40	Reggio nell'Emilia	63.60
41	Pesaro e Urbino	63.46
42	Ascoli Piceno	62.52
43	Treviso	61.80
44	Rimini	61.08
45	Matera	60.91
46	Forlì-Cesena	58.35
47	Asti	57.62
48	Macerata	56.91
49	Udine	56.83
50	Isernia	56.50
51	Frosinone	55.74
52	Fermo	54.81
53	Pistoia	53.63
54	Ferrara	53.23
55	Benevento	51.35
56	Rovigo	51.35
57	Salerno	48.59
58	Campobasso	48.44
59	Padova	48.12
60	Avellino	46.96
61	Foggia	45.23
62	Alessandria	44.91
63	Grosseto	42.98
64	Enna	42.73
65	Teramo	42.61
66	Viterbo	42.06
67	Nuoro	41.62
68	Catanzaro	39.58
69	Ravenna	37.87

70	Mesina	87.91	70	Bologna	75.91	70	Caserta	36.77
71	Vicenza	86.53	71	Pisa	75.78	71	Lucca	35.93
72	Lodi	86.48	72	Grosseto	75.03	72	Roma	35.13
73	Milano	86.41	73	Matera	73.83	73	Venezia	34.60
74	Enna	86.26	74	Cuneo	73.12	74	Mesina	34.20
75	Latina	84.79	75	Pistoia	72.55	75	Ancona	33.93
76	Frosinone	84.10	76	Pordenone	71.49	76	Oristano	33.93
77	Imperia	84.03	77	Reggio di Calabria	71.31	77	Sud Sardegna	32.88
78	Pordenone	83.65	78	Terni	69.34	78	Latina	31.54
79	Rovigo	81.23	79	Rovigo	68.75	79	Palermo	30.55
80	Massa Carrara	73.93	80	Reggio nell'Emilia	67.99	80	Sassari	30.31
81	Isernia	73.84	81	Parma	66.10	81	Pescara	29.93
82	Salerno	73.55	82	Rimini	62.30	82	Catania	29.71
83	Piacenza	72.03	83	Asti	60.27	83	Bari	29.65
84	Udine	69.03	84	Sud Sardegna	58.40	84	Reggio di Calabria	29.56
85	Pavia	67.49	85	Forli'-Cesena	58.35	85	Chieti	29.02
86	Asti	66.30	86	Roma	57.25	86	Pisa	28.61
87	Padova	66.14	87	Udine	56.83	87	Crotone	28.32
88	Catania	63.58	88	Alessandria	56.75	88	Brindisi	27.04
89	Matera	62.70	89	Imperia	55.21	89	Caltanissetta	26.97
90	Treviso	62.34	90	Venezia	53.76	90	Ragusa	26.92
91	Avellino	57.65	91	Ferrara	53.74	91	Siracusa	26.05
92	Bari	57.46	92	Brindisi	52.83	92	Taranto	25.63
93	Ragusa	55.80	93	Barletta-Andria-Trani	51.95	93	Massa Carrara	25.42
94	Benevento	53.09	94	Taranto	51.34	94	Agrigento	25.13
95	La Spezia	49.34	95	Lucca	48.80	95	Barletta-Andria-Trani	23.85
96	Lecce	48.92	96	Mesina	43.23	96	Genova	22.96
97	Alessandria	47.04	97	Viterbo	42.53	97	Cagliari	22.19
98	Savona	44.31	98	Genova	42.52	98	Lecce	21.85
99	Venezia	42.52	99	Ravenna	37.87	99	Trapani	21.22
100	Caserta	38.22	100	Cagliari	34.96	100	La Spezia	20.16
101	Siracusa	33.15	101	Bari	34.29	101	Vibo Valentia	19.92
102	Brindisi	29.05	102	Massa Carrara	29.00	102	Imperia	18.65
103	Taranto	25.96	103	Lecce	25.08	103	Savona	17.25
104	Gorizia	23.62	104	La Spezia	20.70	104	Livorno	15.71
105	Genova	23.26	105	Savona	19.91	105	Gorizia	13.59
106	Napoli	13.49	106	Trieste	15.86	106	Napoli	9.77
107	Trieste	6.93	107	Gorizia	13.59	107	Trieste	6.12

Source: own elaboration on Weiss, Nelson, Gibson et al. (2018) data

4. An analysis of road networks' vulnerability to disruptions through the specification of accessibility indicator *(F. Pagliara, I. Henke, G. Troiani)*

4.1 Introduction

Road networks are vulnerable to a range of risks, both natural and human-made, that can degrade the performance of the system, influencing the mobility of people and goods, with significant economic repercussions. Estimating the vulnerability of road infrastructure is essential for ensuring efficient and resilient urban management, as it allows for the identification of critical sections in the network and the planning of interventions aimed at reducing the impact of external shocks. The purpose of this study is to analyse the vulnerability of road networks in three different territorial contexts in Italy: the metropolitan area of city of Napoli, the medium-sized cities of Avellino, Benevento, and Taranto, and the inner areas of Irpinia and Piana del Sele. Using the Visum software, which allows for the simulation of different traffic disruption scenarios, the study aims to identify vulnerable areas. For each case study, an accessibility index has been calculated to assess the impact of disruptions on mobility and to determine the areas that could be most affected in the event of critical incidents. Although this framework is well-established in the literature (Papilloud and Keiler, 2021; Chen et al., 2007), our study tests this accessibility-based approach in various and new territorial contexts in Italy.

4.2 Outline of literature background

Vulnerability is determined by three factors: network topology, environmental characteristics, and mobility demand. The first factor concerns the physical structure of the network, including the geometric characteristics of the roads, the presence of critical elements such as bridges or tunnels, and the level of maintenance. The second factor relates to the topography of the territory and natural hazards, such as floods and earthquakes, which can affect network performance. The third and final factor involves the analysis of traffic flows and the areas within an urban zone that are most prone to congestion.

In recent decades, scientific literature has developed numerous approaches for analysing the vulnerability of road networks. These approaches include topological modelling, socio-economic analysis, and performance analysis of the transport system. Topological methods focus on network connectivity, aiming to identify critical sections, that is, specific roads whose disruption could cause significant damage to mobility. The study of properties such as redundancy, which measures the ability to reach the same destinations through alternative routes, helps to understand how flexible a network is in response to an external event. Topological methods often lead to determining rankings (hierarchies) of road importance within networks.

Socio-economic analysis assesses the impact of disruptions on mobility and access to essential services. Accessibility, defined as the ease with which people can reach destinations such as workplaces, hospitals, and schools, is often used as a key indicator to evaluate the impact of road interruptions. Variables such as the resident population and/or employees, the number of essential services like hospitals and schools present in a given area, can be used in defining various accessibility indices. As a result, the distribution of activities also plays a fundamental role in determining the mobility patterns of an area. Lastly, the approach based on performance analysis of the system measures the increase in perceived generalized cost by users, the increase in travel time, or the reduction in capacity following the disruption. Regardless of the methodology used, vulnerability analysis involves calculating an indicator, more or less complex, before and after a certain external shock (floods, traffic accidents, etc.).

4.3 Data and descriptive statistics

In this section, the case studies of the metropolitan area of the city of Naples, the medium-sized cities of Avellino, Benevento, and Taranto, and the inland areas of Piana del Sele and Irpinia are presented.

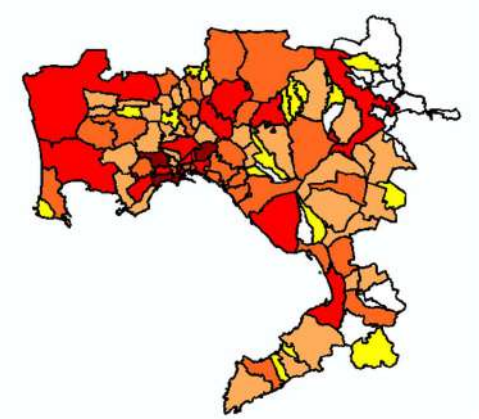
Table 4.4.1. Main characteristics of the 6 case studies considered

Region	Area [Km²]	Traffic zones	Population	Jobs
Metropolitan area of Naples	1.171	112	3.055.000	783.490
Middle sized city of Avellino	30	24	52.063	24.966
Middle sized city of Benevento	130	30	55.815	22.381
Middle sized city of Taranto	250	52	186.258	67.208
Inner area of Irpinia	2.800	138	418.306	97.701
Inner area of Piana del Sele	250	52	160.095	39.193

4.3.1 Metropolitan area of Naples

The metropolitan area of the city of Naples covers approximately 1.171 km². It is bordered to the east by the Sorrentine Peninsula, to the west by the Phlegraean Fields, and to the northwest by the southern side of the Campanian plain. It is the third most populous metropolitan area in Italy, following Rome and Milan, with over 3 million inhabitants. It includes 82 municipalities, while the municipality of Naples, with a population of nearly one million people, is divided into 30 districts. For traffic analysis, the entire area has been divided into 112 zones, with Figure 4.1 showing the jobs distribution (source: ISTAT).

Figure 4.1. Naples: jobs distribution

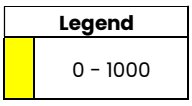


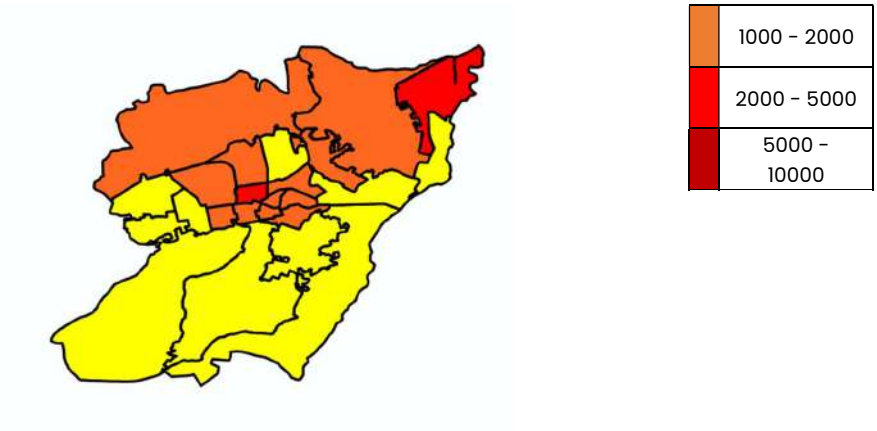
Approximately 41% of the workforce is located exclusively within the municipality of Naples. The road network has been imported from OpenStreetMap. The city plays a crucial role as a major hub for national road and highway networks. From the urban center, the A1 highway extends north, the A3 highway heads south, and the A16 highway leads towards the Adriatic coast. Within the city, the main road for traffic is the ring road (tangenziale), supported by other significant arteries such as the Asse Mediano, the Circumvallazione Esterna, the Melito-Scampia Perimeter Road, and State Road 162.
The demand matrix has been developed using data from the Urban Plan for Sustainable Mobility – Metropolitan City of Naples 2022 (Piano Urbano della Mobilità Sostenibile – Città Metropolitana di Napoli) and has been assigned to the road network using a stochastic user equilibrium assignment method, allowing for the estimation of car traffic during peak hours on a typical weekday morning.

4.3.2 Middle sized city of Avellino

The city of Avellino has approximately 52.000 inhabitants. This city is located in the flat part of a basin, a valley formed by volcanic activity in the southern Apennines. The city is bordered to the east by Mount Tuoro, to the southeast by the Picentini mountain range, and to the northwest by the Montevergine massif. Avellino has been divided into 24 homogeneous traffic zones. Figure 4.2 shows the distribution of workers in the city (source: ISTAT).

Figure 4.2. Avellino: jobs distribution



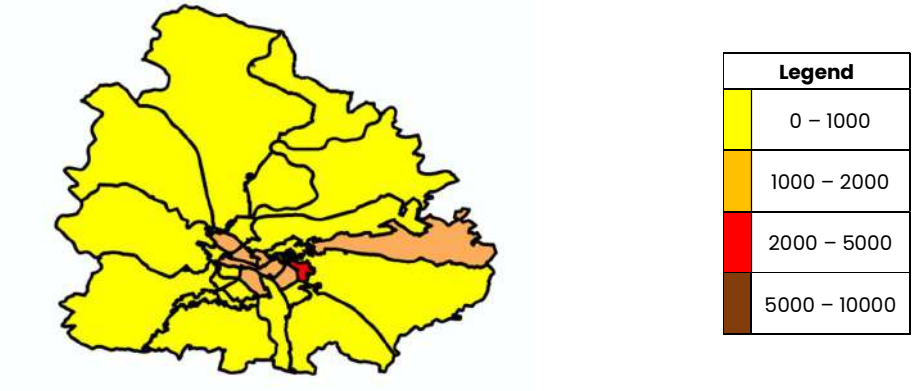


The road network has been obtained from the OpenStreetMap site and covers an area of approximately 30 km². The city is traversed by the A16 highway to the northwest and by State Road 7, known as Via Appia, in the southern part.
The origin-destination (O-D) matrix has been derived from data collected during the 15th general census of population and housing in 2015 (ISTAT), which analysed commuter movements. The O-D matrix was then integrated into the road network using a stochastic user equilibrium approach, allowing for the estimation of car traffic flow between the 24 zones during morning peak hours on a typical weekday.

4.3.3 Middle sized city of Benevento

The city of Benevento has a population of approximately 56.000 inhabitants. It is located in the Apennine inland region and is crossed by the Calore and Sabato rivers. The whole urban center is situated in a large basin surrounded by hills; to the west rises the Taburno Camposauro massif, while to the southwest stands Mount Avella. Benevento has been divided into 30 homogeneous traffic zones, and Figure 4.3 shows the distribution of workers (source: ISTAT).

Figure 4.3. Benevento: jobs distribution



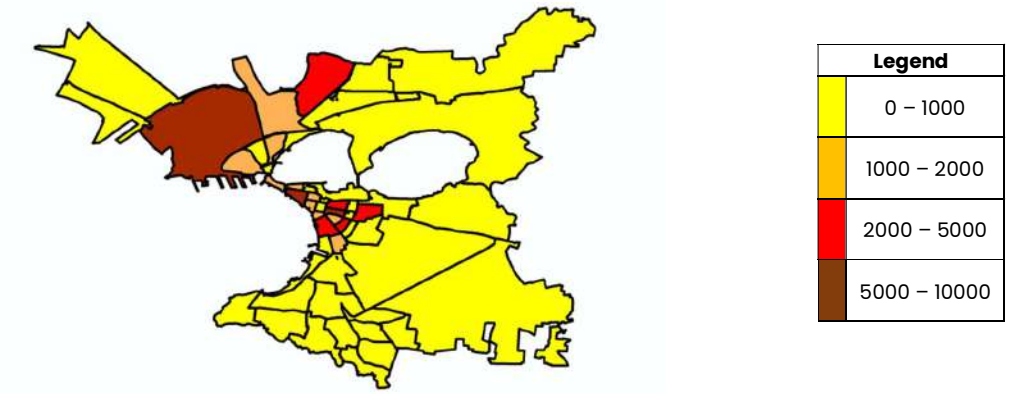
The road network of the city of Benevento has been obtained from the OpenStreetMap site and covers an area of approximately 130 km². The city is encircled by the "SS 752 Benevento Ring Road"

and is crossed by several state roads, including "SS 372 Telesina," "SS 90," "SS 7," "SS 88," and "SS 87."
The origin-destination (O-D) demand matrix for car traffic has been built using data collected during the 15th general census of population and housing in 2015 (ISTAT). The O-D matrix was integrated into the road network through a stochastic user equilibrium method, providing an estimate of car traffic demand between 30 traffic zones during morning peak hours on a typical weekday.

4.3.4 Middle sized city of Taranto

The city of Taranto has approximately 186.000 inhabitants. It is the second most populous city in the Puglia region and overlooks the Ionian Sea. The city's territory is primarily flat and extends over three natural peninsulas and an island, the latter being home to the historic center. Taranto has been divided into 52 homogeneous traffic zones, and Figure 4.4 shows the distribution of workers (source: ISTAT).

Figure 4.4. Taranto: jobs distribution



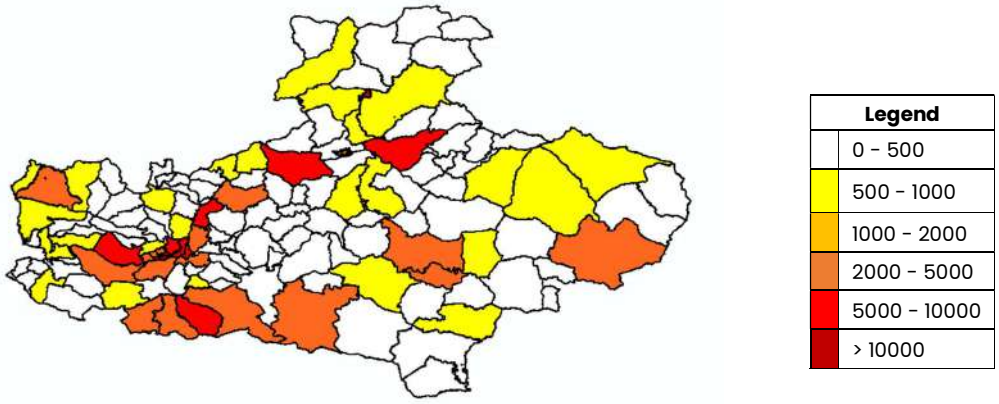
The road network of Taranto has been obtained from OpenStreetMap and covers an area of approximately 250 km². The city is crossed by several major national roads, including the "A14" highway, "SS 106," "SS 100," and "SS 7."
The origin-destination (O-D) demand matrix for car traffic has been created using data collected during the 15th general census of population and housing in 2015 (ISTAT). The O-D matrix was integrated into the road network through a stochastic user equilibrium method, determining car traffic demand between 52 traffic zones during morning peak hours on a typical weekday.

4.3.5 Inner area of Irpinia

Irpinia is an inner region situated within the heart of Campania, spanning a large area of about 2.800 km², predominantly made up of hills and mountains in the Avellino province. To the north, it is bordered by the Picentini Mountains, to the east by the Dauni Mountains, and to the south, it stretches to the Sele River valley and the Terminio massif. Irpinia is predominantly a rural area, with an economy largely based on agriculture and livestock farming. Administratively, Irpinia

comprises 118 municipalities. The total population is about 420.000, with a relatively low population density of around 100 inhabitants per square kilometer. The area has been divided into 138 homogeneous traffic zones, and Figure 4.5 shows the distribution of workers (source: ISTAT).

Figure 4.5. Irpinia: jobs distribution



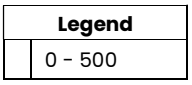
The road network of Irpinia, obtained from OpenStreetMap data, is quite complex and presents several challenges due to the geographical terrain. Among the main arteries crossing this region are State Road 7 (Via Appia), which connects Avellino with Benevento and the rest of Campania; State Road 303, which traverses the mountainous areas connecting the small towns of inland Irpinia; and the A16 Napoli-Canosa highway, which ensures Irpinia's connection to the national highway network.

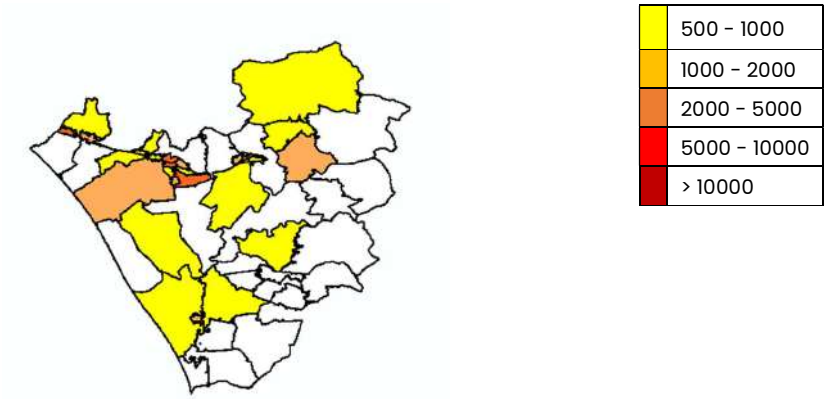
The travel demand matrix has been developed using data collected by ISTAT in the 2015 survey. Subsequently, the mobility demand has been distributed across the road network using a stochastic user equilibrium model, allowing for the calculation of car traffic demand during peak morning hours on a typical weekday.

4.3.6 Inner area of Piana del Sele

The Piana del Sele is a plain located in the province of Salerno. This territory is bounded to the east by the Alburni Mountains, to the north by the Picentini Mountains, to the south by the Cilento hills, and to the west by the Tyrrhenian Sea. The plain covers an area of approximately 250 km² and is known for its strong agricultural and livestock production. Several rivers cross the plain, including the Sele River, which stretches for about 64 km, and the Calore Lucano River, an important tributary of the Sele, extending for about 70 km. Administratively, the Piana del Sele spans 9 municipalities and has been divided into 52 traffic zones. Figure 4.6 shows the jobs distribution (source: ISTAT).

Figure 4.6. Piana del Sele: jobs distribution





The road network has been obtained from OpenStreetMap and includes essential arteries such as State Road 18 Tirrena Inferiore, which runs along the coast, and the A3 highway (Salerno-Reggio Calabria), which connects the area to the rest of the region and the country.
The travel demand matrix has been developed using data collected in the latest ISTAT survey conducted in 2015. This matrix has been assigned to the road network using the stochastic user equilibrium method, allowing for the estimation of car traffic during peak morning hours on a typical weekday.

4.4 Methodology

The methodology used in this study employs the concept of accessibility to identify vulnerable areas. Accessibility measures how easily a user, located in a specific place, can engage in activities in other locations. Active accessibility refers to users' ability to reach a specific destination, such as a shop or a service, and is calculated as follows:

$$AA_i = \sum_{j=1}^{n} K_j^{\beta_1} * \exp\left(-\beta_2 T_{ij}\right) \quad (1)$$

The active accessibility of traffic zone i (AA_i) is a function of the travel time T_{ij} between zones i and j, the number of workers K present in zone j weighted by two parameters β_1 and β_2. The change in accessibility of a traffic zone in the network observed after a traffic disruption represents its degree of vulnerability:

$$Vulnerability_i = \frac{Acc_i^1 - Acc_i^0}{Acc_i^0} \quad (2)$$

Vulnerability of traffic zone i is measured as the percentage change in accessibility before (Acc_i^0) and after (Acc_i^1) a certain event. This event refers to an occurrence that disrupts the normal flow of traffic on a road. A traffic zone is defined as an area from which movements can be assumed to start and end at the same point, referred to as the zone centroid. This area is homogeneous from a transport perspective. This methodology was conducted using Visum software, which calculates travel times between the various traffic zones in the area. It has been tested at different and new territorial scales in Italy. The base scenario represents normal traffic conditions within

the study area, while in the "disruption scenario," a traffic disruption on a specific road is assumed. By comparing the base scenario and the disruption scenario, a vulnerability map can be produced. The vulnerability maps generated from the simulations provide an immediate overview of high-risk areas, allowing local authorities to plan targeted interventions to improve the resilience of the network.

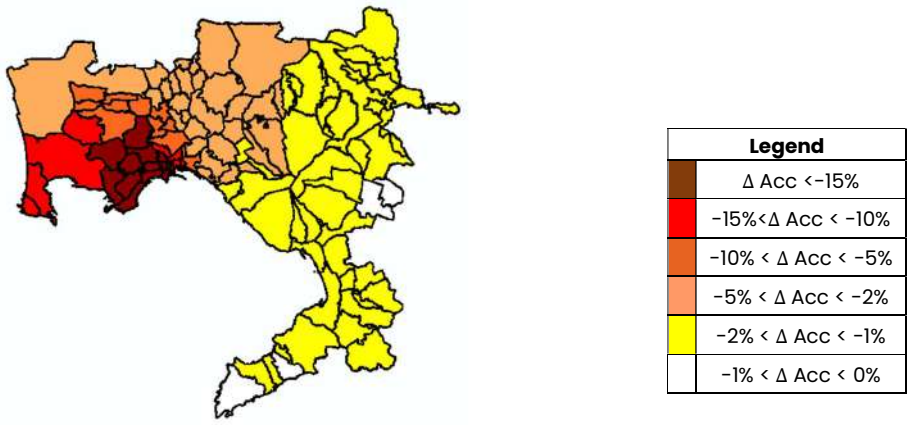
4.5 Findings and discussion

For each case study, various disruption scenarios were hypothesized. Among all the simulated scenarios, the one with the most significant impact on urban mobility will be referenced. In accordance with equations 1 and 2, only the corresponding vulnerability maps are presented.

4.5.1 Metropolitan area of Naples

The worst scenario for the metropolitan area of the city of Naples is with the closure of the section of the ring road (Tangenziale di Napoli from exit 4 to exit 6). Figure 4.7 shows the corresponding vulnerability map.

Figure 4.7. Naples: accessibility variation (%) following the disruption of the Tangenziale di Napoli

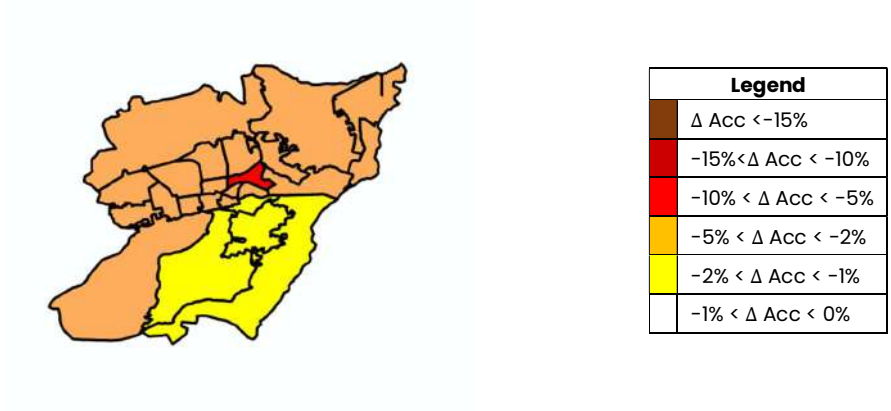


The section of the ring road from exit 4 to exit 6 is approximately 3 km long and has three lanes in each direction. It passes through three neighborhoods in central Naples. According to the PUMS (Urban Plan for Sustainable Mobility – Metropolitan City of Naples, 2022), the Naples ring road is used by about 17.000 vehicles daily and serves as the main artery connecting the western and eastern parts of the city, as well as being the primary access route to the airport. Following the closure, the average accessibility decreased by 5.43%. Only four zones were unaffected by the ring road closure. In 22 zones, accessibility reductions exceeded 10%, while in 11 zones, the decrease ranged between 5% and 10%. Notably, 14 zones recorded a reduction in accessibility of more than 15%.

4.5.2 Middle sized city of Avellino

The greatest impact on mobility within the city of Avellino occurs with the closure of "Via Circumvallazione." Figure 4.8 shows the corresponding vulnerability map.

Figure 4.8. Avellino: accessibility variation (%) following the disruption of via Circumvallazione

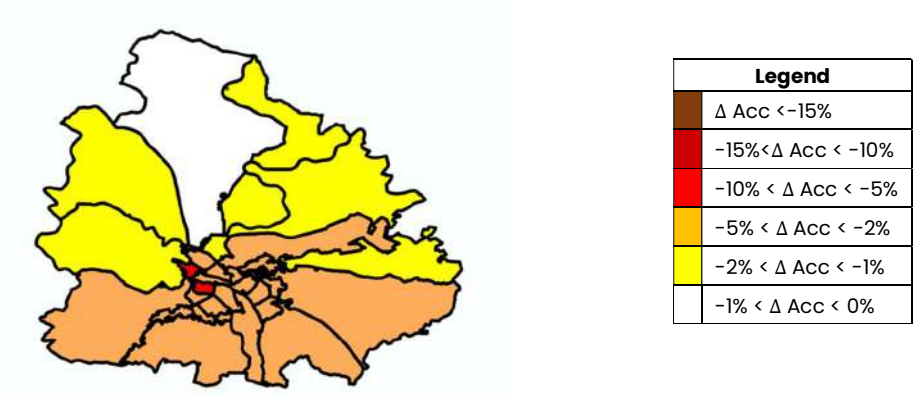


This road crosses two zones in the historic center of Avellino, is approximately 3 km long, and has one lane in each direction. Following the closure of this road, accessibility within the study area decreases by 3.42%. All zones are affected by the disruption, with 19 zones experiencing a decrease in accessibility ranging between 2% and 5%, while only one zone sees a reduction greater than 5%.

4.5.3 Middle sized city of Benevento

The traffic disruption on the "Vanvitelli" bridge in the historic center of Benevento represents the worst-case scenario. Figure 4.9 shows the corresponding vulnerability map.

Figure 4.9. Benevento: accessibility variation (%) following the disruption of Vanvitelli bridge

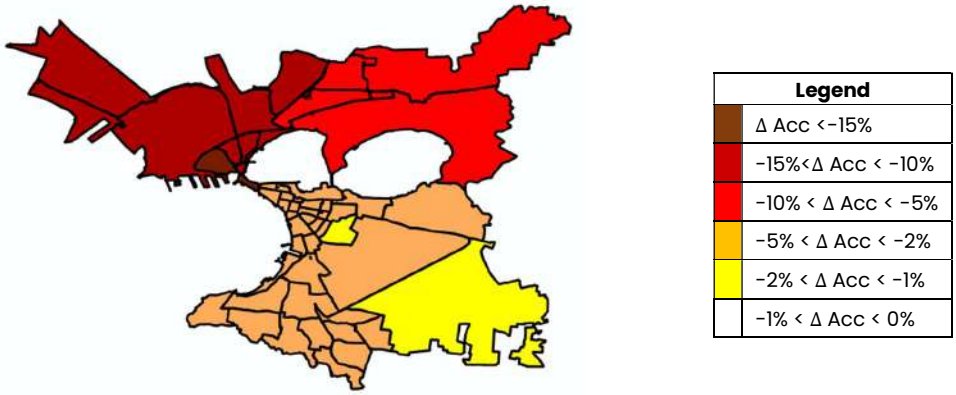


The Vanvitelli bridge is approximately 110 meters long and has two lanes in each direction. It is located in the northwest area of the city center and serves as the main access route to the historic center, passing over the Calore River. Following its closure, two zones experience a decrease in accessibility of over 5%, while in 20 zones, the reduction in accessibility ranges between 2% and 5%. Overall, accessibility across the city decreases by an average of 3%.

4.5.4 Middle sized city of Taranto

For the city of Taranto, the closure of the San Francesco di Paola bridge represents the worst-case scenario. Figure 4.10 shows the corresponding vulnerability map.

Figure 4.10. Taranto: accessibility variation (%) following the disruption of San Francesco di Paola bridge

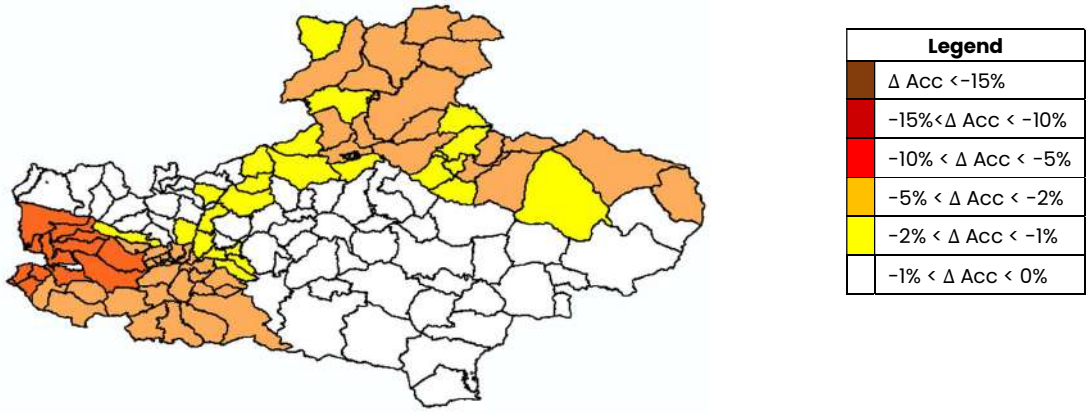


The San Francesco di Paola bridge is 90 meters long and has one lane in each direction. Along with the Porta Napoli bridge, it connects the historic center with the rest of the city. The traffic disruption on the San Francesco di Paola bridge results in an average accessibility reduction within the city of 5.65%. Two zones experience a decrease of over 15%, while nine zones see a reduction of more than 10%.

4.5.5 Inner area of Irpinia

The closure of the tunnel along the A16 highway, which falls within the territory of the municipality of Montemiletto, represents the worst-case scenario for the inland area of Irpinia. Figure 4.11 shows the corresponding vulnerability map.

Figure 4.11. Irpinia: accessibility variation (%) following the disruption of the tunnel



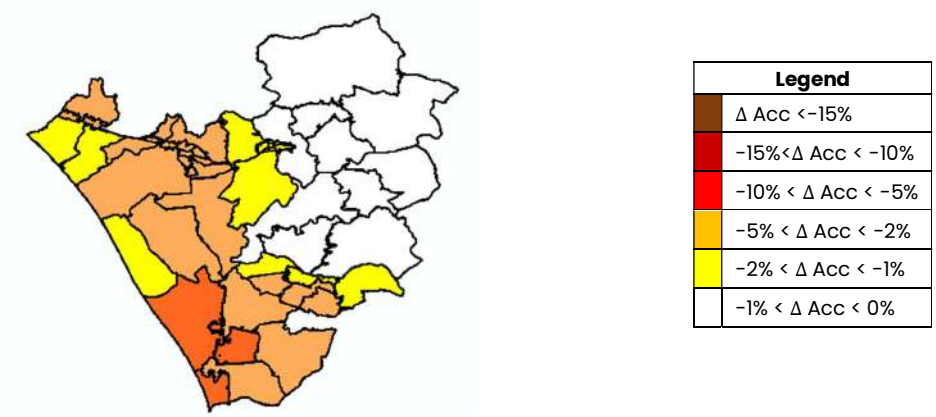
The tunnel along the A16 in the municipality of Montemiletto is approximately 950 meters long and has two lanes in each direction. Following its closure, there is an average decrease of 2.42%

across the entire Irpinia region. In over 30 zones, the decrease ranges between 2% and 5%, while in 13 zones the reduction is between 5% and 10%.

4.5.6 Inner area of Piana del Sele

For the case study of the Piana del Sele, the worst-case scenario occurs with the traffic disruption on the "Barrizzo" bridge along State Road 18. Figure 4.12 shows the corresponding vulnerability map.

Figure 4.12. Piana del Sele: accessibility variation (%) following the disruption of Barrizzo bridge



The Barrizzo bridge is approximately 52 meters long, has one lane in each direction, and is located in the municipality of Capaccio. Following its closure, the accessibility of the Piana del Sele decreases by about 2.22%. Three zones experience an accessibility decrease of more than 5%, while 23 zones see a reduction of over 2%.

4.6 Policy implications and recommendations

Considering the results obtained, road infrastructure management policies must be adapted to the specificities of different territorial contexts. The metropolitan area of Naples is crucial hubs for regional and national mobility. The vulnerability of road networks in this area, especially for key arteries such as ring roads and highways, has significant implications for the entire transportation system. For instance, the blockage or interruption of the Naples ring road could paralyze a large portion of the city's traffic and vital connections to other regions. It is essential to address infrastructure vulnerability through a multi-level approach. This entails managing the network with targeted maintenance interventions focused on the most critical arteries, as well as infrastructure investments aimed at improving network resilience. At the same time, it is advisable to promote the use of efficient public transportation and the development of bike lanes to reduce road congestion. Local authorities should also invest in continuous infrastructure monitoring systems and preventive maintenance to identify and promptly address issues.

Medium-sized cities, such as Avellino, Benevento, and Taranto, face specific challenges related to their geographical location and urban structure. The vulnerability of their road networks can

significantly impact local mobility and the quality of life of residents. An example is Taranto, where the geographic location and the importance of the port necessitate improving the accessibility and safety of key arteries, both to facilitate freight transport and ensure better local mobility. Given the lower complexity of road networks, policies should focus on improving the accessibility and safety of local roads.

The mid-sized areas, such as Irpinia and Piana del Sele, are characterized by low population density and often underdeveloped road networks. However, vulnerability in these areas, often exacerbated by hydrogeological risks, can isolate rural communities and hinder access to essential services. Policies should focus on preventive measures, such as regular maintenance of local roads, and on environmental monitoring systems to prevent risks associated with natural events. In these contexts, it is crucial to invest in resilient and safe infrastructure, implementing alternative routes and enhancing the existing road network to ensure that communities do not become isolated.

4.7 Key references

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5. Analyzing the Accessibility of Rome's Health Services via Public Transportation: A Complex Network Approach *(L. Bellantuono, R. Bellotti, A.S. Bergantino, M. Intini, G. Monturano, N. Kheirkhahan)*

5.1 Introduction

Access to healthcare facilities is a crucial component of urban public health planning. A highly accessible healthcare system increases life expectancy, improving overall quality of life. According to several studies, human development strongly depends on equal access to essential services like healthcare [1]. In this perspective, the literature identifies the availability and accessibility of these services as fundamental to positively influencing economic growth, social equity, and the well-being of communities and territories [2].

When assessing healthcare accessibility, it is key to consider which part of the population most needs these services. The elderly and people with disabilities are among the social groups with the highest demand for healthcare and, at the same time, often lack access to private cars. Therefore, the design of an accessible transit-oriented system is crucial for equitable and effective healthcare provision. Inequities in access to healthcare significantly influence economic development and the quality of life of individuals [3].

The importance of having robust transit access to healthcare under any operating condition raises the need for resilient networks to and from healthcare facilities, which provide a reliable system even when external shocks hit. A resilient transit network is able to cope with disruptions, providing redundancy to users and rapidly recovering to pre-disruption performance levels.

At an empirical level, network analysis emerges as one of the most relevant methodologies for analyzing and studying accessibility to essential services. In general, network analysis allows modeling networks as graphs composed of nodes (e.g., bus stops or health centers) and edges (e.g., distances between services), allowing for an accurate analysis of the structural properties of the network, efficient identification of critical nodes, and an accurate assessment of the resilience of the system.

Although many studies examine access to healthcare facilities or public transportation networks separately, only some have investigated how they interact with each other [4][5][6], and many questions remain to be better addressed. For example, the transit-based accessibility assessment of areas with limited overall connections and resilience to external shocks remains underexplored.

This study aims to fill this gap by offering an integrated analysis that combines network analysis with spatial accessibility measures to comprehensively assess disparities in access to healthcare services through public transportation and its resilience to external disruptions.

This work presents a study specifically focused on measuring the accessibility of healthcare facilities through Rome's bus network under disruptive scenarios. The main objectives are: 1) to assess territorial sustainability by analyzing the equitable distribution and accessibility of healthcare facilities through public transportation in the 155 municipal sections of Rome; 2) to identify disparities in access to healthcare, focusing on areas with limited or difficult connections to hospitals through public transportation; 3) to assess the resilience of the transit network to external shocks that compromise the integrity of the network; 4) to inform policy decisions by providing evidence-based recommendations to improve public transportation infrastructure and enhance accessibility to healthcare services.

The study employs quantitative methods and advanced computational tools to analyze the bus network's structural properties, assess access to healthcare services, and evaluate the network's resilience and reliability. Network topology analysis uses centrality and connectivity metrics to identify critical nodes and paths, while spatial accessibility measurements integrate geographic and transportation data to assess travel distance and time to healthcare facilities. Resilience and reliability assessments explore the network's response to disruptions and the implications for healthcare accessibility. Using real-world data from Rome, the results highlight key transportation hubs, classify stations within the complex network, and measure spatial accessibility to healthcare services, offering valuable insights into how public transportation impacts equity and providing recommendations to improve the Urban Public Transport System's (UPTS) resilience and reliability. By addressing these goals, the research provides critical guidance for policymakers to improve Rome's public transportation infrastructure, promoting a more sustainable and equitable healthcare system for all residents.

The work is structured as follows. Section 2 presents the literature review, analyzing previous studies on spatial inequalities, citizenship services, place-based policies, and network analysis in spatial studies. Section 3 describes the methodology, data, analytical tools, and methodological techniques used. Section 4 presents the results of the analysis, including network mapping and accessibility assessment. Section 5 discusses the policy implications for urban planning and transport policies. Section 6 summarizes the contributions of the study, suggests directions for future research, and concludes.

5.2 Outline of literature background

As discussed in the introductory section, strengthening access to essential services is crucial to promoting social equity, as these services influence the quality of life of citizens and their ability to fully participate in society [7].

Generally, urban accessibility to healthcare facilities has been assessed with GIS methodologies supported by travel time estimates, such as the floating catchment area methods [4][8][9][10], robust space–time accessibility assessments [11], and network analysis [12][13][5][14][15]. The latter mainly uses estimated or self-reported travel times on a network (e.g., road or transit network) to calculate the number of points of interest (in this case, healthcare centers) reachable within a time threshold. Such an "objective" accessibility measure needs to take into account

several factors when dealing with specific user classes, like elderly people. Guida et al. [4] found that using only the transit network and assuming no car access for elderly people, peripheral areas of Milan had significantly lower accessibility to healthcare facilities for this user group compared to central areas, noting spatial patterns of accessibility. Such an example is useful to understand that accessibility measures should be tailored to the user class studied (e.g., elderly people without car access), including relevant modes of transport for the group studied.

Taking a step further into network analysis, complex network analysis can be employed in combination with more traditional elements of network analysis and travel time estimations.

A complex network is made up of a set of nodes that reveal the constituents of the network and a set of links representing the physical connections between each pair of nodes [16]. Several properties and indexes of the network can be used to describe its composition [17][18][19].

Complex network frameworks and tools are also useful for analyzing the network's integrity when external disruptions occur, detailing the resilience properties of the network.

Resilience is generally defined in the literature as the ability of transport networks to resist shocks, maintain functionality, and recover as quickly as possible to a full level of service [20]. In the static part of resilience, at the moment of disruption, robustness defines the amount of performance that the network can maintain. Redundancy, on the other hand, refers to the set of infrastructural and modal alternatives that the system provides to users [21]. Vulnerability, which is the opposite of robustness, indicates the amount of performance loss at the moment of disruption, serving as an index of susceptibility to loss [22].

Important investigations on resilience and vulnerability in transportation studies include, for example, the works of Mattsson and Jenelius [23], Reggiani et al. [24], and Gu et al. [22]. Mattsson and Jenelius [23] indicate that vulnerability analysis can be system-based or topology-based, with the former more focused on the performance of the network (in terms of flows, speeds, etc.), while the latter focuses on the topological features of the networks, i.e., nodes, edges, and their connections. Wang et al. [25] assessed the vulnerability of urban road networks using a system-based approach. Using data from taxi trips, the analysis showed that nodes with high centrality significantly influence network vulnerability and that travel time is directly related to flow loss. Similar studies have been conducted on rail transit networks (e.g., Yang et al. [26]) and urban bus networks (see Sun et al. [27]).

Focusing on transit, an efficient and effective Urban Public Transport System (UPTS) ensures that the transfer of passengers runs smoothly and that stations are properly distributed to businesses and residents [28][29]. Starting from this framework, Baggag et al. [30] used the public transport network (PTN) model to represent nodes, which are the stations and stops of a public transport system, and edges, which connect subsequent stations along a route. The critical nodes identified through the single-modal analysis cannot accurately represent the actual state of public transport. Therefore, it is useful to explore methods to identify pivotal nodes from a topological perspective within multimodal public transport networks [31]. Murray-Tuite [32] introduces the concept of quantitative metrics to measure the resilience of the transport system, analyzing the four dimensions of transport resilience and exploring the influence of traffic assignment on resilience.

This paper builds upon the surveyed literature by combining complex network resilience analysis with classical network-based accessibility assessment to create a healthcare facilities transit-network-based accessibility index tested under several disruption scenarios. The analysis, like that of Guida et al. [4], focuses on transit to address the car-less elderly user group, who are among those most in need of healthcare services. This is a novel contribution to healthcare accessibility analysis that incorporates resilience, an aspect still underexplored.

5.3 Data and descriptive statistics

The present research used a variety of open sources data and formats to analyze public transportation networks and healthcare accessibility in Rome's urban areas.

- Public Transport Data: The General Transit Feed Specification (GTFS) format was used as the primary data source for public transportation information, including the public bus transportation system across Rome. The GTFS format, developed by R. Kujala and colleagues [21], provided detailed transit schedules, station locations, and route information, which was critical for building transportation networks.
- Healthcare Services Data: Data on healthcare facilities in Rome, with a specific focus on cardiology services, was collected and preprocessed to exclude healthcare facilities outside the city. This ensured that the analysis was limited to healthcare services accessible within the urban area.
- Geographical Data: Geographic coordinates of the urban zones in Rome were sourced from the Rome Municipality website. The coordinates were further processed using the Geocoder Python library to ensure accurate spatial mapping and integration into Geographic Information Systems (GIS) for network analysis [22].

5.3.1 Software tools and libraries

The analysis was conducted using a variety of open-source Python libraries, including:

- NetworkX for network construction and centrality metric calculations.
- Geocoder for geographic coordinate conversion to find each of 155 urban area locations.
- Folium and Streamlit for interactive mapping and data visualization.
- OpenStreetMap (OSM) and GTFS data for building the transport network background as an actual interactive map.

5.3.2 Outputs

As we shall discuss, this research work generated the following datasets as outputs:

- The transportation networks of Rome with stations and routes marked.
- Accessibility rankings of healthcare facilities in Rome, illustrating the proximity of public transport nodes to each health service.
- Critical transportation hubs and vulnerable nodes identified through the centrality and resilience analysis.

5.4 Methodology

This research focuses on evaluating the accessibility of healthcare services through buses as a public transportation network in Rome. The methodology involves the application of complex network theory to analyze transport infrastructure, node importance, and system resilience concerning the accessibility of health services in Rome. The study was carried out in several stages, outlined below.

5.4.1 Complex network construction

A key part of the research was the construction of a complex network to model the accessibility of health services in Rome, using the bus as a public transportation system.

- Nodes and Links Representation: In the complex network, transportation stations (bus stops) were modeled as nodes, while the routes connecting them (bus lines) were represented as links. This network-based model allowed for analyzing the structural properties of the urban public transportation systems in Rome.
- Multi-layer Network Construction: The research involved the creation of single-mode networks that accounted for the bus network.

5.4.2 Network topology and centrality analysis

To understand the importance of each station within the transport network and to evaluate the accessibility of healthcare services, several centrality metrics were applied.

Topology-based metrics emphasize the internal dynamics of transportation networks. These metrics, also known as "centrality metrics", are constructed using the essential graph-based elements of the transportation network, such as nodes and edges for traffic flow [23]. Centrality, a key concept in network theory, measures the importance of a network's nodes. Public transport stations with high node degrees are more likely to serve as transport hubs, due to their high level of connectivity with other stations. They are likely to receive a higher volume of passenger and vehicle flows and serve as key nodes for the consolidation and distribution of residents.

Researchers have developed numerous centrality metrics to determine the significance of nodes and to characterize the properties of urban public transportation in complex networks [24, 25]. Understanding the significance of transportation network components and protecting them accordingly can help increase the network's resilience and reduce its susceptibility to vulnerabilities. This study employs four centrality metrics to analyze resilience: Degree Centrality (DC), Betweenness Centrality (BC), Closeness Centrality (CC), and Eigenvector Centrality (EC) [26]. A node is considered significant if it keeps the network connected. Centrality measures vary based on the method of measuring the system's coherence, such as the number of shortest paths that pass through a node. Below, we discuss the analytical formulation of each measure, which is considered applicable in transportation systems.

Degree centrality (DC) measures the number of links that a node has and by measuring this feature, it identifies the network hubs [27]. Mathematically, the degree centrality of specific node v is expressed as

$$DC(v) = \frac{Degree(v)}{N-1}$$

where $Degree(v)$ denotes the number of connections of node v, and N is the total number of nodes in the network [28, 29]. Nodes with a high degree centrality in a transportation system are referred to as transportation hubs [30]. A stop with a high degree centrality serves as a significant point for transfers between different modes of transport systems or various lines. While nodes with numerous connections are important, degree centrality does not consider traffic loads, which is a limitation of this metric. Therefore, additional metrics are needed to address this limitation [31].

Betweenness Centrality (BC) measures the importance of a node by evaluating the frequency at which it lies on the shortest path between pairs of other nodes [27]. The formula is given by:

$$BC(v) = \sum_{s \neq t} \frac{\sigma_{st}(v)}{\sigma_{st}}$$

where σ_{st} represents the number of shortest paths from node s to node t, and $\sigma_{st}(v)$ is the number of paths passing through node v. Nodes with high betwenness centrality are frequently critical because they serve as checkpoints, usually the only nodes connecting to different parts of the network, for example, a bridge on the major route [32]. The application of betweenness centrality has been studied in numerous studies; for instance, to examine the geopolitical aspects of a city, the rank of betweenness centrality was measured [33].

Closeness Centrality (CC) measures how close a node is to all other nodes in a network [27]. The closeness centrality of node i is formulated as follows:

$$CC_i = \frac{N-1}{\sum_{i,j \in V} d_{ij}}$$

where N is the number of nodes, d_{ij} is the length of the shortest path between nodes i and j, and V is the set of all nodes in the network. Based on closeness centrality, the nodes that have a closer distance than the rest are more important. From a transportation point of view, nodes with high centrality are important because they can reach plenty of other nodes, so they are proper to assume as hub points. Wang studied the level of centrality of each node, and the nodes were bus stations in Guangzhou [34].

Eigenvector Centrality (EC) covers the limitation of degree centrality, where the node is important based on the number of connections it has with the other nodes. Degree centrality does not account for the significance of the connected nodes and assumes all nodes are equal [35]. However, eigenvector centrality considers a node important if it connects to other important nodes. Thus, a node's eigenvector centrality is examined by the importance of its neighbors [36]. The formula for Eigenvector Centrality of node v is

$$EC(v) = \frac{1}{\gamma} \sum_{u \in N(v)} EC(u)$$

where γ is a constant, and $N(v)$ is the set of neighbors of node v. Eigenvector centrality can be used to determine nodes that strongly impact the network's overall connectivity and structure. From a transportation perspective, high-ranked eigenvector centrality nodes are transportation hubs that have the most significant influence on the network's overall cohesion. Each measure focuses on a unique aspect of system properties and has potential applications in transportation networks with differing theoretical assumptions. However, nodes with high flow rates can be

identified using metrics like degree centrality. Assessments show that some measures are strongly correlated with each other, despite their differing theoretical assumptions, leading to redundant data. For instance, in physical networks, there is a strong correlation between eigenvector centrality and closeness centrality [15]. All the mentioned metrics were proposed for further investigation.

5.4.3 Spatial accessibility to healthcare services

We obtained the geographical coordinates for 155 urban zones in Rome from Wikipedia. These coordinates were initially in degrees, minutes, and seconds (DMS) format. Using the open-source Python library Geocoder, we converted them into decimal degrees (DD) format, which is commonly used in geographic information systems (GIS). This conversion was crucial for seamless integration into the Folium library, a Python package widely used for interactive mapping and visualization tasks. To process the coordinates, we wrote a script to parse the DMS format and convert it to DD automatically. This script utilized the Geocoder library to ensure accuracy and consistency in the conversion process. Once converted, these coordinates were stored in a structured format suitable for GIS applications.

Accessibility to healthcare services, particularly in Rome, was measured using a transit network-based approach:

- Shortest Path Calculation: The Python library NetworkX was used to calculate the shortest path between urban zones and healthcare facilities, taking into account both the number of stations close to each healthcare service and the route distance (in terms of time and transfers) required to reach those facilities.
- Distance Estimation: The Haversine formula was applied to estimate the geographical distance between urban zones and healthcare facilities, considering the Earth's curvature for accurate results. OpenStreetMap (OSM) data was used to map the transport network and facilitate the distance calculations.
- Service Accessibility Ranking: Healthcare facilities were ranked based on their accessibility from different urban zones. This analysis was conducted by considering the proximity of bus, subway, and train stations to each facility and calculating the transit time required to reach them.

5.4.4 Resilience and robustness assessment

The research also examined the resilience and vulnerability of the transport systems in Rome. This was essential to evaluate how these networks respond to disruptions, such as infrastructure failures or natural disasters.

- Resilience Triangle Analysis: The resilience triangle concept was applied to measure the time it takes for the transport system to recover from shocks. By simulating disruptions (such as the closure of key transportation hubs), the study assessed how quickly the network could return to normal operations.
- Vulnerability Analysis: The vulnerability of each city's transport system was evaluated by simulating the removal of critical nodes (stations) and observing the resulting changes in

network performance. This analysis helped identify which nodes, if compromised, would significantly reduce the system's overall functionality.

5.5 Findings and discussion

This section presents the analytical and graphical results. This research project focused on evaluating healthcare accessibility across Rome's 155 municipal divisions using public transport networks. By analyzing various metrics and employing advanced computational tools, we identified several key findings related to disparities in healthcare accessibility, the distribution of health services, and the impact of public transport infrastructure. Below, we outline the main findings of this research.

Using a georeferenced approach, the routes of the bus transportation network in Rome have been mapped. Figure 5.1 illustrates the network related to our case study; notably, we constructed an unweighted graph to represent these networks.

To analyze transportation infrastructure using insights from bus centrality metrics, the following parameters have been measured for each node (Bus stop) in the network: Degree Centrality, Closeness Centrality, Betweenness Centrality, and Eigenvector Centrality. Incorporating these centrality metrics into the analysis allows for a nuanced understanding of the transportation network. By visualizing the spatial distribution of top-ranked nodes, as shown in Figure 5.2, urban planners can prioritize key nodes for infrastructure investments, maintenance, and strategic planning to strengthen the network's long-term resilience against potential environmental hazards.

5.5.1 Disparities in healthcare accessibility

One of the primary outcomes of this research was the identification of areas within Rome that face limited or challenging access to hospitals via public transport. Through a detailed spatial analysis, we uncovered significant disparities in healthcare accessibility across different urban zones. Areas located farther from central transport hubs were found to have reduced access to hospitals, highlighting a need for targeted interventions to improve public transport routes in underserved regions.

Figure 5.1. Illustration of the bus network routes of Rome urban areas

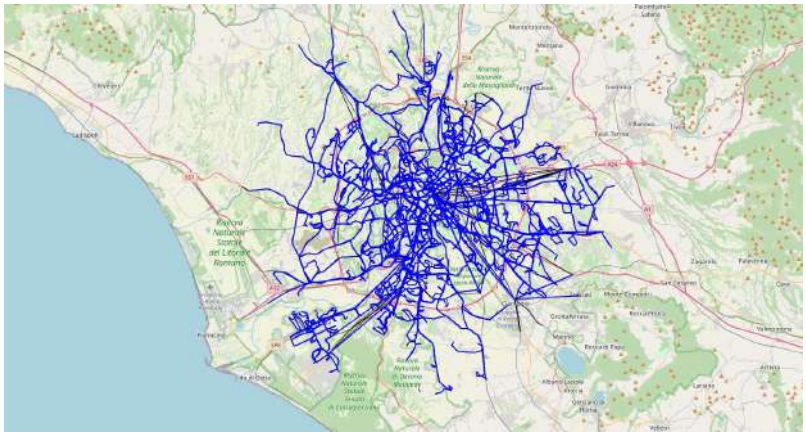
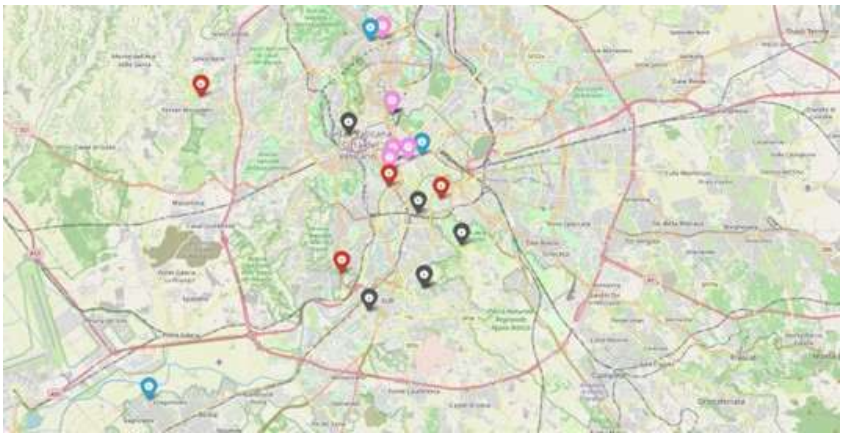


Figure 5.2. Mapping the high-centrality-ranked stops in Rome. The red pop-ups indicate the results obtained from the combined network betweenness centrality analysis, while the pink pop-ups symbolize the nodes with high Eigenvector centrality. The gray pop-ups represent nodes with high closeness centrality, and the blue pop-ups show the results from degree centrality; for each centrality metric, the top 5 have been mapped, but some results have been correlated, so we don't have 5 pop-ups for each color



The results suggest that underserved areas could benefit from expansions in bus routes, increased service frequency, and improved connections between transportation modes. This would enhance accessibility to essential healthcare services and support territorial sustainability, ensuring equitable healthcare access for all residents. Table 5.1 below represents the top 5 node bus stops in decreasing order.

Table 5.1. Top 5 node bus stops

id	Name	latitude	longitude
72	COLLATINA/BIROLLI	1.905024	12.599527
1659	PIAZZALE DELLA FARNESINA	41.937368	12.459218
73	PESENTI/TIBURTINA	41.932137	12.599443

5563	REDATTORI/GRAFICI	41.764272	12.469673
3158	DI MATTEI/S. MARIA PIETA' (H)	41.941596	12.419322

5.5.2 Visualization of hospital and transport accessibility

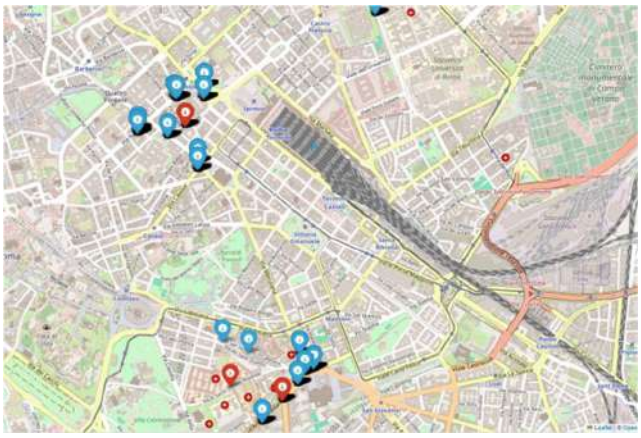
We developed an interactive map to visualize the distribution of hospitals and public transport stations, enabling a comprehensive analysis of healthcare accessibility across Rome. We evaluated the spatial distance from the center of each urban zone to the nearest healthcare service using open-source data on health services in Rome and UPTS (Urban Public Transport System). Figure 5.3 shows the location of these health services.
Firstly, we assessed the accessibility of UPTS stops in Rome by measuring the distance from each urban zone to the nearest health service and the number of bus stops within 300 meters of the healthcare main entrance door. This analysis helps determine the ease of access to healthcare services for residents of different zones. In the second part, we analyzed the number of UPTS bus stops that need to be passed to reach the nearest healthcare services. This provides insights into the convenience and efficiency of the public transport routes for health services. The third part of the workflow involved generating interactive maps of the real UPTS network, allowing users to visualize and explore the spatial distribution and accessibility of health services in Rome. This comprehensive approach helps us understand the overall accessibility and identify areas that may require improvements in public transport connectivity to healthcare services.

Figure 5.3. Health services located in Rome

We uploaded the health dataset and overlaid the hospital locations onto the same interactive map. This approach allows users to quickly compare the distribution of hospitals with the locations of the urban zones, enhancing the analysis of accessibility to healthcare services across Rome. Figure 5.4 below illustrates this mapping, with red markers highlighting the hospitals and blue markers denoting the urban zones. To assess the accessibility of bus stops, we identified and mapped the bus stops located within 300 meters of each cardiology health service. In the

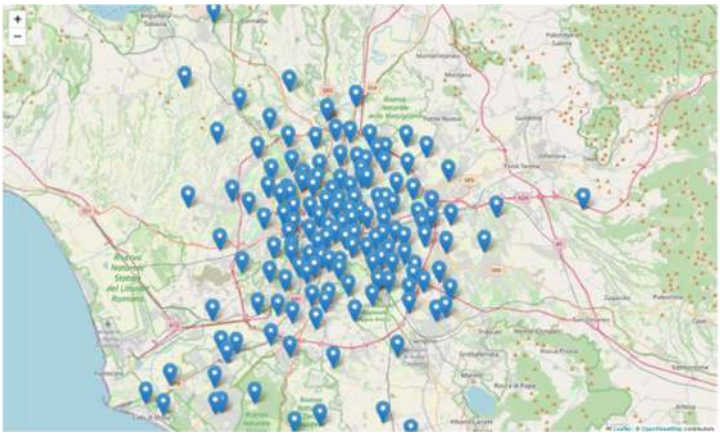
resulting visualization, red pop-ups represent the healthcare services, while blue pop-ups indicate the urban zones.

Figure 5.4. Bus stops which are within 300 meters of cardiology centers, Red pop-ups are cardiology services and Blue pop-ups show the closest bus stops.



Then, using the Municipality Geoportal of Rome, we find the geometry of all 155 areas located in Rome; utilizing Folium, we created an interactive map displaying Rome's urban zones. Each zone was marked with a blue pop-up for easy identification. The interactive map allows users to explore and analyze the spatial distribution of these zones, providing valuable insights into the geographic layout of Rome. Additionally, the map includes features such as zooming and panning, enhancing the user's ability to interact with and examine specific areas in detail. Figure 5.5 below visualizes the 155 zones in Rome with blue pop-ups. Fig 5.5 maps the location of these 155 areas.

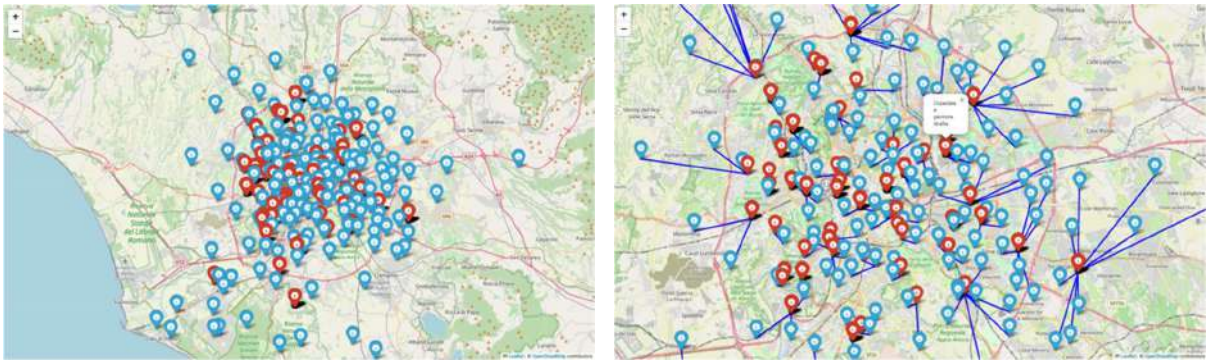
Figure 5.5. 155 Urban areas located in Rome



A framework to study the distance between all Rome zones and healthcare services has been developed. After obtaining the coordinates for 155 urban zones in Rome and converting them into

decimal-degree format, the next step involved developing a Python script to calculate the nearest hospital for each zone. This process required implementing the Haversine formula, which calculates the shortest distance between two points on the Earth's surface based on their latitude and longitude. The Haversine formula considers the Earth's curvature, providing accurate distance measurements. By applying this formula to each urban zone's coordinates and the coordinates of nearby hospitals, the script identified the closest hospital and computed the distance. Consequently, we obtained a dataset that included the nearest bus stop station for each healthcare service. Figure 5.6 (left) shows the overview of the location of both areas and health services. We filtered bus data out of UPTS data frames and then combined datasets of UPTS and dataset of healthcare services in Rome, Figure 5.6 (right) illustrates the interactive maps that have been generated to reveal the distance between the center of each zone and its closest healthcare service; the red pop-ups stand for health service and the blue pop-ups show all 155 areas located in Rome.

Figure 5.6. Distribution of Rome areas and health services



To deepen the study on public transit access to healthcare services, we identify the nearest hospital to each rail station in Rome, as illustrated in Figure 5.7.

Figure 5.7. Nearest healthcare service from Rome's railway stations

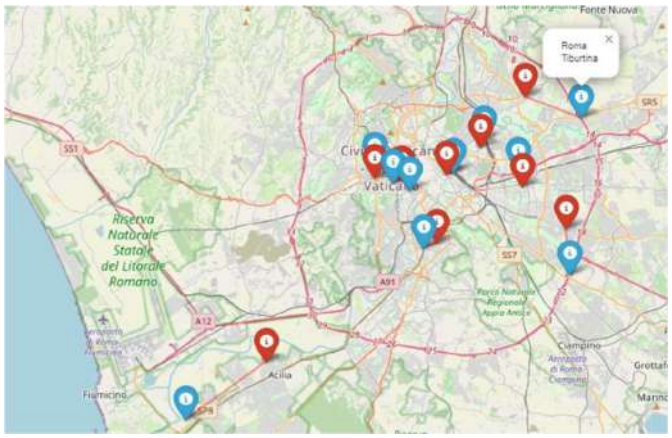
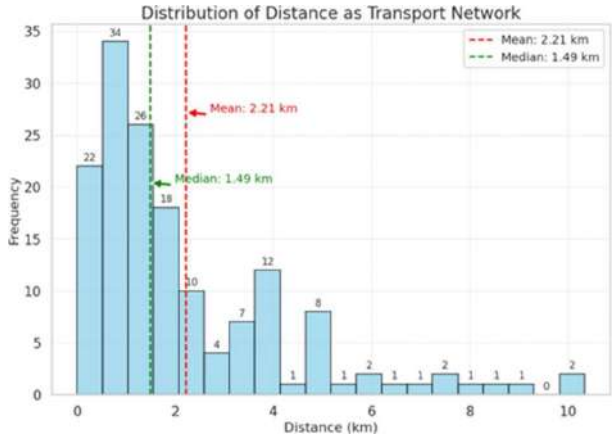


Figure 5.8 summarizes the accessibility of health services from each of the 155 zones, providing an overview of the distance distribution throughout the city. According to the graph analysis, the points closest to hospitals are 11C Garbatella, 19C Ottavia, 17A Prati, 18B Val Cannuta, and 6A Torpignattara, with respective distances of 0.02 km, 0.09 km, 0.12 km, 0.16 km, and 0.18 km. In contrast, the points with the largest network-based distances from health facilities are 20O Martignano, 8H San Vittorino, 20N Cesano, 19H Santa Maria di Galeria, and 12N Santa Palomba, with distances measuring 19 km, 14 km, 13 km, 9.8 km, 8.9 km, and 8.6 km, respectively.

Figure 5.8. Distribution of network-based distances from each zone to the nearest healthcare facility



5.5.3 Visualization of hospital and transport accessibility

As the next phase of the project, we aimed to enhance the presentation of visualizations by utilizing the open-source library Stream-lit. This allowed us to create both local and public links for the applications. We set up a public GitHub repository containing all the input data and notebooks. This setup enables users to share the application link without requiring them to run all the code themselves. The repository includes detailed documentation, data preprocessing scripts, and interactive visualization tools, making the analysis accessible and easily reproducible. The public link to the application: https://rometerminals.streamlit.app/. Technically, we employed Stream-lit to build a user-friendly interface for data visualization and interaction. The application dynamically loads and processes data, allowing users to interactively explore various aspects of the dataset. The GitHub repository features structured directories for data, scripts, and notebooks, ensuring organized and straightforward navigation. Additionally, the repository leverages GitHub Pages for documentation, providing detailed instructions and context for each project component.

5.5.3 Resilience analysis

The study of resilience in public transportation networks, such as the bus stop and route system in Rome, is essential for assessing the network's ability to withstand disruptions, such as the removal of certain nodes (bus stops). Resilience in this context refers to the network's capacity to maintain overall functionality and connectivity even when parts of it are compromised or

removed. In this analysis, we examined the worst-case scenario and we removed the top five nodes (from the point of view of centrality) in bus network (Nodes: 28, 72, 1659, 29, 304).

LCC Size (Largest Connected Component): This metric represents the number of nodes in the largest sub-network where each node is reachable from every other node. A decrease in LCC size indicates a loss of connectivity. Initially, the LCC size was 7474, and after removing nodes, it reduced slightly to 7471. This minimal change in size indicates that the network retained most of its connectivity, showcasing strong resilience. Despite the node removals, the majority of the network remained interconnected, which is a positive indicator for the system's robustness. LCC Density: Network density is defined as the ratio of the number of edges (connections) to the number of possible edges between nodes. The initial density was 0.000345, which is typical for sparse networks like public transportation systems. After node removal, the density slightly increased to 0.0003451. This suggests that even with fewer nodes, the remaining bus stops became slightly more interconnected, potentially as a result of fewer redundant or isolated nodes. The minimal change here further indicates resilience, as the network structure remained intact.

Global Efficiency: This metric measures how efficiently information (or passengers, in this case) can travel across the network. Higher efficiency indicates shorter paths between nodes. The initial global efficiency was 0.0377, and it dropped slightly to 0.03766 after node removal, indicating a minor loss in the ability to provide efficient travel routes. The small change in this metric demonstrates that the network remained relatively efficient, but some routes might require longer connections due to node removals.

Average Clustering Coefficient: This measures the degree to which nodes in the network tend to cluster together, forming interconnected groups. A low clustering coefficient, such as the initial 0.0259, suggests that bus stops are primarily organized in linear routes rather than clusters. After node removal, the clustering coefficient increased marginally to 0.02594, indicating a negligible effect on the network's overall structure. The small increase suggests that while some stops were removed, the overall tendency toward forming small clusters of stops remained unaffected.

Average Path Length: This metric represents the average number of steps needed to travel between two randomly selected nodes in the network. Initially, the average path length was 34.86, indicating that traveling between bus stops typically required many connections or transfers. After node removal, the path length increased slightly to 34.88, suggesting that while the overall structure remained intact, the removal of some stops slightly increased the number of connections required to travel between certain points. This slight increase could lead to marginally longer travel times for passengers, which is a factor to consider in resilience studies. Table 5.2 summarizes the resilience metric results.

Table 5.2. Summary of the resilience metrics pre and post node removal

Metric	Description	Initial Value	Post-Removal Value	Interpretation
LCC Size	Number of nodes in the largest connected component.	7474	7471	Minimal change indicates strong resilience; most of the network remained interconnected.
LCC Density	Ratio of edges to possible edges between nodes.	0.000345	0.0003451	Slight increase suggests remaining bus stops became more interconnected despite fewer nodes, indicating resilience in network structure
Global Efficiency	Measures the efficiency of information travel across the network.	0.0377	0.0375	Minor drop indicates slightly longer paths between nodes; overall efficiency remains relatively intact.
Average Clustering Coefficient	Degree to which nodes cluster together.	0.0259	0.02594	Negligible increase indicates that network structure remains primarily linear, with small clusters forming as well.
Average Path Length	Average number of steps needed to travel between randomly selected nodes.	34.86	34.88	Slight increase in connections required suggests marginally longer travel times for passengers, but overall structure remains robust.

From a resilience perspective, the minimal changes in the key metrics after node removal demonstrate that the bus network in Rome is resilient. The slight reductions in global efficiency and the increase in path length indicate that while some localized effects (such as longer routes for certain areas) might occur, the overall structure of the network remains robust and functional. The resilience of this network is especially evident in the small change in LCC size, which suggests that most of the network remains connected even when parts of it are removed.

This analysis is critical for transportation planners aiming to enhance the system's resilience. Even though the network can withstand certain disruptions, further improvements could focus on optimizing routes or adding redundancy to minimize the impact of node failures, thus ensuring both connectivity and efficiency are maintained during unforeseen events. The next phase of the project is to expand the resilience study into accessibility of health services from each urban point through the public bus routes, and the node removal scenario will measure the effectiveness of each critical node in health services accessibility in Rome.

5.5.4 Interactive application for public use

As the next phase of the project, we aimed to enhance the presentation of visualizations by utilizing the open-source library Stream-lit. This allowed us to create both local and public links for the applications. We set up a public GitHub repository containing all the input data and notebooks. This setup enables users to share the application link without requiring them to run all the code themselves. The repository includes detailed documentation, data preprocessing scripts, and interactive visualization tools, making the analysis accessible and easily reproducible. The public link to the application: https://rometerminals.streamlit.app/. Technically, we employed Stream-lit to build a user-friendly interface for data visualization and interaction. The application dynamically loads and processes data, allowing users to interactively explore various aspects of the dataset. The GitHub repository features structured directories for data, scripts, and notebooks, ensuring organized and straightforward navigation. Additionally, the repository leverages GitHub Pages for documentation, providing detailed instructions and context for each project

component. The info which can be found in the interactive map has been summarized in Table 5.3.

Table 5.3. Closest hospital to each train station

Train station	Nearest Hospital	Distance (km)
Roma Termini	CASA DI CURA MARCO POLO	0.441
Roma Nomentana	CASA DI CURA POLICLINICO ITALIA	0.518
Roma San Pietro	OSPEDALE PEDIATRICO BAMBINO GESU*	0.597
Roma Valle Aurelia	OSPEDALE SAN CARLO DI NANCY	0.754
Roma Trastevere	OSPEDALE PEDIATRICO BAMBINO GESU	0.831
Roma Ostiense	CONCORDIA HOSPITAL	0.905
Roma Prenestina	C.D.C. FABIA MATER	1.015
Roma Tuscolana	POLICLINICO CASILINO	2.972
Roma Tiburtina	VILLA TIBERIA HOSPITAL	3.368
Roma Ostia Antica	CASA DI CURA MERRY HOUSE/O.GERIATRICO RO	6.464

5.6 Policy implications and recommendations

Analyzing Rome's health services spatial patterns reveals that different locations with varying levels of accessibility experience different reaching network-based distances to the closest health service.

Some outer areas fail in terms of vertical equity and average accessibility and have a more than 10 km network-based distance to reach the closest health service using a Bus as a public transportation, which means reaching them is particularly problematic during emergencies. On the other hand, central urban zones are found to be the most accessible through public bus transportation routes. This easy accessibility is due to the high density of health services located in central areas and the availability of alternative routes to get a health service [37]. Enhancing infrastructure leads to physical redundancy, closes infrastructure gaps, and provides various alternatives to create and strengthen more resilient networks. Based on the findings of this research, several key recommendations can be made to improve healthcare accessibility in Rome:

- Expand public transport routes and frequency: Especially in underserved areas, increasing the number of available transport routes and reducing waiting times could significantly enhance access to healthcare facilities.
- Improve connections between transport and healthcare facilities: Establishing direct routes between major transport hubs and hospitals would reduce travel times and improve accessibility for residents.
- Implement fare policies: Reducing travel costs for healthcare-related journeys, particularly for vulnerable populations, could help minimize financial barriers to accessing essential services.

These recommendations, based on data-driven insights, can inform future policy decisions aimed at enhancing the public transport infrastructure in Rome. By improving connectivity and reducing travel costs, the city can foster a more sustainable and equitable healthcare system for all residents.

A key benefit of this research is its potential to contribute to the reduction of health inequities within Rome. By identifying areas with poor healthcare accessibility and providing data-driven solutions, the study offers practical steps toward addressing disparities in healthcare access. Improvements in public transport infrastructure can have a direct impact on health outcomes, especially for vulnerable populations in underserved regions. Enhancing accessibility will not only improve the efficiency of healthcare delivery but also promote a more equitable urban environment.

Policymakers should leverage the data-driven insights provided by this research to inform their decisions. By utilizing network analysis and geographic information system (GIS) tools, decision-makers can:

- Continuously monitor healthcare accessibility and adjust transport policies based on real-time data.
- Use predictive modeling to anticipate future transportation needs in response to demographic or urban changes.

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6. Estimation of Dynamic Origin-Destination Matrices in a Railway Transportation Network integrating Ticket Sales and Passenger Count Data *(G. Galliani, P. Secchi, F. Ieva)*[32]

6.1 Introduction

The present study is published in Galliani et al (2024) and aims to develop a new methodology for estimating dynamic Origin-Destination (OD) matrices specifically designed for railway transportation networks. This methodology is innovative in its integration of diverse data sources, namely ticket sales and Automated Passenger Counting (APC) systems. This fulfills GRINS goals in developing tools for supporting sustainable mobility, with a focus on green mobility and mobility of densely populated areas.

In this perspective, the core objective of the paper is to enhance the accuracy and reliability of OD matrices, which are essential tools for understanding passenger flow, optimizing transportation schedules, and making informed policy decisions. Additionally, the study seeks to address common challenges in the field, such as data incompleteness and the need for real-time analysis. Also, these latter issues are relevant to GRINS assets in terms of data fusion and gap filling of missing information.

Within the challenge of estimating dynamic Origin-Destination (OD) matrices in a railway network – which represents a critical task for effective transportation management and urban planning - traditional methods often fall short due to limitations in data availability and accuracy, particularly in the context of evolving mobility patterns post-COVID-19. This study seeks to overcome these challenges.

The paper's key objectives include:

1. Developing a robust pipeline for dynamic OD matrix estimation that can adapt to various data environments.
2. Demonstrating the application of this pipeline on the Trenord railway network in Lombardy, Italy.
3. Evaluating the effectiveness of the Iterative Proportional Fitting (IPF) algorithm in refining OD matrices derived from ticket sales and APC data.

The research is driven by the following key questions:

- Integration of Data Sources: How can ticket sales and APC data be effectively integrated to provide a more accurate and comprehensive estimation of OD matrices in railway networks?

32 This chapter summarizes the content of an article published in 2024 on Transportation Research Part A: Policy and Practice (https://doi.org/10.1016/j.tra.2024.104246).

- Methodological Challenges: What are the primary challenges in merging these two different types of data, and how can they be overcome?
- Effectiveness of the Proposed Method: To what extent does the proposed methodology improve the detection of anomalies in passenger mobility, and what are the implications for urban transport management?

6.2 Outline of literature background

The paper provides a thorough review of the existing literature on OD matrix estimation methods. It delves into the historical and contemporary approaches to OD matrix estimation, highlighting the evolution from static to dynamic matrices. Traditional methods like travel surveys and AFC systems are discussed, with an emphasis on their limitations in modern, complex transportation networks. In fact, pursuit of estimating OD matrices in transportation networks dates back to the late 1970s [Low, 1972, Robillard,1975, Wilson, 1970]. Early efforts heavily relied on surveys and manual data collection, posing challenges due to the sporadic availability of passenger surveys, mainly because of their cost and relevance limitations [Ben-Akiva and Morikawa, 1989].

Then the literature review covers the impact of recent advancements in data collection technologies, such as APC systems, mobile data, and smart cards, which have transformed the field of OD estimation. These methods, while valuable, often suffer from limitations such as incomplete data, the high cost of data collection, and delayed availability of results. The review includes a discussion of the benefits and challenges of these technologies, especially in terms of data accuracy, cost, and privacy concerns.

In particular, advancements in Automatic Data Collection Systems (ADCS) and mobile communication data collection have transformed the landscape. An extensive literature review on the topic may be found in [Mohammed and Oke, 2023]. Technologies like Automatic Fare Collection (AFC), Automatic Vehicle Location (AVL), and Automatic Passenger Counting (APC) have significantly enhanced the accuracy and efficiency of OD estimation. Examples of the use of such technology for OD estimation can be found in [Ait-Ali and Eliasson, 2019, Cui, 2006, Gordon, 2012, Liu et al., 2021, Torti et al., 2021, Wang, 2010, Zhao et al., 2007].

Despite not initially designed for integrated OD estimation, these technologies offer rich data, reduce collection costs, provide larger sample sizes than surveys, and automate the estimation process [Zhao, 2004]. As a result, the availability of OD matrices in the future is expected to significantly increase [Cui, 2006].

Among these technologies, AFC systems, particularly smart card data, have become the focal point of recent research [Wu et al., 2021, Yang et al., 2020, Chen and Fan, 2020]. Smart cards are widely used in transportation networks across major cities such as Milan, Paris, London, New York, Boston, Beijing, and Hong Kong [Torti et al., 2021, Zannat and Choudhury, 2019, Hussain et al., 2021], offering substantial and almost real-time insights into people's movements. Consequently, smart cards are increasingly replacing surveys in tackling OD estimation challenges. However, estimating accurate OD data for bus or railway networks without AFC systems remains challenging. A potential solution involves leveraging mobile phone data (e.g., Wi-Fi traces, call

data records, or global positioning system for mobile communication data) combined with AVL to infer boarding and alighting passengers at stops [Ge and Fukuda, 2016, Jafari Kang et al., 2020, Munizaga and Palma, 2012].

The section also explores the challenges of data integration, particularly when dealing with incomplete or heterogeneous data sources. The concept of data fusion, where multiple data sources are combined to fill gaps and enhance accuracy, is a key focus. In fact, data fusion combines multiple data sources to enhance the robustness of OD estimates. To do this, the literature outlines various approaches, including the use of smart card data, mobile communication data, and advanced computational algorithms like neural networks, regression models, and gravity models. These studies underscore the benefits and limitations of each method, highlighting the potential for integrated data approaches to overcome specific challenges related to data sparsity and real-time applicability.

Our work develops an approach to estimate, with high time frequency, OD matrices. It exploits data readily available to most transportation operators equipped with APC systems but not disposing of AFC ones. Specifically, we leverage ticket and subscription data from a railway network, developing appropriate assumptions to convert this data into OD seeds. These seeds are then combined with passenger counts collected by the APC system to correct the partial estimates accounting for the totality of trips happening in the network.

In general, information provided by ADCS may be incorporated into a model for OD estimation in a twofold way. On one hand, AFC or APC counts may be integrated into iterative algorithms, in a data fusion flavour, to generate seeds of matrices estimation and/or adjust marginal counts. This approach is becoming more and more popular due to the growing availability of data coming from automated digital counting systems. On the other hand, a more traditional approach to tackle the OD estimation challenge comes from the field of trip distribution modeling. A broad review of models for human mobility is presented in [Barbosa et al., 2018]. Among them, growth factor, genetic algorithms and gravity models are some of the most widely applied techniques [Mohammed and Oke, 2023]. Growth factor models involve updating a seed OD matrix based on growth rates calibrated to match alighting and boarding counts. In this class of models, the Iterative Proportional Fitting (IPF) [Evans, 1970, Macgill, 1977], also known as the Furness method, is the state-of-the-art approach for estimating OD flows [Ji et al., 2014] and has been employed in several works in the field [Cui, 2006, Gordon, 2012, Liu et al., 2021, Torti et al., 2021, Zhao et al., 2007]. Gravity models, on the other hand, estimate OD matrices using a gravitational attraction model, incorporating population masses and distance or travel cost measures. They assume a positive association between flow volume and population size and factors in the effects of distance, space, cost, or travel time on interactions [Wheeler, 2005]. Other works rely on entropy maximization, proven to be an equivalent approach to gravity models [Ait-Ali and Eliasson, 2019, Ge and Fukuda, 2016, Wong, 2005].

Lastly, it is important to notice that many studies focus on static OD matrix estimation, describing trips between zones within a fixed reference period. However, the increasing abundance of data provided by the introduction of ACDS prompts interest in dynamic OD matrix estimation,

introducing a temporal dimension which shifts the focus on monitoring mobility patterns instead of estimating them only [Khoshkhah et al., 2022].
Literature in this area is still quite limited [Ait-Ali and Eliasson, 2019, Bierlaire and Crittin, 2004, Cerqueira et al., 2022, Zeng et al., 2015, Fujita et al., 2017] and divides into dynamic a posteriori estimates [Ait-Ali and Eliasson, 2019] and real-time estimation for short-term prediction [Bierlaire and Crittin, 2004, Zeng et al., 2015].
Our proposed dynamic procedure estimates weekly OD matrices over six months, thus placing itself in the a posteriori estimates field.

6.3 Data and descriptive statistics

The study is geographically focused on the Trenord railway network in Lombardy, Italy. This network is crucial for regional mobility, connecting key urban centers and serving as a lifeline for daily commuters. This region represents a complex and densely populated area, making it an ideal case study for testing the proposed OD matrix estimation method. Obviously this case study focuses on highly populated urban areas, but the methodology developed is flexible enough to be adapted also in other contexts where different conditions are present.
The data covers a substantial time period from May 1, 2022, to December 31, 2022, with a focus on the months from June to December to capture seasonal variations in passenger behavior.
The study integrates three primary data sources:

- Ticket and Subscription Sales Data: Covering transactions from May 1 to December 31, 2022, detailing journeys involving 46 stations within the study scope, the dataset includes detailed records of ticket and subscription sales, encompassing 2,676,629 transactions over the study period. This data provides critical information on origin and destination stations but lacks details on the direction of travel and intermediate stops, necessitating further data integration.
- Automated Passenger Counting (APC) Data: Automated Passenger Counting (APC) data is collected using sensors that monitor passenger boardings and alightings at each station, for each train of the selected lines. This data is vital for validating and refining the OD matrices, providing a ground truth against which ticket data can be calibrated.
- Timetable Data: This data provides actual departure and arrival times for each train ride within the study period.

In the paper, detailed statistics on the data are presented, including a) visual representations of the Trenord network and the lines/stations under study, b) graphical displays of ticket sales trends, passenger counts, and train operations over time, and c) summaries of key statistics such as the number of transactions, train rides, and passenger movements, stratified by time period and station. These descriptive statistics provide a foundational understanding of the passenger flow patterns and the scope of data available for the OD matrix estimation.

6.4 Methodology

The paper employs a multi-step methodology centered on the Iterative Proportional Fitting (IPF) algorithm to estimate dynamic OD matrices. The approach begins by converting ticket and subscription sales data into initial OD matrices, which are then refined using APC data to account for actual passenger movements, then a gravity model is applied to estimate missing data within the OD matrices, based on factors such as the number of passengers boarding and alighting and the distance between stations.

A detailed explanation of the IPF algorithm is provided, including its role in iteratively adjusting the OD matrices to ensure consistency with observed passenger counts. The methodology is designed to be adaptable, allowing it to be applied to different transportation networks and varying data availability.

The main steps of the procedure can be summarized as follows:

- Data Preparation: This involves cleaning the ticket and APC datasets to address inconsistencies and missing values. Techniques such as imputation and smoothing are employed to ensure that the data is suitable for integration.
- OD Seed Matrix Generation: The initial step in generating the OD matrices involves using ticket sales data to create a "seed" matrix. This matrix provides a preliminary estimate of passenger flows, which is then adjusted using APC data to account for trips not captured by ticket sales alone.
- Iterative Proportional Fitting (IPF): The study uses the IPF algorithm to iteratively adjust the OD matrices. The IPF process ensures that the final matrices are consistent with both the ticket sales data and the APC counts, thus enhancing the accuracy of the passenger flow estimates.
- Anomaly Detection: The methodology includes advanced techniques for detecting anomalies in passenger flow. By continuously updating the OD matrices with real-time data, the system can identify unusual patterns that may indicate operational issues or external events affecting travel behavior.

The paper also discusses common challenges in OD matrix estimation, such as dealing with zero cells in the data and ensuring consistency in marginal totals, and the strategies employed to address these issues.

The chosen methodology is justified based on its ability to leverage the strengths of both ticket sales and APC data while mitigating their respective weaknesses. By integrating these data sources, the approach provides a more comprehensive and accurate picture of passenger movements. Additionally, the use of the IPF algorithm allows for dynamic updates to the OD matrices, and the estimation of a time-series of matrices allows the set up of an almost-real-time control system of the anomalies that may be employed for both surveillance and scenario analyses.

6.5 Findings and discussion

The findings of the study demonstrate the effectiveness of the proposed methodology in accurately estimating OD matrices for the Trenord railway network.

Key results include:

- Enhanced Accuracy: The integration of ticket and APC data provides a more accurate estimation of passenger flows compared to traditional methods that rely on a single data source. The refined OD matrices capture the complexity of passenger movements, including variations by time of day, day of the week, and season.
- Anomaly Detection: The study successfully identifies several anomalies in passenger flow patterns, such as unexpected spikes or drops in passenger numbers. These anomalies are linked to specific external events (e.g., strikes, special events) or operational issues (e.g., delays, cancellations). The ability to detect such anomalies in real time is highlighted as a key benefit of the proposed methodology.

A comparison is made between the proposed approach and traditional OD estimation methods, with a focus on the improvements in accuracy, timeliness, and applicability to dynamic transportation systems.
More in general, the dynamic OD matrices generated for the study period are analyzed to reveal interesting patterns that may be included in a post-hoc investigation. In the considered case, anomalies highlighted specific strikes or extraordinary intervention on the networks, confirming the ability of the actual pipeline to properly and timely identifying the disruptions and the related consequences in terms of mobility.
The discussion highlights the strengths of the proposed pipeline, such as its ability to integrate diverse data sources and its adaptability to different contexts. The accuracy of the results, as compared to traditional methods, is also discussed. The paper also acknowledges the limitations of the approach, such as potential inaccuracies in data inputs and the complexity of implementing the IPF algorithm in real-time scenarios.
Specifically, Limitations and Challenges may be resumed in the following:

- the reliance on accurate APC data,
- the need for sophisticated data integration techniques,
- computational and expert knowledge effort in scaling the methodology to other networks or regions with different data characteristics

Suggestions for improving the methodology, particularly in terms of enhancing data quality and refining the gravity model, are provided.

6.6 Policy implications and recommendations

Based on the findings, the paper outlines several policy implications and recommendations for urban transportation planning and management. In fact, the study provides actionable insights for transportation operators, emphasizing the importance of using dynamic OD matrices for more responsive and efficient network management. The ability to monitor and respond to real-time changes in passenger flows is highlighted as a key benefit.
Recommendations are offered for policymakers and urban planners on the use of dynamic OD matrices in long-term infrastructure planning and sustainable transport development. The paper

suggests that such matrices can provide crucial data for optimizing network design, improving service quality, and reducing environmental impact.

Specifically:

- Improved Transportation Planning: The dynamic OD matrices provide valuable insights that can be used to optimize train schedules, manage passenger congestion, and plan for future infrastructure investments. This can lead to more efficient use of resources and improved service quality for passengers.
- Data Integration Policies: The study advocates for enhanced data integration policies among transportation authorities. By promoting the sharing and integration of diverse data sources (e.g., ticket sales, APC data, smart card data), authorities can achieve more accurate and comprehensive insights into passenger behavior and network performance.
- Real-Time Monitoring and Response: The paper recommends adopting real-time monitoring tools to detect and respond to anomalies in passenger flow. This can help transportation operators quickly identify and address issues, such as delays or service disruptions, minimizing their impact on passengers and improving overall network reliability.

The paper concludes with recommendations for future research, particularly in the areas of data integration and real-time OD matrix estimation. The potential for extending the methodology to other modes of transport and different geographical contexts is also discussed.

6.7 Key references

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7. Statistical methods for evaluating the environmental sustainability of urban infrastructure *(A. Gilardi, F. Ieva, L. Sangalli, P. Secchi)*

7.1 Introduction

PM_{10}, particulate matter with a diameter of 10 micrometers or less, is an air pollutant that poses significant environmental and public health challenges, particularly in urbanized and industrial regions. These fine particles, primarily generated by traffic, industrial activities, and residential heating, can penetrate deep into the respiratory system, contributing to a range of health problems, including respiratory infections, cardiovascular diseases, and premature mortality. Several studies have consistently shown a strong association between PM_{10} exposure and adverse health outcomes, particularly in areas with high population density and industrial activities (Pope and Dockery 2006; Brunekreef and Holgate 2002). In Lombardy, one of the most industrialized and densely populated areas of Italy, PM_{10} levels frequently exceed both national and European air quality standards (Marcazzan et al. 2003; Cattaneo et al. 2011), despite a long-standing commitment to reducing air pollution levels. This has raised serious concerns about the long-term health implications for the region's inhabitants, making the analysis of PM_{10} data crucial for developing effective public health policies.

Analyzing PM_{10} data is not only important for tracking compliance with regulatory standards, but also for identifying seasonal and geographical patterns that influence air quality. Numerous studies have demonstrated that PM_{10} concentrations vary significantly across regions depending on external factors such as topography, orography, weather conditions, and human activities (Querol et al. 2004). In Lombardy, where industrial activity and heavy vehicular traffic are concentrated in urban centres, understanding these patterns is essential for formulating mitigation strategies.

In this document, we present a statistical analysis of PM_{10} quality data exploring a method to predict the probability that concentrations exceed a health-related threshold. The analysis starts from the estimation of PM_{10} density distributions at the monitoring station level, followed by a principal component analysis which was developed in the space of density functions to properly account for the compositional nature of the data. The principal component scores were then interpolated at the municipal level using a spatial interpolation technique known as block-kriging and showcasing a possible method for down-scaling air pollution data. The final step of the analysis consisted in computing the probability of exceeding a PM_{10} threshold at the municipal level, providing a detailed map of areas with the highest risk of air pollution.

The remainder of this document is structured as follows. We first provide an overview of the literature regarding air quality data analysis. Then, we describe the database used in our analysis and the statistical framework. We finally present the results and discuss possible policy implications.

7.2 Outline of literature background

Analysis of air quality data is a topic of great interest in environmental science and public health research. Several studies investigated the spatial and temporal variability of air pollution levels and their impact on human health and the environment. For example, Pope and Dockery (2006) conducted a comprehensive review of the health effects of air pollution, highlighting the association between particulate matter exposure and respiratory and cardiovascular diseases. More recently, Chen and Hoek (2020) replicated their efforts and performed a systematic review of evidence of associations between long-term $PM_{2.5}$ and PM_{10} exposure in relation to all-cause and cause-specific mortality. The authors found that long-term exposure to particulate matter is associated with increased mortality from cardiovascular diseases, respiratory diseases, and lung cancer.

In the context of air quality data analysis, several statistical methods have been proposed during the past years to model and understand the spatial and temporal variability of air pollution levels. In particular, focusing on the spatial domain, Berrocal, Gelfand, and Holland (2010) applied spatio-temporal kriging (N. Cressie and Wikle 2011) to model PM_{10} concentrations combining observed data with output from numerical models. Their proposal represents a valuable tool to spatio-temporally downscale and predict air-pollution at a finer spatial scale. Fotheringham, Yue, and Li (2019) used Geographically Weighted Regression to examine the influences of air quality in China's cities, highlighting the importance of considering local factors when analysing air pollution data. We refer to Gelfand et al. (2019) for a comprehensive overview of statistical methods in environmental science.

More recently, also Functional Data Analysis (FDA) (Ramsay and Silverman 2005) tools have been applied to the analysis of air quality data. Ignaccolo, Mateu, and Giraldo (2014), for example, proposed a (universal) kriging approach to model spatially-distributed functional data (e.g. PM_{10} concentrations) taking into account exogenous variables related to meteorology, topology, and orography. Aguilera-Morillo, Durbán, and Aguilera (2017) proposed the adoption of penalized approach methods (as an alternative to kriging and kernel smoothing techniques) to predict the spatial distribution of functional variables.

Probability density functions represent a particular example of functional data (Egozcue, Díaz–Barrero, and Pawlowsky–Glahn 2006) and an idea tool to evaluate the probability that air pollutants' concentrations exceed their regulatory constraints. Their statistical modelling is particularly challenging due to the (infinite) compositional nature of the data and their intrinsic constraint: $\int f = 1$ and $f \geq 0$. The literature is still at the beginning, but some recent contributions have proposed innovative methods to address these challenges. For example, Hron et al. (2016) proposed a method called Simplicial Functional Principal Component Analysis (SFPCA) that allows for the analysis of density functions in the Bayes Space, providing a powerful tool for extracting key patterns of variability from functional data. Their application in the context of air quality data analysis is still limited, but the potential of these methods is promising.

7.3 Data and descriptive statistics

The data provider considered for the analyses described in this study is the European Environment Agency (EEA), which is a supra-national institution that collects and harmonizes air quality measurements for a panel of 38 countries.[33] More precisely, the EEA shares[34] a database that includes both raw and validated air quality measurements obtained from geo-referenced time series data. The data exchange process between each member country and the EEA is handled by a partnership network named European Environment Information and Observation Network (EIONET).

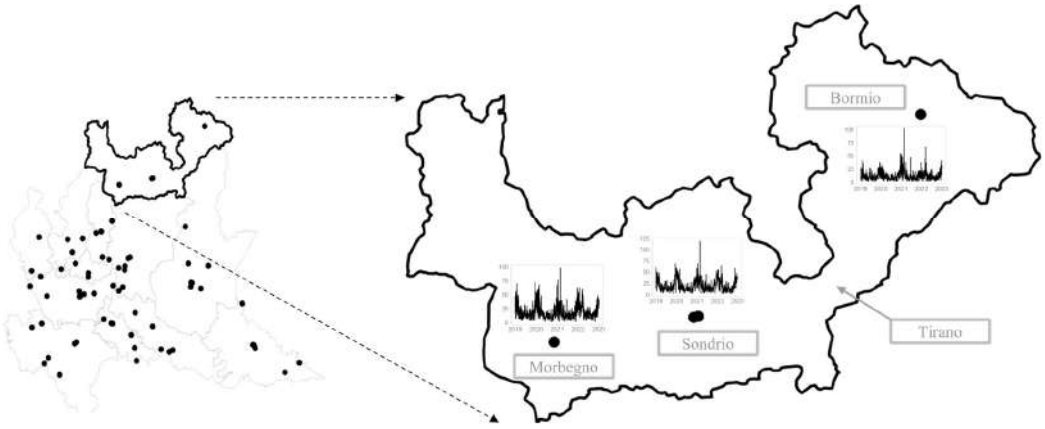
After downloading the complete database from the aforementioned sources, we selected the PM_{10} measurements pertaining to the monitoring station located in the Lombardy region (Italy) during the time period 2018 - 2022. We decided to focus on PM_{10} since it is one of the most commonly measured air pollutants and it has well-known adversarial effects on human health and the environment. Therefore, it is a good candidate to showcase the potential of developing statistical analysis to study environmental and health-related issues. The Lombardy region was selected as a first case study since it is characterized by high population density (especially in the areas near Milan and other parts of the Po Valley), high level of industrialization, and a mix of urban, rural, and mountainous territories. Finally, we focused our efforts on the period 2018 - 2022 since it is, in our opinion, a sufficiently long time period to collect a meaningful amount of data for a statistical approach, but not too long to confound the analyses, mixing long-term trends with short-term fluctuations.

The spatial distribution of the monitoring stations recording PM_{10} in Lombardy during the period under analysis is displayed in Figure 7.1 (left) as black dots. As we can see, the stations are spread in several parts of the region, with a higher concentration near the most important cities like Milan, Bergamo, or Brescia. The right part of Figure 7.1 zooms on the province of Sondrio. Each dot represents a monitoring station, whereas the (spatially-referenced) time series represent the PM_{10} concentration recorded by the closest station. The time series shows that PM_{10} is higher in the winter months and lower in the summer months, which is a well-known pattern due to the increased use of heating systems during colder times. Similar behavior is observed in the other provinces of the region.

[33] The 38 countries are collectively named EEA38 and the complete list can be browsed at the following link: https://land.copernicus.eu/en/faq/general-questions/what-is-eea38

[34] The air-quality database created and shared by the EEA, together with the corresponding meta-data, can be browsed at the following link: https://www.eea.europa.eu/en/datahub/datahubitem-view/3b390c9c-f321-490a-b25a-ae93b2ed80c1

Figure 7.1. Monitoring stations recording PM_{10} in Lombardy in 2018-2022 (left) and zoom on the province of Sondrio (right).

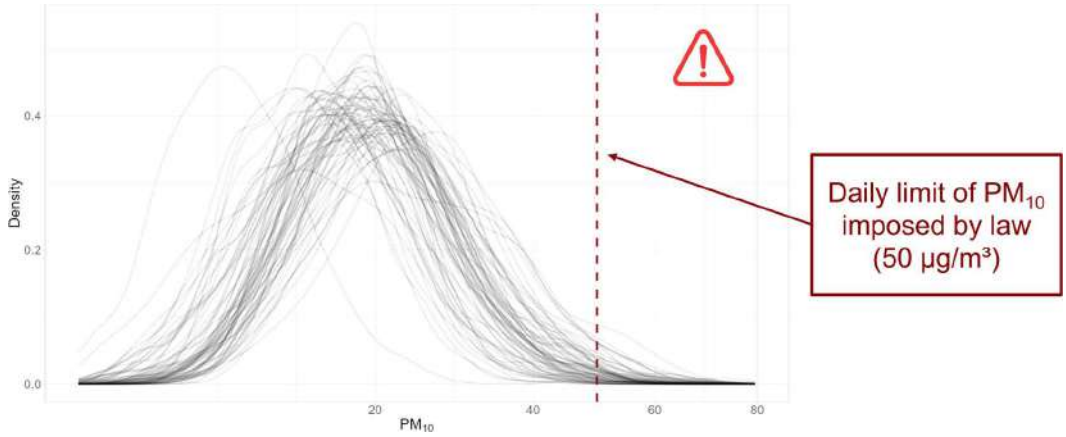


As already mentioned, the objective of our study was to develop a statistical analysis that evaluates the environmental sustainability at the municipal level. As a case study, we decided to focus on the PM_{10} pollutant and predict the probability that, at a certain point, the PM_{10} concentration exceeds a health-related threshold set by local and national authorities. In particular, we focused on the PM_{10} threshold set by the Italian legislative decree n. 155/2010[35], which is equal to 50 $\mu g/m^3$ and must not be exceeded more than 35 times in a year.

The practical computation of such probabilities of exceedance requires a shift in the data representation, going from (spatially-referenced) time series, such as those displayed in Figure 7.1, to (spatially-referenced) density functions. In fact, a density function is a functional data object that represents the probability distribution of a set of data (e.g. air pollution measurements). We computed the PM_{10} density distribution for each monitoring station in Lombardy via Kernel Smoothing methods (Silverman 1986), considering only the measurements recorded during Spring and Summer months. The output is displayed in Figure 7.2. As we can see, the density curves are reasonably symmetric around the mean value (which is around 20 $\mu g/m^3$), but they are sometimes characterized by long right tails, especially in stations located near industrial areas in the Po Valley. The vertical red dashed line denotes the threshold value of 50 $\mu g/m^3$ set by law.

[35] The complete text regarding the legislative decree can be browed at the following link: https://www.gazzettaufficiale.it/eli/id/2010/09/15/010G0177/sg. In particular, we refer to Allegato XI.

Figure 7.2. Density of the PM_{10} concentration for each monitoring station in Lombardy in 2018-2022, considering only spring and summer. The density curves are computed via Kernel Smoothing methods



7.4 Methodology

A proper analysis of PM_{10} density curves must take into account the particular nature of the data. In fact, density curves are not only functional observations, but they are also strictly positive functions that integrate to 1 over their domain. Traditional methods (such as functional logistic regression) do not account for these characteristics and may lead to incomplete or biased conclusions. Therefore, we adopted an ad-hoc approach whose theory is rooted in the so-called Bayes Space, hereby denoted as B^2 (Egozcue, Díaz–Barrero, and Pawlowsky–Glahn 2006).
The Bayes Space represents a generalization of the Aitchison geometry (Aitchison 1982) to density functions, which is crucial for ensuring that statistical analyses respect the compositional nature of the data and their constraints (Egozcue, Díaz-Barrero, and Pawlowsky–Glahn 2006). Furthermore, the Bayes Space, equipped with a certain definition of sum, inner product, and product-by-constant, is a Hilbert Space and, as such, it is isomorphic to L^2 (the space of square-integrable functions) (Van den Boogaart, Egozcue, and Pawlowsky-Glahn 2014). This isomorphism allows us to perform standard operations (e.g. functional regression or functional principal component analysis) on B^2 in a statistically sound manner via the following pipeline:

1. Transform the data from B^2 to L^2 via the centred log-ratio (clr) transformation.
2. Perform the statistical operation in L^2 using, for example, the techniques described in Ramsay and Silverman (2005).
3. Transform the results back to B^2 via the inverse-clr transformation.

We employed the aforementioned strategy to develop a statistical model that predicts the probability of exceeding the PM_{10} threshold using a technique known as Simplicial Functional Principal Component Analysis (SFPCA) (Hron et al. 2016). The SFPCA allows us to extract the functional principal components (FPC) and the corresponding scores of the density functions in the L^2 space. By construction, the (SFPCA) scores are real numbers representing the projection of the original density curves onto the FPC. Considering the spatial dependence among the PM_{10} values recorded by proximate monitoring stations and the need to predict probabilities at the

municipal level, we projected the SFPCA scores on the municipality grid using a spatial interpolation technique known as block kriging (N. A. C. Cressie 1993). Finally, we rebuilt the density curves from the kriged scores and computed the probability of exceeding the PM_{10} threshold.
The complete pipeline of the analyses is detailed as follows:

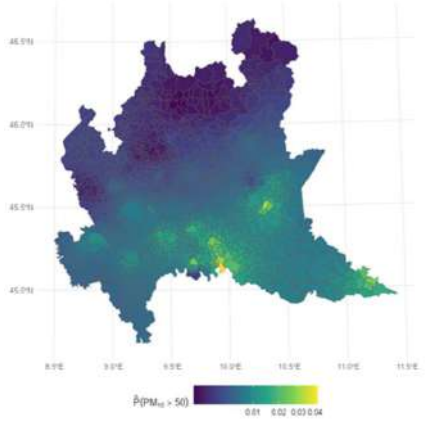
4. Compute the density curves for each monitoring station in Lombardy via Kernel Smoothing methods.
5. Transform the density curves from B^2 to L^2 via the clr transformation.
6. Perform the SFPCA on the clr-transformed density curves. The analyses summarized in the remaining part of this document were performed considering 3 FPC.
7. Krige the SFPCA scores at the municipal level to obtain a map of values all over the Lombardy region.
8. Build the clr-transformed curves from the kriged scores.

Transform the clr-transformed curves back to B^2 via the inverse-clr transformation and compute the probability of exceeding the PM_{10} threshold of 50 $\mu g/m^3$.

7.5 Findings and discussion

The application of SFPCA to the PM_{10} density functions revealed strong spatial dependencies among the FPC scores. These scores provide a compressed representation of the data, highlighting key patterns of variability across Lombardy. Notably, the spatial dependence indicates that certain areas of Lombardy are consistently subject to higher PM_{10} levels, while others experience more modest fluctuations. The analysis also demonstrates that the scores corresponding to the three principal components are almost uncorrelated, indicating that the dominant sources of variability in PM_{10} levels are distinct from one another. This suggests that different geographical or environmental factors may be driving these patterns, such as proximity to industrial activities, traffic density, or topographical features.
As already mentioned, we applied block kriging to reconstruct the PM_{10} densities across Lombardy for areas without direct monitoring. The most relevant outcome of the analysis is the estimation of the probability of exceeding the PM_{10} threshold and the results are displayed in Figure 7.3. As we can see, the highest probabilities are located in the Po Valley, near the most industrialized and flat areas. In contrast, the northern parts of the region (which are characterized by mountainous areas) exhibit lower probabilities, reflecting the lower population density and industrial activity in these areas, but also the combined effect of the topology and orography which influence the dispersion of pollutants.

Figure 7.3. Predicted probability of observing a PM_{10} concentration higher than 50μg/m^3 at the municipal level in Lombardy. The probabilities are computed via the application of Simplicial Functional Principal Component Analysis and block kriging methods



7.6 Policy implications and recommendations

The results of our analysis may have important implications for environmental policy and public health in Lombardy. By identifying areas and municipalities with the highest probability of exceeding the PM_{10} threshold, we can help local authorities target interventions to reduce air pollution and protect public health. For example, local governments could implement traffic management measures, such as low-emission zones or congestion charges and, similarly, urban planning policies could be adjusted to reduce the impact of industrial activities on air quality in these areas.

To conclude, we point out that the spatial interpolation method considered in this document represent an example of down-scaling method which might be particularly valuable for predicting air pollution levels in smaller municipalities or rural areas where data coverage is limited. By combining these instruments with additional statistical analyses that estimate the uncertainty of the PM_{10} predictions, we might also provide local authorities with a toolkit to 1) assess the effectiveness of current policies, 2) evaluate the potential impact of new interventions, and 3) optimize the placement of new monitoring stations (see, for example, Zimmerman and Buckland (2019) and Zidek and Zimmerman (2019) and references therein).

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Final considerations and conclusions

Accessibility – the capacity of a city or territory to ensure that users can easily and effectively reach their destinations – is fundamental to the well-functioning of the socio-economic life of cities and territories. Accessibility makes a territory attractive for economic actors and tourists and contributes to the well-being of people. Accessibility is also crucial to reduce traffic, congestion and emissions, thus contributing to the environmental sustainability. To make cities resilient, accessibility has to be guaranteed also when the territory is hit by disruptions and shocks.

This report focuses on accessibility in general, and on its relationship with mobility in particular. The contributions presented in this report improve our knowledge of this relationship, by developing indicators and methodologies of analysis, and discussing empirical results and case studies. This knowledge can support urban and transport planners in developing solutions, investments and policies.

In particular, the policy recommendations that can be drawn from the contributions contained in this report can be summarized as follows.

First, any policy to improve accessibility should be targeted. As this report shows, there are tremendous differences across Italian territories in terms of accessibility and emissions, and also within the same city or area there are roads or infrastructure that are critical to ensure resilience.

Second, mobility policies should be inspired by a principle of integration of different modes. In particular, the integration between the public transportation system and the new forms of shared mobility seems to be an effective way to guarantee accessibility even when negative shocks occur. A promising solution to guarantee a successful integration is the realization of mobility hubs.

Third, policies should take into account that accessibility has significant welfare and equity implications. As discussed in the study on the health system in Rome, a small and otherwise negligible reduction in accessibility may be fatal when it pertains to a hospital.

Fourth, any policy to sustain accessibility should be based on a deep knowledge of the peculiar characteristics of the territory, of the existing network and of the potential users. In this respect, this report identifies indicators, statistical methods and strategies to exploit the huge amount of available data (or that can be collected through ad-hoc surveys). Again, integration of diverse data sources is crucial to achieve a more accurate and comprehensive picture of the phenomenon at hand. Moreover, new technology allow to collect information on the status of the mobility system in real time, and this information should be used by operators to continuously monitor accessibility and quickly identify and address issues, such as delays or service disruptions.