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ORIGINAL PAPER

Smart and green. The uneven effects of the twin transition in European regions

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Abstract

The European Union's strategic emphasis on climate neutrality and digital leadership, embodied in the European Green Deal and the Digital Compass, has placed the twin transition (TT) at the forefront of regional development policy. The growing integration of environmental sustainability and technological transformation into Smart Specialisation Strategies (S3) reflects increasing expectations that European regions align their innovation agendas with green and digital priorities. Despite this policy momentum, empirical evidence remains limited on how regions incorporated green and digital strategic orientations into their S3 strategies and how these orientations are associated with regional economic performance. This paper contributes to filling this gap by examining the green, digital, and twin orientation embedded in European regions' 2014–2020 S3 strategies. Within a regional growth and convergence framework, we analyse how these policy orientations are associated with labour productivity growth while controlling for initial economic, institutional, and structural conditions. Our results reveal substantial heterogeneity across regions. Digital and twin strategic orientations are positively associated with productivity growth in less developed regions, whereas the associations become weaker or negative in regions at intermediate stages of development and generally insignificant in the most advanced regions. Overall, the findings indicate that the relationship between S3 strategic orientation and regional productivity varies systematically with initial regional conditions. The paper contributes to the emerging literature on the TT by highlighting the importance of place-sensitive policy approaches in the evolution towards Sustainable Smart Specialisation strategies.

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1 Introduction

In recent years, the European Union (EU) has placed the pursuit of climate neutrality and digital leadership at the core of its policy agenda, as reflected in the European Green Deal and the Digital Compass (European Commission 2022). These two initiatives jointly define the strategic vision now known as the twin transition (TT), which aims to foster environmental sustainability and technological advancement while ensuring global competitiveness. Together, these transitions outline a comprehensive strategy for building a sustainable, digitally empowered, and resilient Europe.

The TT's dual focus on environmental sustainability and digital innovation presents both opportunities and challenges for policymakers and regions. While digital technologies, such as Artificial Intelligence (AI) and the Internet of Things (IoT), can enhance green objectives through smarter resource use and energy efficiency, digital infrastructures can have environmental impacts and high energy consumption. Therefore, integrating these policies requires substantial investments and effective governance. This dual policy has been increasingly embedded within the Smart Specialisation Strategy (S3), the EU's framework for regional innovation (Foray et al. 2009). Its most recent evolution – labelled Sustainable Smart Specialisation Strategy (S4) – explicitly integrates environmental sustainability as a central objective of regional development agendas (European Commission 2024).

Despite the growing policy relevance of the TT, systematic quantitative evidence remains limited on how European regions incorporated green and digital strategic orientations into their S3 strategies and how these orientations are associated with subsequent regional economic performance. Gao (2024) investigated the risk of fragmentation for transition policies in Europe and emphasises the need for a deeper understanding of regional strategies. Faggian et al. (2025) note that the success of these transitions relies heavily on recognising the diverse capacities and challenges faced by regions, which is intrinsic to S3's place-based approach. These considerations highlight the importance of developing strategies that adapt to local contexts, enabling regions to leverage their specific strengths while addressing structural disadvantages. This is even more relevant because regions may face specific trade-offs between short-term economic outcomes and long-term sustainability goals, particularly when implementing green priorities, which often require substantial upfront investment for overall restructuring or upgrading systems and the pursuit of societal goals (biodiversity conservation, pollution reduction, and sustainable and fair management of natural resources). Moreover, region-specific challenges have been further exacerbated by common external shocks, such as the COVID-19 pandemic, geopolitical tensions and a huge increase in energy prices, which caused resource reallocation and delays in implementation.

The existing literature emphasises that the implementation of regional green and digital policies is far from uniform, reflecting disparities in resources, institutional settings, and innovation potential. Most studies analyse green or digital priorities

separately, with limited attention to their joint orientation, particularly within the S3 framework. Diodato et al. (2023) identify key research directions, including the interaction between digital and green transitions, their economic implications, and their potential role in shaping regional inequalities. However, systematic quantitative evidence linking declared regional policy orientations to subsequent economic performance remains scarce.

Against this background, this paper examines how the strategic orientation embedded in European regions' S3 priorities—captured through the intensity of digital, green and twin domains—is associated with subsequent labour productivity growth. The analysis is positioned within a regional growth and convergence framework, where S3 strategic orientation is interpreted as one of the factors potentially associated with heterogeneous productivity dynamics across regions.

A first clarification concerns the temporal perspective adopted in the analysis. Since the TT emerged as an integrated European policy agenda only after the 2014–2020 programming period, the paper does not attempt to measure the TT directly. Instead, it interprets the green and digital content embedded in regional S3 priorities as early policy orientations that, ex post, can be viewed as precursors to the TT framework.

The analysis also adopts an explicitly associational perspective. S3 priorities, which do not feature a time dimension, capture declared strategic orientations rather than actual investment flows or implementation outcomes, and the empirical framework does not seek to establish causal relationships. Rather, it identifies conditional associations between regional strategic orientation and subsequent productivity growth after controlling for a comprehensive set of initial economic, institutional and structural characteristics.

More specifically, the paper examines how European regions incorporated green, digital and combined priorities into their S3 strategies during 2014–2020 and, controlling for initial economic and institutional conditions, how these strategic orientations are associated with subsequent labour productivity growth. The paper makes three main contributions. First, it provides a systematic mapping of the green, digital, and twin strategic orientations embedded in European regions' S3 priorities, offering a comprehensive picture of how regions positioned themselves with respect to these transitions before the TT emerged as an integrated EU policy framework. Second, it examines how these strategic orientations are associated with regional labour productivity growth within a regional growth and convergence framework, explicitly accounting for heterogeneity across different stages of regional development. Third, it examines whether the association is moderated by funding or institutional quality. This is particularly relevant for less developed regions because they receive substantial Cohesion Policy support and generally have weaker institutional quality. By incorporating ERDF funding and institutional quality into the analysis, we assess how the relationship between strategic orientation and productivity growth appears across different regional conditions.

The empirical analysis reveals substantial variability in how regions selected green and digital priorities. Using a growth convergence framework, the econometric analysis shows that the association between digital, green, and twin strategic orientations and labour productivity growth differs systematically according to regions'

initial development levels. In less developed regions stronger digital and twin strategic orientations are positively and significantly associated with productivity growth. By contrast, the estimated associations become weaker—or, in some cases, negative—in regions at intermediate stages of development, while they are generally not statistically significant in the most advanced regions.

These heterogeneous patterns are consistent with the broader literature on uneven regional development and development traps (Iammarino et al. 2019; Diemer et al. 2022), although our analysis does not seek to test these mechanisms directly. Rather, they suggest that similar strategic orientations may be associated with different productivity dynamics depending on regions' initial structural conditions and development trajectories.

Overall, the findings indicate that the relationship between S3 strategic orientation and regional productivity is inherently place-dependent. By documenting this heterogeneity, the paper contributes to a better understanding of how digital and green strategic priorities relate to regional development in the European Union. These findings also support the growing emphasis on place-sensitive and sustainability-oriented regional strategies, as reflected in the evolution of smart specialisation towards the S4 framework.

The paper is organised as follows. Section 2 reviews the literature on S3 and the TT and presents the conceptual framework guiding the analysis. Section 3 describes the data and methodology used to quantify and analyse green, digital, and twin policy orientations. Section 4 outlines the empirical model. Section 5 presents the aggregate results, while Sect. 6 investigates heterogeneity across regions at different stages of development. Section 7 presents a series of robustness analyses and examines how the observed heterogeneity relates to ERDF funding and institutional quality. Section 8 summarises our main findings and discusses the implications for regional policymakers.

2 Twin transition, regional heterogeneity, and smart specialisation

2.1 Literature review

The TT, combining green and digital transformations, has become a central theme in European policy and scholarly debate. By jointly pursuing environmental sustainability and technological upgrading, the TT aims to address climate change while enhancing productivity, resilience, and innovation. Rather than representing two parallel processes, the TT reflects the interaction between a green dimension entailing structural changes to reduce emissions and environmental degradation, and a digital dimension centred on deploying advanced technologies to improve efficiency, coordination, and knowledge diffusion.

A growing body of literature reveals that digital technologies, including AI, IoT, blockchain, and data analytics, can support green objectives by enhancing resource efficiency and enabling applications such as smart grids and energy management. At the same time, evidence from patent data suggests that technologies explicitly combining green and digital functions remain relatively limited and concentrated,

indicating the still nascent nature of these complementarities (Jindra and Leusin 2022). Macro-level evidence supports the potential of these complementarities. Benedetti et al. (2023) show that digitalisation enhances energy productivity across EU member states. At the same time, digitalisation generates trade-offs, including higher energy demand, electronic waste, and dependence on critical raw materials, with associated environmental and geopolitical risks (Bianchini et al. 2023). Although policy narratives often portray these dynamics as mutually reinforcing, their joint implementation remains complex and uneven across territories. The TT can therefore be interpreted as a coordination problem, requiring policy mixes capable of fostering complementarities while mitigating unintended costs.

Firm-level evidence suggests that the TT is not merely the juxtaposition of green and digital investments, but rather that economic returns depend on how these technologies are combined. Cattani et al. (2023) document strong urban–rural divides in the adoption of Industry 4.0 technologies for eco-innovation: while eco-innovation is relatively widespread outside urban cores, its integration with digital tools is far more common in cities, where digital infrastructure, skills, and innovation ecosystems are more developed. Complementary causal evidence is provided by Marrocu et al. (2026), who evaluate ERDF-funded projects in Italy and show that firm-level investments explicitly combining green and digital components generate stronger and more persistent gains in value added and productivity than single-focus interventions, while also exhibiting substantial spatial and sectoral heterogeneity.

These firm-level patterns motivate a shift to the regional level, where a growing literature examines how green and digital transformations unfold across heterogeneous territorial contexts. A consistent finding is that regions differ markedly in their capacity to integrate the two transitions, reflecting variations in production structures, institutional quality, and pre-existing knowledge bases. Regions with stronger digital capabilities are systematically better positioned to develop "twin innovation" trajectories, benefiting from both internal complementarities and spatial spillovers that reinforce innovation potential (Fazio et al. 2024). At the same time, diversification into green and twin technologies depends not only on local capabilities but also on access to interregional and global knowledge networks (Fatikhova et al. 2024; Fusillo et al. 2023). These differences extend beyond adoption, affecting the quality and economic relevance of transition outcomes: regions with stronger green and digital capabilities generate more complex and higher-quality innovations and experience stronger productivity effects from digitalisation (Damioli et al. 2025; Apostol & Hernández-Rodríguez 2024). Consistent with this evidence, digital technologies tend to amplify existing green capabilities rather than compensate for their absence, reinforcing path dependence and cumulative development processes (Cicerone et al. 2023).

Because digital technologies amplify existing regional strengths, the TT risks generating uneven economic and social outcomes across space. These asymmetric capacities are central to the Just Transition discourse, which frames the TT not only as a technological transformation, but also as a social and territorial challenge, explicitly recognising that regions differ in their exposure to transition-related shocks and in their capacity to adapt (European Commission 2025). Rodríguez-Pose and Bartalucci (2024) argue that, without compensatory and place-sensitive

mechanisms, the green transition may exacerbate territorial inequalities and fuel political discontent. Complementing this argument, Kostarakos et al. (2025) show that territories with high exposure to green and digital shocks, combined with low readiness, are disproportionately concentrated in poorer regions, highlighting the structural conditions that necessitate territorially differentiated policy responses.

These considerations point to the need for an analytical framework able to account for heterogeneity, path dependence, and coordination across policy domains. In this respect, S3 provides a relevant lens for analysing the TT at the regional level and its association with economic performance. Introduced as a place-based innovation policy, S3 encourages regions to prioritise activities aligned with their existing strengths while diversifying into related domains, allowing for strategic experimentation beyond current specialisations (Foray et al. 2009; McCann & Ortega-Argilés, 2015; Marrocu et al. 2023). Central to this approach is related diversification, through which regions develop new specialisations by recombining existing capabilities rather than pursuing unrelated technological shifts (Santoalha & Boschma 2021). In the context of green and digital transformation, this logic implies that the effectiveness of new technologies depends on their integration within existing capability structures and policy frameworks. Consistent with this view, Montresor and Quatraro (2020) show that regions can develop new green-tech specialisations by leveraging non-environmental capabilities, while Serafini et al. (2025) find that digital Industry 4.0 investments generate stronger firm-level performance when embedded within regional S3 strategies.

More recently, the evolution of S3 towards the S4 framework reflects a broader shift in EU regional policy towards sustainability- and transformation-oriented agendas (European Commission 2024). Harding et al. (2021) show how smart specialisation can be leveraged to support the green transition, while Moujaes (2024) interpret this evolution as a paradigmatic shift towards mission-oriented policies. At the same time, the literature stresses that the effectiveness of S3/S4 depends critically on governance capacity, coordination, and genuinely place-based implementation.

Despite growing attention, recent contributions (Faggian et al. 2025) and (Diodato et al. 2023) highlight that important questions remain open in the analysis of the TT. While existing studies provide substantial evidence on heterogeneous green and digital innovation, adoption, and outcomes, systematic quantitative evidence linking declared regional policy orientations to subsequent regional economic performance remains limited.

2.2 Conceptual framework and hypotheses

In the context described by the literature, the contribution of this paper is positioned primarily within the regional growth and convergence literature, while using the smart specialisation framework to capture policy orientation. This paper examines how European regions incorporated green and digital priorities into their S3 strategies during the 2014–2020 period and assesses how these orientations are associated with subsequent productivity dynamics. By focussing on declared priorities, the analysis captures intended strategic directions at a time when green and digital

transformations were still only partially integrated. This perspective is particularly relevant in a context of strong structural heterogeneity, where path dependence and uneven adjustment capacities shape long-term development trajectories (Iammarino et al. 2019; Diemer et al. 2022). In this respect, due to data limitations, the paper does not seek to test development traps, structural lock-in, or regime switching directly. Rather, these concepts serve as interpretative lenses to motivate why the association between S3 policy direction and productivity growth may differ across regions at different stages of development. A further clarification concerns the retrospective perspective adopted in the paper. Since the TT was formalised as an integrated policy framework only after the 2014–2020 programming period, the analysis does not measure the TT directly. Instead, it uses the green and digital content of S3 priorities as a proxy for policy orientation that can be interpreted ex post as precursors of the TT.

Building on the preceding discussion, the paper conceptualises S3 strategic orientation as being associated with regional productivity dynamics through a set of interrelated transmission channels whose relevance is grounded in the mechanisms identified in the TT and smart specialisation literature. Rather than treating digital and green priorities as direct sources of performance, the analysis interprets them as signals of strategic direction that may influence how regional economies adopt technologies, generate innovation, reallocate resources and, ultimately, achieve productivity gains. Figure 1 summarises these conceptual relationships and the expected transmission channels linking S3 strategic orientation to regional productivity dynamics.

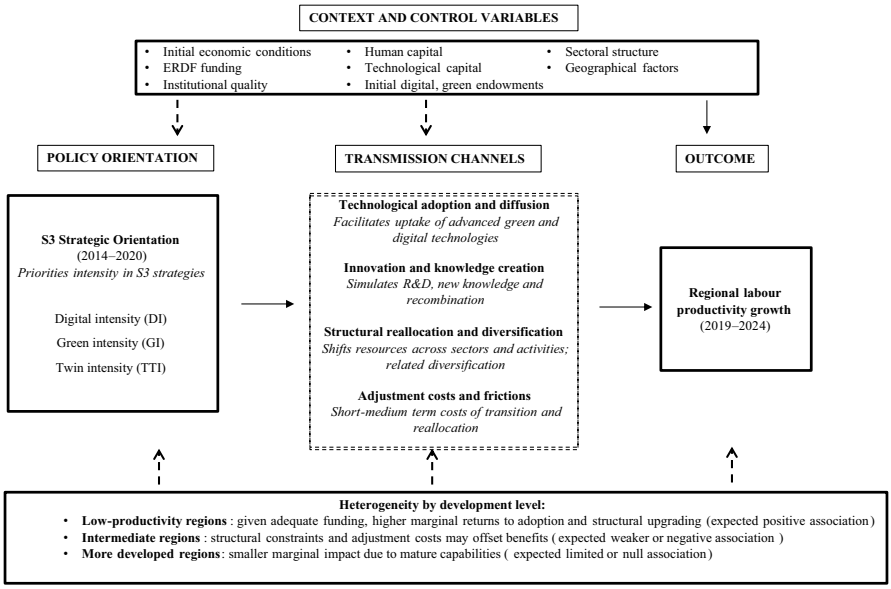

Fig. 1 Conceptual framework

First, a stronger emphasis on digital and green priorities may facilitate technological adoption and diffusion by encouraging the uptake of new production processes and organisational practices. These effects are likely to depend on the availability of complementary infrastructures and capabilities, which condition the extent to which new technologies can spread across firms and sectors. Second, policy orientation towards digital and green investments may influence innovation dynamics by guiding knowledge creation and recombination. In line with the logic of smart specialisation, strategic priorities can coordinate expectations and channel resources towards related activities, potentially fostering new combinations of existing capabilities and supporting the emergence of more complex innovation trajectories. Third, the adoption of TT strategies may be associated with processes of structural reallocation, as regions shift resources towards activities aligned with digital and environmental objectives. While such reallocations are expected to enhance efficiency and long-term productivity, they can also involve transitional frictions, particularly in regions where existing specialisations are less compatible with new technological directions. Fourth, these digital and green transformations may entail adjustment costs and coordination challenges. The orientation of investments, institutions, and capabilities required by the TT is inherently complex, and in some contexts these frictions may delay or weaken the translation of strategic orientation into measurable economic outcomes. Finally, the joint emphasis on green and digital priorities may generate complementarities, but also additional complexity. When coherent strategic priorities are accompanied by adequate capabilities and implementation conditions, digital and green orientations may reinforce one another.

Taken together, these mechanisms suggest that the relationship between S3 strategic orientation and productivity growth is not univocal at the aggregate level. While digital and green priorities may be associated with productivity gains through technological upgrading, innovation, and structural transformation, these potential benefits may be offset or delayed by adjustment costs, coordination failures, or misalignment with local capabilities. Accordingly, at the aggregate level, the association between transition-oriented priorities and productivity growth is expected to be positive on average, but potentially weak and heterogeneous across regions and policy dimensions.

This ambiguity becomes more pronounced when considering differences in regional initial conditions. In less developed regions, where opportunities for technological upgrading and structural catching-up are greater, a stronger orientation towards digital and green priorities may be more closely associated with productivity growth. In contrast, regions at intermediate levels of development may face structural constraints—such as weaker innovation systems, limited absorptive capacity, or difficulties in reallocating resources—that hinder the effective translation of strategic priorities into economic performance. In more advanced regions, the marginal association between broad policy orientation and productivity dynamics is likely to be more limited, reflecting the complexity and maturity of their economic structures.

From this perspective, the paper examines whether regions whose Smart Specialisation Strategies place greater emphasis on digital, green, and twin priorities are systematically associated with higher labour productivity growth, and whether this relationship varies across different stages of regional development after accounting

for initial structural characteristics. It also examines whether these associations differ across levels of Cohesion Policy support and institutional quality.

3 Data

In this section, we examine how EU regions have selected digital and green initiatives within their S3 priorities over the programming period from 2014 to 2020. The primary data source for this analysis was the Eye@RIS3 database from the Smart Specialisation Platform (S3P), which offers comprehensive details on the strategic priorities of the European regions. This platform provides data on the specific focus areas and objectives outlined in regional S3 documents, essential for assessing alignment with the TT goals.

Our analysis encompasses 164 territorial units, as reported in Table 8 of the Appendix, with a primary focus on NUTS-2 level areas.[1] These territories formulated 1,145 policies – the so-called priorities (i.e. plans or projects)—listed on the S3P. The average number of priorities per region is approximately seven, with considerable variability.[2] Interesting elements of the S3 priorities arise from their categorization in the Eye@RIS3 database, which classifies priorities into three categories: Economic Domains, based on Eurostat's NACE2 sectoral codes; Scientific Domains, using the NABS 2007 system; and Policy Objectives, based on the policy areas of EU Horizon 2020 "Societal Grand Challenges". For this contribution, we focus on the Policy Objectives classification, as it provides a direct link between S3 priorities and overarching EU innovation and societal goals. This classification encompasses 72 specific objectives grouped into ten broad policy areas. These areas range from advanced technological fields, such as Digital Transformation and Key Enabling Technologies (KETs), to sustainability-focussed categories, including Nature & Biodiversity, Sustainable Innovation, and Blue Growth. They also address societal challenges, including Public Health & Security, Social Innovation, and Service Innovation, alongside specialised domains like Cultural & Creative Industries and Aeronautics & Space.

Table 1 illustrates the substantial heterogeneity in how regions have interpreted S3 guidelines and selected their S3 priorities. The number of Policy Objectives addressed by each region varies greatly, reflecting the differing capacities, governance frameworks, and strategic preferences across territories. For instance, regions like Länsi-Suomi (FI19) and Slovenia (SI) target, respectively, 61 and 57 objectives (out of the existing 72), showing broad and diversified approaches. Conversely, regions such as Kärnten (AT21) and Steiermark (AT22), focussing on just 2 and 4 objectives, exhibit much narrower strategies. This variability reflects the flexibility of the S3 framework. While it allows regions to tailor priorities to local strengths, it

[1] In cases where S3 has been defined at the NUTS-3 level (Sweden and Finland), these were aggregated to the NUTS-2 level for consistency.

[2] For example, Peloponnesus has a minimum of two priorities, while North & East Finland have a maximum of 30.

Table 1 Regions per coverage of 72 policy objectives in S3 priorities

Regions with highest coverage	n. domain	Regions with lowest coverage	n. domain
FI19—Länsi-Suomi	61	AT13—Wien	7
SI—Slovenia	57	ITC4—Lombardia	7
FI1C—Etelä-Suomi	52	NL3—West-Nederland	6
FRD2—Haute-Normandie	52	FRC1—Bourgogne	6
FRE1—Nord—Pas-de-Calais	49	CZ07—Střední Morava	6
ES30—Comunidad de Madrid	48	NL2—Oost-Nederland	5
ITI2—Umbria	48	EL65—Peloponnisos	5
ES11—Galicia	46	NL4—Zuid-Nederland	4
FI1D—Pohjois- ja Itä-Suomi	46	AT22—Steiermark	4
FRI1—Aquitaine	40	AT21—Kärnten	2

may also reflect fragmented strategies or the influence of vested interests rather than genuine regional capabilities (Marrocu et al. 2023).

Table 2 shifts the focus to the specific policy objectives within the classification, offering insights into which themes are most and least frequently targeted by the EU regions. Objectives like "G.49—Public health & well-being" and "J.68—Sustainable energy & renewables" are among the most common targeted, respectively, by 136 and 115 regions (out of the 164 considered), indicating widespread alignment with societal and sustainability topics. Meanwhile, objectives such as "D.34—Quantum computing" and "G.47—Dual use", which appear in fewer than 20 regions, highlight specialised or niche interests.

The key step in our empirical strategy is the identification of priorities with digital and green content. To this aim, we use the Policy Objective classification. More

Table 2 Policy objective in 164 EU regions in S3 priorities

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 Count of digital, green and twin projects in S3 priorities

	n. priorities	%
Digital projects		
D—Digital transformation	*390*	*34.1*
E—KETs	*372*	*32.5*
Total Digital	625	54.6
Green projects		
J—Sustainable innovation	*463*	*40.4*
F—Nature and biodiversity	*75*	*6.6*
B.09—Blue renewable energy	*42*	*3.7*
Total Green	510	44.5
Twin projects	235	20.5
Total number of S3 priorities	1145	

The sum of category counts exceeds the total because a priority may belong to more than one category

The italics distinguish the individual Policy Objective categories and their corresponding counts and percentages from the aggregate digital and green totals, which are shown in regular type

precisely, a priority is labelled "digital" when it is classified under D – Digital Transformation or E – Key Enabling Technologies (KETs); "green" when assigned to F – Nature & Biodiversity, J – Sustainable Innovation, or the specific sub-objective B.09 – Blue Renewable Energy. Because S3 priorities may belong to multiple Policy Objectives, the same priority can be simultaneously classified as "digital" and "green" and thus as a "TT" priority. Our approach is fully rule-based and depends exclusively on the coding provided by managing authorities on the Eye@RIS3 platform; no textual interpretation or manual recoding was introduced. Thus, it is robust to concerns about ad-hoc classification. To illustrate the practical application of the coding scheme, the Appendix reports three representative examples from the Eye@RIS3 dataset, along with Table 10, which details the operational mapping between the Policy Objective categories and the digital and green priorities.

As shown in Table 3, among the 1,145 priorities in the S3 database, 625 (54.6%) are associated with digital initiatives, while 510 (44.5%) target green programmes. Within the digital objectives, "D—Digital Transformation" is the most common, encompassing 390 priorities, followed by "E—KETs" with 372. The most prominent green category is "J—Sustainable Innovation," counting 463 priorities.[3]

TT priorities are defined as priorities that simultaneously include at least one digital and one green Policy Objective—as detailed in Table 10 in the Appendix—thereby integrating both dimensions within the same strategic priority. Table 3 shows that 235 priorities – representing 20.5% of the total – reflect such integration, signalling that although digital and green objectives are frequently pursued independently, their joint inclusion within the same priority remains less frequent.

[3] Note that a priority may include more than one green or digital objective simultaneously.

Such a pattern might reveal a critical gap in regional S3 and emphasises the need for greater alignment and synergy between green and digital initiatives to fully harness the transformative potential of the TT.[4]

Because regions differ substantially in the number of priorities included in their S3 strategies, absolute counts would provide a measure that is not directly comparable of commitment to digital and green transitions. We therefore define digital (DI), green (GI), and twin (TTI) intensity as the share of priorities related to each transition relative to the total number of priorities in the region.

The list of top and bottom regions for each transition intensity is reported in Table 4, while Fig. 2 illustrates the spatial distribution of these intensity measures. Digital priorities are widely adopted, with 95.1% of regions including at least one in their S3, and an average intensity of 0.55. Notably, 81 regions have a digital intensity above 0.5, while La Rioja, Nord-Pas-de-Calais, Lorraine, and the Brussels-Capital Region reach the maximum value of 1.00. Green objectives are also widespread, with 94% of regions including at least one and an average intensity of 0.45. Sixty-five regions exceed 0.5 in green intensity, with Peloponnisos, La Rioja, Warminsko-Mazurskie, and Vest achieving scores of 1.00. As mentioned above, priorities combining both transitions within the same priority are less common: the average TT intensity is 0.21, and only 17 regions exceed 0.5 in twin intensity, with La Rioja leading at 1.00.

This high variability underlines the diverse approaches taken by regions. While some regions have similar shares of digital and green priorities in their S3 strategies, others concentrate more narrowly on either green or digital objectives, as also recently documented by Barbero et al. (2025). These differences likely reflect variations in regional capabilities, governance arrangements, stakeholder involvement, and strategic priorities, highlighting the challenges of integrating green and digital objectives into coherent TT strategies.

4 The empirical model

In this section, we outline the main estimation strategy of our empirical analysis, which aims to assess how regional productivity growth is associated with the regions' S3 focus in digital, green, and TT policies, while accounting for the specific characteristics of each territory. It is important to remark that the data used reflect declared regional strategies and thematic orientation rather than direct measures of investment allocation or execution. The extent to which these strategies lead to substantive outcomes may vary depending on the quality and depth of their implementation. Therefore, our analysis does not aim to establish definitive causal relationships; rather, we intend to provide evidence on patterns of association that

[4] In our robustness analysis, we also consider alternative indicators for the regional twin orientation based on complementarity at the portfolio level. In this case, a region pursues both green and digital transitions through separate priorities even if it may not have formally integrated "twin" priorities under the within-priority rule.

Table 4 Digital, green and twin intensities in S3 priorities among EU regions

Top regions	Intensity	Bottom regions	Intensity
Digital projects			
ES23—La Rioja	1	EL53—Dytiki Makedonia	0.17
FRE1—Nord—Pas-de-Calais	1	PT15—Algarve	0.17
FRF3—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
Green projects			
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	0.80	PT17—Lisboa	0
PT18—Alentejo	0.80	RO12—Centru	0
Twin projects			
ES23—La Rioja	1	62 regions have an intensity score of 0 given the definition of twin projects as being simultaneously green and digital	
FRE1—Nord—Pas-de-Calais	0.83		
FRF3—Lorraine	0.80		
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		
BE3—Région Wallonne	0.67		

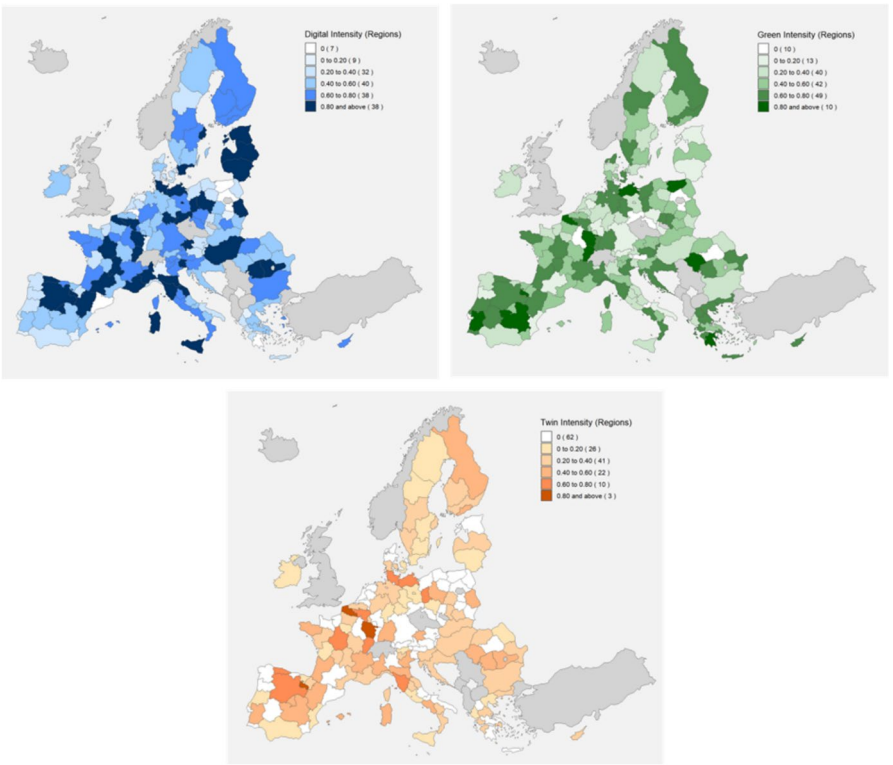

Fig. 2 Digital, green and twin intensity in S3 priorities. For each region *i*, intensities are computed as (Priorities_{iX} / $\text{Total priorities}_{i}$) where X can be either Digital, Green or Twin

can inform regional policy design.[5] By controlling for several potential confounding factors, the regression framework aims to unveil informed associations between these policies and the region's economic performance, particularly across areas with differing initial conditions. The estimation analysis starts by considering a standard growth regression model:

$$\Delta LP_i = \alpha + \beta XI_i + \gamma LP_i + \sum_{j=1}^{J} \delta_j control_{ji} + \varepsilon_i$$

where ΔLP_i is the annual average growth rate of the labour productivity (LP), measured as GDP per employee in region *i* over the years 2019–2024. Our variables of interest (XI) are included as either Digital Intensity (DI), Green Intensity (GI), or TT Intensity (TTI), during the programming period. Due to the high correlation

[5] In the context of investments linked to S3 priorities, causal effects can be properly identified only at firm level, as data on the amount of financial support received are available and the application of methods such as difference-in-differences allows controlling for pre-treatment trends (Marrocu et al. 2026).

between these intensities (correlation coefficients of 0.67 for DI-GI and 0.60 for DI-TTI), we do not include all three in the same specification to avoid multicollinearity issues. The initial level of labour productivity is included to account for the convergence process across regions, as in the standard growth regression models.

We use labour productivity growth, measured as GDP per employed person, as the dependent variable because the technological upgrading, innovation, and more efficient resource allocation envisaged by digital, green, and twin S3 priorities may be reflected in output per worker, as previously discussed in Sect. 2.2. At the same time, these processes may involve adjustment costs and coordination frictions, particularly in regions with weaker capabilities or less adaptable production structures. Labour productivity therefore provides a suitable summary measure of the net economic outcome of these potentially offsetting mechanisms. This indicator is also particularly suitable within a regional growth and convergence framework, as it reflects differences in regions' capacity to absorb new technologies and modernise their economic structures. Such dynamics are especially relevant in lower-productivity regions, where opportunities for catching-up and efficiency gains may be larger. Finally, labour productivity is less sensitive to short-term labour market fluctuations, such as changes in participation or unemployment rates, allowing for more meaningful comparisons of economic performance across regions characterised by different labour market conditions.[6]

Our analysis focuses on regional economic performance from 2019 to 2024. Although the S3 was developed during the 2014–2020 programming period, the strategies require time to become fully operational, also because of the *n+3* rule in the use of cohesion funds.[7] By starting the analysis in 2019, we aim to capture a phase in which S3 strategies had already moved beyond their initial implementation stage, allowing sufficient time for regional priorities and related interventions to become operational. The endpoint of 2024 allows us to assess regional performance beyond the acute COVID-19 shock and initial rebound. The pandemic and subsequent recovery may nonetheless have affected regions differently. Our dependent variable is computed as the annual average growth rate between the initial level in 2019 and the final level in 2024. As such, year-to-year fluctuations in the intermediate years do not enter the calculation directly. The longer window reduces sensitivity to the immediate shock and rebounds and provides a broader view of regional productivity dynamics.[8]

The model also incorporates several potential confounding factors to control for key dynamics between the TT policies and the region's economic performance, particularly across areas with differing initial conditions in the relevant socio-economic context.

[6] In the robustness analysis, we also employ hourly productivity as an alternative indicator of regional economic performance.

[7] Under the n+3 rule of the 2014–2020 programming period, regions were allowed to continue spending allocated financial resources, including those related to S3, until 2023.

[8] The main pattern of results is also found with alternative growth windows and when productivity growth is calculated using averages of adjacent years at the beginning and end of the period.

More specifically, while our intensity measures capture the regions' propensity to select TT policies, they do not consider the amount of EU financial resources allocated to these strategies. Unfortunately, data on S3 financial flows explicitly targeted at these technologies are unavailable for the whole set of European regions. To partially address this limitation, we include the amount of European Regional Development Fund (ERDF) received per employee by each region during the 2014–2020 programming period. This variable is expected to control for the scale effect of the EU Cohesion financing.

Additionally, the selection of digital and green priorities over the period considered is likely to be influenced by pre-existing regional endowments related to these technologies. Capturing the complexity of regional digital and green capabilities with a single indicator is inherently difficult, particularly at the regional level and over a long time horizon. For this reason, we rely on two broad proxies intended to reflect the general technological and economic environment in which regional strategies are formulated.

Digital endowment is proxied by the share of households with broadband access. This indicator does not capture firm-level digital capital, digital skills, the quality of connectivity, or the adoption of advanced production technologies. Rather, it reflects the overall availability and diffusion of basic digital infrastructure at the regional level, which constitutes a necessary background condition for digital activities. We therefore interpret it as a proxy for the general digital environment in which regional strategies are formulated, rather than as a direct measure of advanced digital capabilities.

To account for green endowment, we include a regional competitive environmental suitability indicator measured at the beginning of the outcome period. The indicator is constructed as the regional share of total employment in 56 NACE economic activities that are systematically both more competitive and more environmentally sustainable than the EU median. It is therefore a baseline, time-invariant proxy for the green orientation of the regional productive structure. In this sense, it captures pre-existing regional specialisation in environmentally relevant activities, rather than contemporaneous green investment, innovation, or policy effort.

Drawing on established literature, we also account for regional endowments of intangible factors (Dettori et al. 2012; Männasoo et al. 2018). More specifically, we include the quality of institutions index since a high-quality institutional framework is expected to facilitate the identification of policies that address the specific regional needs and to effectively mobilise the local resources and capacities for their timely implementation, thereby fostering local economic development (Rodriguez-Pose and Ganau, 2022; Aresu et al. 2023). Institutional quality is represented by an index developed by the University of Gothenburg (Charron et al. 2019), which synthesises measures of corruption, impartiality, and public service quality. Human capital has long been recognised as a critical driver of economic performance (Benhabib and Spiegel 1994; Gennaioli et al. 2013; Marrocu et al. 2022). In this model, it is measured as the proportion of individuals aged 25–64 with a tertiary education level (ISCED 5–8). We also include technological capital, measured as per capita R&D expenditure, as it enhances firms' productivity and regional economic performance (Audretsch and Feldman 2004; Rodríguez-Pose and Crescenzi 2008; Basile

et al. 2012). To account for regional production structure characteristics, the model includes a specialisation index for high-technology manufacturing and knowledge-intensive high-technology services. Finally, population density is included to control for agglomeration externalities, which can promote sectoral specialisation and enhance economic performance (Marrocu et al. 2013). All control variables are measured in the initial year.[9] Table 9 in the Appendix reports the complete list of variables' sources and definitions.

Before presenting the main results, it is important to reiterate that our analysis is strictly associative rather than causal. Data limitations—notably the absence of information on the financial resources allocated to individual S3 priorities and the lack of time variation in regional S3 strategies—preclude the implementation of an identification strategy capable of supporting causal inference. Although the explanatory variables precede the observed productivity growth period, concerns about potential endogeneity, which may arise from these channels (selection, simultaneity, or omitted variables), remain. First, regions with stronger long-term growth prospects may be more likely to adopt transition-oriented strategies. Second, regions facing persistent economic stagnation may strategically place greater emphasis on transition priorities in an attempt to foster future growth. Third, unobserved regional characteristics may simultaneously influence both the design of S3 strategies and subsequent productivity performance. S3 priorities are selected in light of existing productive structures, technological capabilities, and development objectives. In some cases, the strategies may have formalised activities and directions that regions were already pursuing, rather than initiated entirely new ones. Our intensity indicators may therefore reflect pre-existing regional trajectories as well as declared strategic orientations; they are not measures of exogenously assigned interventions. To mitigate these concerns, the empirical specification includes a rich set of pre-determined regional characteristics—including human capital, technological capabilities, institutional quality, ERDF funding, initial digital and green endowments, and specialisation patterns—that are likely to be correlated with both regional strategic orientation and productivity performance. While these controls reduce the scope for omitted-variable bias, they cannot fully rule out residual endogeneity. Accordingly, the estimated coefficients should be interpreted as capturing conditional associations between regional strategic orientation towards digital, green and TT and subsequent productivity growth, conditional on a rich set of pre-existing regional characteristics, rather than as causal effects of S3 strategies.

5 The aggregate estimation results

Table 5 presents the results of the three empirical models, where the variable of interest is either digital, green, or TT intensity. All models include the comprehensive set of control variables described in the previous section, as well as the initial

[9] For the European Quality of Government Index (Charron et al. 2015), we used the year 2017, as it is not calculated on a yearly basis.

Table 5 Digital, green and twin intensities and labour productivity growth

	(1)	(2)	(3)
Digital Intensity	0.404		
	(0.338)		
Green Intensity		−0.115	
		(0.417)	
Twin Intensity			0.411
			(0.407)
Labour productivity	−1.979***	−1.971***	−2.030***
	(0.538)	(0.572)	(0.568)
Controls			
Cohesion Funds	−0.167	−0.184	−0.173
	(0.132)	(0.139)	(0.132)
Digital Endowment	0.044***	0.045***	0.044***
	(0.014)	(0.014)	(0.014)
Green Endowment	−0.005	−0.004	−0.003
	(0.009)	(0.010)	(0.009)
Quality of Institution	0.349**	0.305**	0.338**
	(0.157)	(0.146)	(0.152)
Human Capital	−0.025*	−0.024*	−0.026*
	(0.013)	(0.014)	(0.013)
Technological Capital	−0.398*	−0.381*	−0.364*
	(0.210)	(0.202)	(0.204)
HTEC Specialisation	0.408	0.409	0.419
	(0.372)	(0.355)	(0.368)
Population density	0.035	0.006	0.018
	(0.082)	(0.079)	(0.079)
Adjusted R^2	0.398	0.392	0.397

Dependent variable: Labour productivity growth, annual average rate, 2019–2024

All models include a constant and are estimated on the full sample of 164 observations. Labour productivity and control variables refer to 2019 (only QoI refers to 2017). Labour productivity, Cohesion funds, Technological Capital and Population density are log transformed. Cohesion Funds are per employee, Technological Capital is per capita. Robust Standard Error in parentheses. Significance levels: ***(1%), **(5%), *(10%)

level of productivity to account for convergence dynamics. The coefficient of initial productivity is negative and statistically significant in all three models. This result is consistent with conditional convergence: regions with lower initial productivity tend to display higher subsequent growth, conditional on the observed regional characteristics included in the models. Among the controls, digital endowment and institutional quality are positively and significantly associated with productivity growth, while human capital and technological capital enter with negative coefficients. Cohesion Policy funding, green endowment, high-technology specialisation,

and population density do not display statistically significant associations in these aggregate specifications.

Focussing on the main variables of interest, none of the three transition intensities is significantly associated with labour productivity growth at the aggregate level. This absence of a common association across the full sample may reflect substantial heterogeneity across regions. If the relationship between strategic orientation and productivity differs according to regional structural conditions and stages of development, aggregate estimates may conceal associations of different magnitude or even opposite sign. This possibility is consistent with the place-based nature of S3 and provides the main motivation for the heterogeneity analysis developed in the following section. At the same time, implementation differences may provide an additional source of heterogeneity. Existing evidence shows that regional priorities and the allocation of Cohesion Policy resources may evolve during the programming cycle (Aresu et al. 2026), so that similar declared strategic orientations may be translated into different interventions across regions.

For digital intensity, the absence of a statistically significant aggregate association may also partly reflect substantial variation in the content and complexity of regional digital strategies. As suggested by Apostol and Hernández-Rodríguez (2024), the economic implications of digitalisation depend on the nature and complexity of the underlying technological capabilities. A broad aggregate indicator of digital strategic orientation may therefore conceal important differences in the types of digital priorities pursued across regions.

Similarly, no common association between green intensity and productivity growth emerges across the full sample. Green-oriented priorities encompass a broad range of objectives, many of which extend beyond productivity-related goals. They may also be associated with processes of structural reorientation whose economic implications differ across regions and unfold over different time horizons.

Regarding TT priorities, the absence of a statistically significant aggregate association may reflect the highly context-dependent nature of complementarities between digital and green orientations. As highlighted by Benedetti et al. (2023), such complementarities may materialise only under specific regional conditions, including adequate infrastructures and coherent strategic frameworks. A common aggregate coefficient may therefore conceal substantial differences in the extent to which regions are able to combine green and digital strategic orientations with favourable productivity dynamics.

Taken together, the aggregate results provide no evidence of a significant relationship between transition-oriented S3 priorities and productivity growth across European regions. Rather than implying that strategic orientation is unrelated to regional performance, this finding points to the importance of examining whether the estimated associations differ systematically across territorial contexts. Regions at different stages of development may differ substantially in their capabilities, structural characteristics, and adjustment processes, potentially generating heterogeneous relationships between similar strategic orientations and productivity growth. This motivates the analysis presented in the following section, where heterogeneity across initial development levels is explicitly examined.

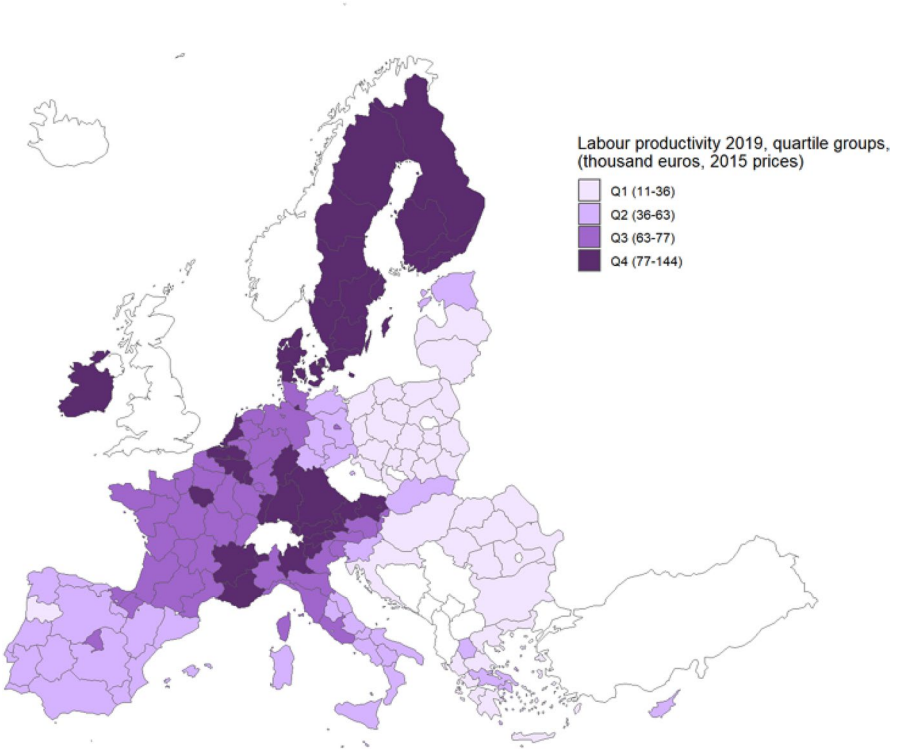

Fig. 3 Labour productivity by quartile groups in 2019

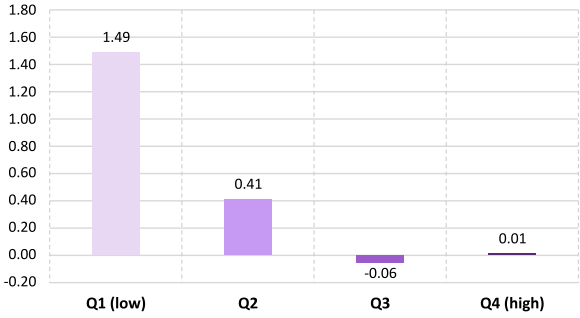

Fig. 4 Labour productivity growth (% average 2019–2024). By 2019 labour productivity quartile groups

6 Considering heterogeneity across regions' development stage

To address the issue of territorial heterogeneity, we consider how initial levels of labour productivity vary across regions. Figure 3 displays the distribution of productivity in 2019, categorised into four quartiles. A well-known spatial pattern emerges: most new accession regions in Eastern Europe, along with Greece, fall into the lowest group (Q1); regions in Scandinavia, Austria, Denmark, Ireland, Germany, and a

Table 6 Estimation results by labour productivity quartile

	Digital	Green	Twin
Panel A: Estimated coefficients by 2019 productivity quartile			
Intensity	1.868**	0.410	3.129**
	(0.720)	(0.800)	(1.494)
Intensity* LP Q2	−1.473***	−0.778	−2.445*
	(0.553)	(0.587)	(1.381)
Intensity* LP Q3	−2.328***	−1.648	−4.328***
	(0.692)	(0.739)	(1.487)
Intensity* LP Q4	−1.885**	−0.905	−3.167**
	(0.754)	(0.892)	(1.558)
Controls	yes	yes	yes
Adjusted R^2	0.349	0.297	0.349
Panel B: conditional associations by 2019 labour productivity quartile group			
Q1 (low)	1.868**	0.410	3.129**
	(0.720)	(0.800)	(1.494)
Q2	0.395	−0.367	0.684
	(0.382)	(0.526)	(0.461)
Q3	−0.460	−1.238***	−1.199***
	(0.294)	(0.389)	(0.303)
Q4 (high)	−0.017	−0.495	−0.038
	(0.441)	(0.417)	(0.611)

Dependent variable: Labour productivity growth, annual average rate, 2019–2024

Observations: 164. All models include a constant and controls as in Table 5. Robust standard errors in parentheses. Significance levels: ***(1%), **(5%), *(10%)

few regions in Northern Italy belong to the highest productive group (Q4). Meanwhile, the majority of regions in Italy, France, and Spain are located in the middle groups (Q2 and Q3).

Crucially for our analysis, these four groups of regions exhibit different growth trajectories, as shown in Fig. 4. Between 2019 and 2024, the least productive regions (Q1) experienced average annual productivity growth of 1.49%, well above the sample average of approximately 0.46%. Growth was lower in Q2 (0.41%), while Q3 recorded a slight contraction (−0.06%). Average growth in the most productive group (Q4) was close to zero (0.01%). Thus, the higher growth observed in Q1 was not shared by regions elsewhere in the initial productivity distribution.

As shown also by Diemer et al. (2022) and Iammarino et al. (2019) in the context of regional development traps, regions may face different growth challenges depending on their initial economic conditions. Less developed regions may display higher growth dynamics during phases of structural adjustment, while regions at intermediate productivity levels often experience more persistent growth difficulties. Highly productive regions, in turn, tend to follow more stable but less dynamic growth

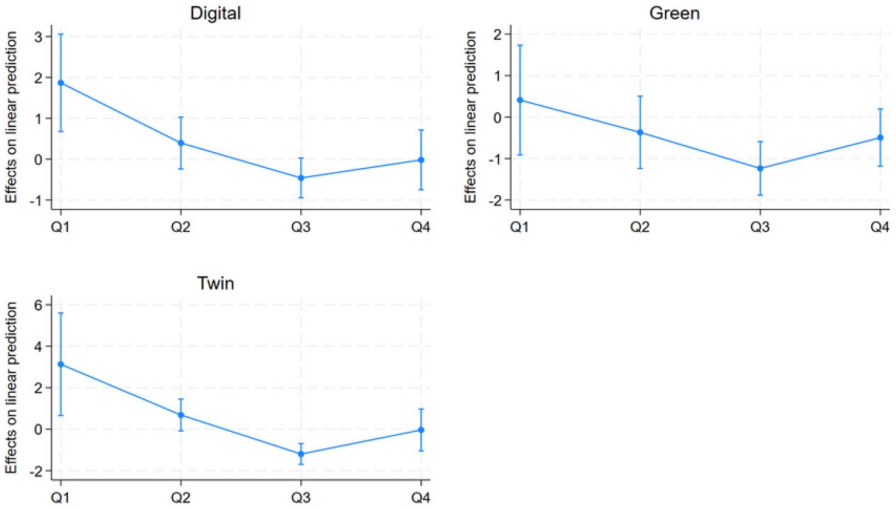

Fig. 5 Conditional associations of digital, green and twin intensity by productivity quartile groups. Conditional associations from Table 6. Confidence interval 90%

paths. To capture these heterogeneous dynamics, we integrate regional starting conditions into our empirical framework by interacting each intensity variable (digital, green, and twin) with quartile-based indicators of initial productivity. The set of control variables remains unchanged.

The results reported in Panel A of Table 6 provide evidence that the relationship between transition intensity and productivity growth varies across regions with different initial productivity levels. Rather than indicating a common association across the full sample, the interaction estimates point to substantial heterogeneity across development stages. To facilitate the interpretation of these differences, Panel B reports the corresponding conditional associations for each productivity quartile,[10] which are also visualised in Fig. 5.

The conditional associations reveal a clear differentiated pattern. In the least productive regions (Q1), digital and twin intensities are positively and significantly associated with productivity growth, whereas the positive estimate for green intensity is not statistically significant. None of the three associations is statistically significant in Q2. In Q3, green and twin intensities display negative and statistically significant associations, while digital intensity is not significantly associated with productivity growth. Finally, no statistically significant association emerges for any of the three transition intensities in the most productive regions (Q4). Overall, the clearest positive associations therefore emerge for digital and twin strategic orientations in the least productive regions.

These differentiated patterns can be discussed in light of the literature on regional development traps. Regions at intermediate productivity levels may face

[10] Conditional associations are computed as average marginal effects. In text we refrain from using the term "effect" so as not to imply a causal interpretation.

dual competitive pressures from lower-cost economies and innovation leaders, while lacking some of the structural conditions needed to exploit the opportunities offered by digital and green transitions. As noted by Diemer et al. (2022), regions facing persistent development difficulties often exhibit a declining manufacturing base, increasing reliance on non-market services, lower educational attainment, and adverse demographic trends. Such conditions may shape the relationship between transition-oriented priorities and productivity growth and, as suggested by Kostarakos et al. (2025), increase exposure to the adjustment costs associated with the TT.

At the upper end of the productivity distribution, the absence of statistically significant associations suggests that broad transition-oriented strategic priorities are not systematically related to subsequent productivity growth. In these more advanced regions, productivity dynamics may depend on a broader and more complex set of technological, innovation, and structural factors that are not captured by the thematic orientation of S3 priorities.

Overall, the quartile analysis helps explain why no common association emerges from the aggregate estimates reported in Table 5. The relationship between transition-oriented strategic priorities and productivity growth is strongly heterogeneous across initial development conditions: positive associations are concentrated in the least productive regions, particularly for digital and twin orientations, while no comparable positive relationship emerges elsewhere in the productivity distribution. This evidence reinforces the place-dependent interpretation of S3 strategic orientation that motivates the empirical analysis.

7 Robustness analysis and contextual factors

7.1 Robustness checks

Table 7 reports the main robustness checks and complementary analyses. Unless otherwise stated, all specifications follow the model presented in Sect. 6 and report conditional associations by quartiles of initial labour productivity.

As a first robustness check, we consider hourly productivity as an alternative measure of regional economic performance. This measure accounts for cross-regional differences in working time and labour utilisation that may not be fully captured by productivity per employee. Panel A of Table 7 confirms the main result obtained with the baseline productivity measure: digital and twin intensities remain positively and significantly associated with productivity growth in the least productive regions (Q1), with estimates of comparable magnitude, while the association with green intensity remains statistically insignificant. Outside Q1, the estimates are less stable across transition dimensions and productivity groups. Overall, the results based on hourly productivity confirm that the positive associations for digital and twin strategic orientations in the least productive regions are not specific to the baseline measure of productivity per employee.

A second robustness check concerns the definition of digital intensity. As discussed in Sect. 3, the baseline measure identifies a priority as digital when it is classified under either D – Digital Transformation or E – Key Enabling Technologies

Table 7 Robustness and contextual factors: conditional associations under alternative specifications (2019–2024)

Panel A: Alternative outcome variable: hourly labour productivity

	Digital	**Green**	**Twin**
Q1 (low)	1.567 (0.676)**	0.621 (0.684)	2.857 (1.265)**
Q2	−0.700 (0.338)**	−1.416 (0.436)***	−1.222 (0.417)***
Q3	−0.404 (0.322)	−1.582 (0.441)***	−1.498 (0.363)***
Q4 (high)	0.748 (0.437)*	−0.839 (0.632)	−0.120 (0.870)

Panel B: Alternative digital/twin definitions

	Digital no KET	**Twin** *portfolio (DI x GI)*	**Twin** *min (DI, GI)*
Q1 (low)	3.785 (1.046)***	2.988 (1.496)**	2.688 (1.084)**
Q2	0.745 (0.496)	0.719 (0.535)	0.686 (0.471)
Q3	−0.670 (0.276)**	−1.312 (0.329)***	−1.035 (0.336)***
Q4 (high)	−0.011 (0.425)	−0.200 (0.651)	−0.299 (0.541)

Panel C: Interaction of transition intensities with ERDF funding intensity

	Digital	**Green**	**Twin**
Q1 (low)	1.704 (0.713)**	0.165 (0.773)	2.997 (1.440)**
Q2	0.252 (0.409)	−0.477 (0.522)	0.584 (0.468)
Q3	−0.362 (0.305)	−0.966 (0.418)**	−1.126 (0.316)***
Q4 (high)	0.116 (0.459)	−0.174 (0.432)	0.041 (0.614)

Panel D: Interaction of transition intensities with institutional quality

	Digital	**Green**	**Twin**
Q1 (low)	1.996 (0.774)**	0.219 (0.817)	3.139 (1.528)**
Q2	0.505 (0.444)	−0.581 (0.547)	0.705 (0.488)
Q3	−0.544 (0.288)*	−1.036 (0.376)***	−1.209 (0.308)***
Q4 (high)	−0.184 (0.464)	−0.072 (0.465)	−0.056 (0.661)

Observations: 164. All results are presented by 2019 labour-productivity quartile. All the estimated models include controls as in Table 5. Robust standard errors in parentheses. Significance levels: ***(1%), **(5%), *(10%). Detailed model estimation results are available from the authors upon request. Panels C and D report average marginal associations by productivity quartile, calculated using the ERDF funding or institutional quality values observed for each region

(KETs). Since KETs constitute a broad category that may include technologies that are not digital in a strict sense, the baseline results could partly capture a more general orientation towards technological upgrading rather than digitalisation per se. We therefore construct a narrower digital intensity indicator based exclusively on priorities classified under Digital Transformation. The first model in Panel B of Table 7 confirms the main pattern reported in Table 6. The positive association in Q1 becomes larger (3.79) and remains statistically significant, while the estimate is negative and significant in Q3 and statistically insignificant in Q2 and Q4. Most importantly, the positive association between digital strategic orientation and

subsequent productivity growth in the least productive regions does not depend on the inclusion of KET-related priorities in the baseline measure.

The remaining robustness checks concern the definition of twin intensity. Our baseline indicator follows a within-priority intersection rule, whereby a priority is classified as twin when it simultaneously includes digital and green policy objectives. Although this definition captures the most explicit form of integration between the two transitions, it may not capture regions that pursue digital and green objectives through separate but complementary prioritiesWe therefore construct two new twin intensity variables, one is a portfolio-based measure of "twin-ness," constructed as DI × GI, the other is a balance index, computed as min(DI,GI). For both variables, the higher the values the higher the importance simultaneously placed by a region on the digital and green domains. The last two models in Panel B of Table 7 yield results very similar to the baseline specification. In Q1, the conditional association is positive and statistically significant under all three definitions, with estimates of 3.13 (Table 6) for the within-priority measure and 2.99 and 2.69 for the two portfolio-based measures. The positive association between twin strategic orientation and productivity growth in the least productive regions therefore does not depend critically on its specific operational definition: it emerges whether digital and green objectives are integrated within individual priorities or jointly emphasised across the regional portfolio of priorities.

Overall, the robustness checks provide consistent support for the main finding in the least productive regions and confirm that it is robust to alternative measures of productivity and alternative definitions of digital and twin strategic orientation.

7.2 Exploring contextual factors

In this section, we examine whether the associations between transition intensities and subsequent productivity growth vary with ERDF funding or institutional quality. For each transition intensity, we extend the model specification discussed in Sect. 6 by adding an interaction with either ERDF funding or institutional quality, retaining the main effects, the interactions with initial-productivity quartiles, and the other controls. The interaction coefficients test for moderation. Panels C and D of Table 7 report average marginal associations by productivity quartile, calculated using the ERDF funding or institutional quality values observed for each region. Focussing first on ERDF funding, none of the interaction terms between transition intensity and ERDF is statistically significant ($p = 0.228$ for digital, $p = 0.107$ for green, and $p = 0.176$ for twin intensity). The estimates therefore provide no statistically significant evidence that higher ERDF funding systematically strengthens or weakens the association between transition-oriented strategic priorities and productivity growth. ERDF support should accordingly be interpreted here as part of the regional context rather than as an empirically identified moderating mechanism.

Panel C nevertheless shows that the main pattern identified in Table 6 remains clearly visible when ERDF funding and its interaction with transition intensity are explicitly incorporated into the specification. Digital and twin intensities remain positively and significantly associated with productivity growth in Q1, while green

and twin intensities display negative and significant associations in Q3. No statistically significant association emerges in Q2 or Q4. Thus, the positive digital and twin associations in the least productive regions are robust to explicitly accounting for differences in Cohesion Policy support, although the insignificant interaction terms do not support the stronger claim that ERDF funding itself explains or systematically reinforces these associations.

This result should also be viewed against the pronounced territorial heterogeneity in transition-related Cohesion Policy investments documented by Barbero et al. (2025). Using project-level ERDF data for European regions during the 2014–2020 programming period, they show substantial geographical variation in the allocation of green, digital, and twin-transition investments. Their evidence highlights the importance of the territorial distribution of EU support as part of the context in which regional transition strategies operate. Our results complement this evidence by showing that the positive digital and twin associations in Q1 persist after ERDF support is explicitly incorporated into the model, but they do not establish ERDF funding as the mechanism generating this pattern.

Turning to institutional quality, the interaction estimates similarly provide little evidence that EQI systematically moderates the relationship between transition intensity and productivity growth. The interaction terms are statistically insignificant for digital ($p = 0.413$) and twin intensity ($p = 0.912$). The green interaction is positive and significant only at the 10% level ($p = 0.085$), providing at most weak evidence of moderation for this dimension. Overall, therefore, the results do not support institutional quality as a general explanation for the heterogeneous associations identified across productivity groups.

The conditional associations reported in Panel D again remain remarkably close to the baseline results. Digital and twin intensities are positively and significantly associated with productivity growth in Q1, while green and twin intensities display negative and significant associations in Q3. The remaining associations are generally not statistically significant, apart from a weakly significant negative digital association in Q3. Thus, the central Q1 pattern persists when institutional quality and its interaction with transition intensity are explicitly taken into account. This should not be interpreted as implying that the relatively lower institutional quality characterising many less developed regions favours productivity growth. Rather, the results indicate that the positive associations observed in Q1 cannot be attributed to superior institutional conditions and are likely to reflect a broader combination of structural characteristics and opportunities for productivity catch-up.

Overall, these additional analyses reinforce the robustness of the heterogeneous pattern identified in Sect. 6 while placing clear limits on its interpretation. The positive associations of digital and twin strategic orientations with productivity growth in the least productive regions remain visible after explicitly accounting for ERDF support and institutional quality. However, the interaction estimates provide no robust evidence that either ERDF funding or institutional quality systematically moderates these relationships. These variables should therefore be regarded as important dimensions of the regional context rather than as mechanisms explaining the stronger associations observed in Q1.

8 Conclusions

This study examined how European regions integrated green and digital priorities into S3 during the 2014–2020 programming period. By assessing the extent of this policy orientation and analysing its association with labour productivity growth, we provide new evidence on how diverse regional contexts are associated with heterogeneous patterns of green and digital transition.

Our findings, which remain consistent across a series of robustness checks, reveal substantial heterogeneity in the association between green and digital priorities and productivity growth across EU regions, reflecting the interplay between strategic focus, local capacities, and initial development conditions. While less developed regions display positive associations between digital and twin intensities and productivity performance, the estimated relationships become weak, or, in some cases, negative, in middle-income and more advanced regions.

In less developed regions, typically located in Eastern Europe and characterised by lower initial productivity levels, higher digital and twin intensity is positively associated with productivity growth. Conversely, regions with intermediate initial productivity levels, often facing industrial restructuring, weaker innovation systems, or institutional constraints, do not display similar positive associations. In these contexts, the prioritisation of green and digital themes within S3 strategies does not systematically coincide with higher productivity growth, especially in middle-level developed regions facing structural adjustment challenges. In more advanced regions, transition-related strategic priorities display only modest or statistically insignificant associations with productivity dynamics. This suggests that, in these contexts, broad thematic prioritisation may be less closely related to productivity patterns, which are likely influenced by more complex innovation processes and established economic structures.

Overall, the analysis shows that the way green and digital priorities are articulated within S3 is systematically associated with different labour productivity dynamics across European regions. These findings are consistent with the conceptual framework proposed in the paper, suggesting that the relationship between S3 strategic orientation and regional productivity reflects the interaction of heterogeneous regional capabilities, innovation dynamics, and adjustment processes, rather than a uniform association between transition-oriented strategies and economic performance. By documenting these differentiated patterns, the paper contributes to the emerging literature on the TT, showing that the economic implications of green and digital strategic orientations cannot be understood independently of regions' initial development conditions and territorial context. More broadly, it contributes to a better understanding of how the strategic orientation of S3 policies is associated with regional labour productivity growth across heterogeneous territorial contexts, supporting the evolution of place-based approaches towards Sustainable Smart Specialisation strategies.

Building on this evidence, future research could further investigate how strategic priorities are translated into concrete investment choices and policy instruments, and how these, in turn, relate to a wider set of economic and environmental outcomes.

Linking strategic orientations to information on project-level funding, expenditure intensity, and implementation characteristics would enable a more comprehensive assessment of the channels through which green and digital transitions interact with regional development processes. As the TT continues to reshape the European policy landscape, understanding the conditions under which it can contribute to inclusive and sustainable regional development will remain a central challenge for cohesion policy.

Appendix

See Tables 8, 9 and 10.

Table 8 Territorial levels of S3 in the EU countries

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

Table 9 Variables sources and definitions

Variable	Primary source	Description
Labour productivity growth	Eurostat	Growth rate of GDP per worker, annual average
Digital intensity	S3 Platform	Digital projects / Total number of S3 priorities
Green intensity	S3 Platform	Green projects / Total number of S3 priorities
Twin intensity	S3 Platform	Twin projects / Total number of S3 priorities
Labour productivity level	Eurostat	GDP per person employed, constant price 2015, Euro
Cohesion fund	Eurostat, Cohesiondata	European Regional Development Fund (ERDF) per worker, 2014–2020, Euro
Digital endowment	Eurostat	Households with broadband access, %
Green endowment	JRC	Regional Competitive Environmental Suitability Indicator (employment share in 56 NACE activities more competitive and sustainable than the EU median)
Quality of institution	Univ. of Gothenburg	Composite index based on citizens' perceptions on impartiality, quality of public service, corruption
Human capital	Eurostat	Population aged 25–64 by educational attainment level ISCED 5–8, %
Technological capital	Eurostat	R&D expenditure per inhabitant, Euro
HTEC specialisation	Eurostat	Revealed Comparative Advantage Index in High-technology sectors (high-technology manufacturing and knowledge-intensive high-technology services)
Population density	Eurostat	Persons per square kilometre

Table 10 Classification of digital and green policies based on policy objectives

	Digital		Green
D	*Digital transformation*	*F*	*Nature & Biodiversity*
D.18	Advanced or High performance computing	F.43	Biodiversity
D.19	Artificial intelligence, cognitive systems, augmented	F.44	Ecotourism
D.20	Big data, data mining, database management	F.45	Nature preservation
D.21	Broadband, spectrum and other communication networks	*J*	*Sustainable innovation*
D.22	Cleaner environment & efficient energy networks	J.61	Bioeconomy
D.23	Cloud computing and software as a service	J.62	Climate change
D.24	Digitising Industry (Industry 4.0, smart and additive)	J.63	Eco-innovations
D.25	E-Commerce & SMEs online	J.64	High-speed rail-road transportation systems
D.26	E-Government (e.g. e-Procurement, open data)	J.65	Resource efficiency
D.27	E-Health	J.66	Smart green & integrated transport systems
D.28	E-Inclusion (e.g. E-Skills, E-Learning)	J.67	Sustainable agriculture
D.29	ICT trust, cyber security & network security	J.68	Sustainable energy & renewables
D.30	Intelligent inter-modal & sustainable urban areas	J.69	Sustainable land % water use
D.31	Internet of Things (e.g. connected devices, sensors)	J.70	Sustainable production & consumption
D.32	Location based technologies (e.g. GPS, GIS)	J.71	Waste management
D.33	New media & easier access to cultural contents	*B.09*	*Blue renewable energy*
D.34	Quantum computing		
D.35	Robotics, autonomous and cyber physical systems		
D.36	Smart system integration		
E	*KETs*		
E.37	Advanced manufacturing systems		
E.38	Advanced materials		
E.39	Industrial biotechnology		
E.40	Micro/Nano-electronics		
E.41	Nanotechnology		
E.42	Photonics		

Examples of green, digital and twin coding from the Eye@RIS3 dataset

The first example considers a green priority in the Austrian region Steiermark (AT22), entitled "Green Technology." The priority focuses on technological development linked to the sustainable use of natural resources, with particular emphasis

on wood as a renewable raw material, green energy, green resources, and green buildings. It also explicitly addresses environmental protection objectives, including pollution monitoring, protection of ambient air and water, climate mitigation, protection of soil and groundwater, and solid-waste management. In Eye@RIS3, this priority is assigned to J – Sustainable Innovation and it is therefore identified as a green-only priority.

The second example refers to a digital priority in the Romanian region Sud-Est (RO22), entitled "ICT, High Tech, Nanotechnologies and Advanced Materials". The priority targets the development of advanced ICT and high-technology capabilities, with a strong focus on digital infrastructures and the diffusion of digital solutions across manufacturing and technology-intensive activities, including nanoscale developments. In Eye@RIS3, the priority is classified under D – Digital Transformation and E – Key Enabling Technologies. As no environmental or sustainability-related objectives are included, the priority is classified as digital only.

The final example focuses on a Twin priority in the Italian region Sardegna (ITG2), entitled "Smart networks for efficient energy management". The priority aims to modernise regional energy systems through the adoption of digital technologies to improve the efficiency and sustainability of energy production, storage, distribution, and consumption. It explicitly targets smart grids, energy-saving technologies such as smart metres, and electric mobility. In Eye@RIS3, the priority is classified under both D – Digital Transformation and J – Sustainable Innovation. Since the digital and green dimensions are jointly embedded within the same strategic priority, it is classified as a twin transition priority under our framework.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

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