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KEYWORDS

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Conversely, green policies generally posed short-term economic challenges, with negative effects on overall productivity, though some positive impacts were observed in lowerproductivity 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.

# Smart and Green. The spatial effects of the Twin Transition in EU regions

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## Abstract

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.

**Keywords:** Twin Transition; Smart Specialisation Strategy (S3); Green Transition; Digital Transition; Regional Growth; Labour Productivity; European Regions; Innovation Policy.

**JEL Codes:** O18, O33, Q56, R11, O31.

# 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.

# 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.

# 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 1 - 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 2 - 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 & renewables | 115 | I.58 - Social innovation and environmental | 16 |
| E.38 - Advanced materials | 107 | B.13 - Offshore mining | 15 |
| E.37 - Advanced manufacturing systems | 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 3 - 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 4 - 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 5 - 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 |

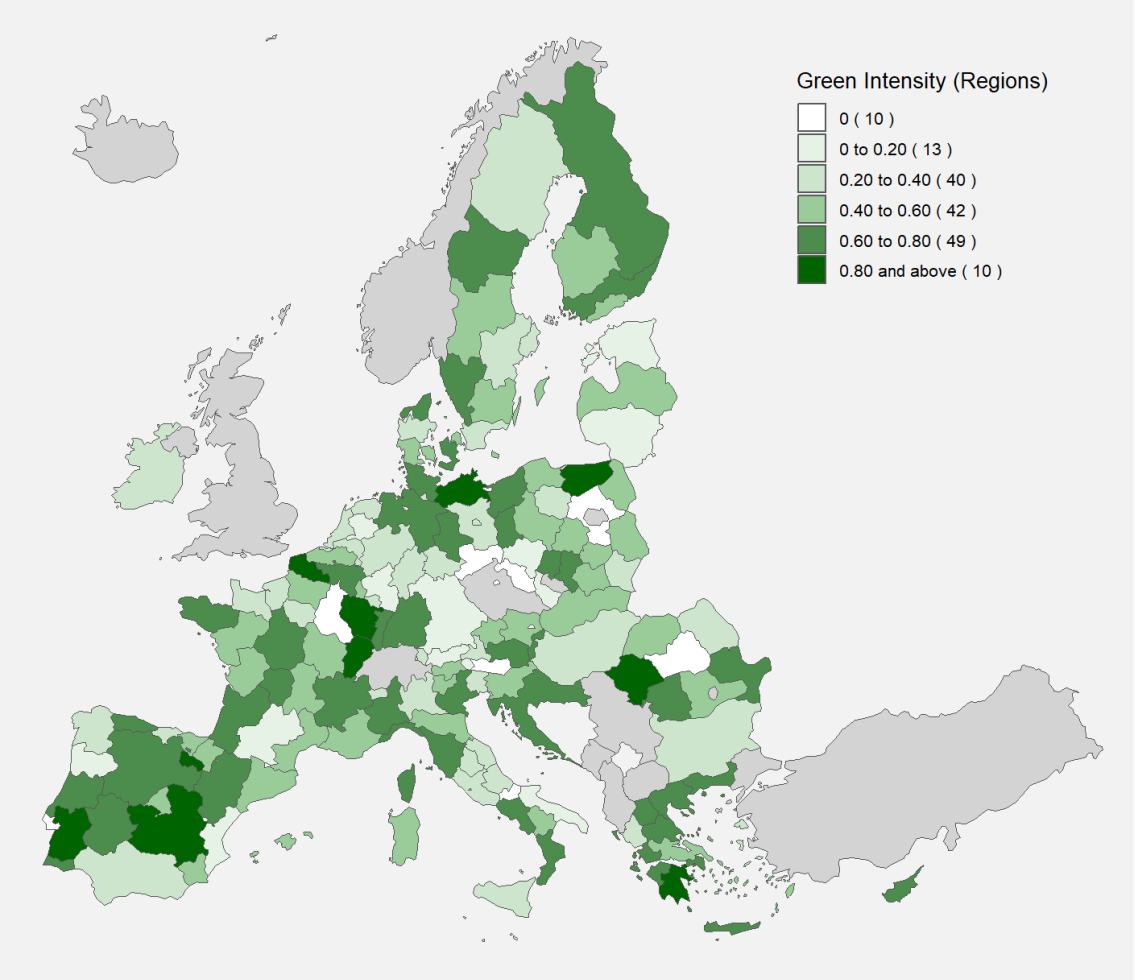
**Twin transition**

| | | |
|---|---|---|
| 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 |

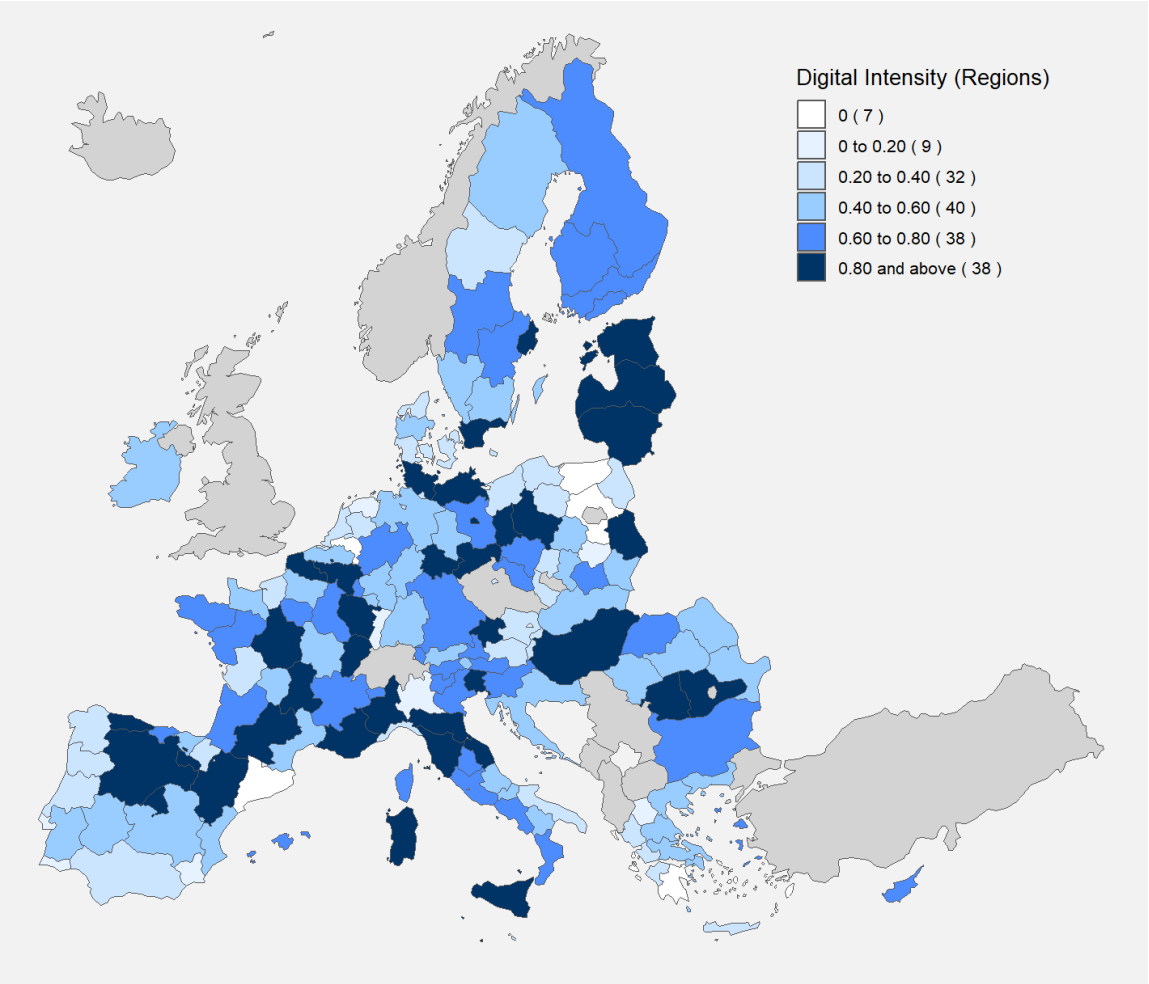
Figure 1 illustrates the distribution of green-related priorities across Europe. Nearly 94% of regions have at least one green priority, with an average green intensity of 0.45. Notably, 65 regions show green intensities above 0.5, highlighting a strong focus on sustainability. Leading regions with perfect 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 1 - Green-intensity in S3 priorities**



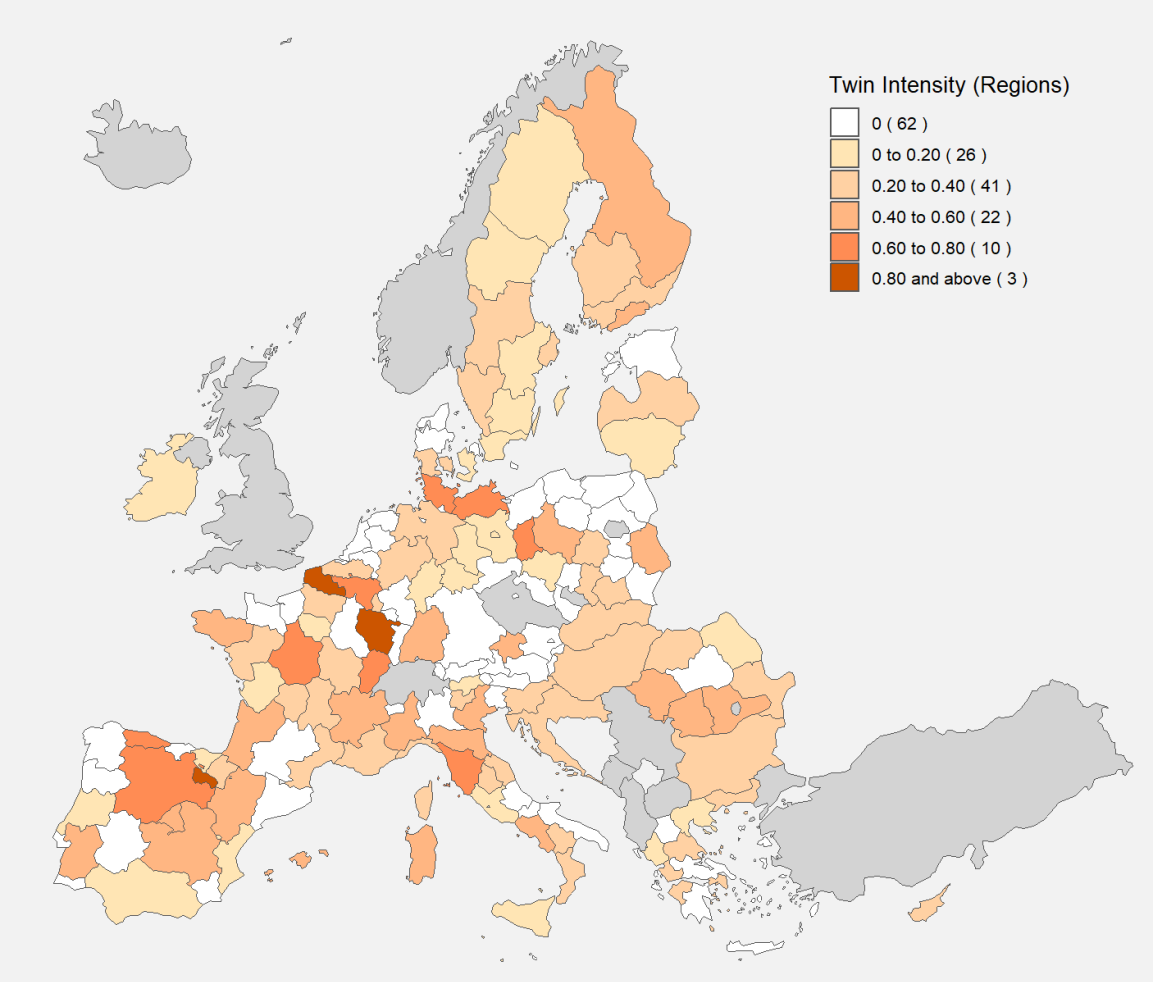
In the digital sphere (Figure 2), an even higher proportion of regions (95.12%) have at least one digital-related priority, with an average intensity of 0.55. A total of 81 European regions show a strong focus on digital innovation, with intensity scores above 0.5. Regions such as La Rioja, Nord - Pas-de-Calais,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

**Figure 2 - 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 3 - 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.

# 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 6 - 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. [1]

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.

[1] 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.

# 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.

**Table 7 - 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 8 - 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 9 - 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 10 - 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 11 - 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 12 - 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.

# 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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