Is the Twin Transition Also a Just Transition? Green and Digital Technological Capabilities, Labour Outcomes, and Productivity in the Italian Automotive Industry

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Introduction

Whether the twin transition is also a just transition has become one of the defining questions for advanced manufacturing economies. Over the past decade, the European Union has placed the twin transition at the centre of its industrial strategy through initiatives such as the European Green Deal, the Digital Decade, and the Net-Zero Industry Act, promoting simultaneous investments in green and digital technologies to strengthen productivity, resilience, and international competitiveness. As argued by Carbonell (2024), the twin transition has emerged not only as a technological transformation but also as an institutional and policy paradigm, reflecting the European Union's ambition to simultaneously pursue decarbonisation, digitalisation, and industrial competitiveness. While this policy framework assumes that green and digital transformations are mutually reinforcing, empirical evidence on whether complementarities between green and digital technological capabilities also translate into improved labour market outcomes remains scarce.

Recent firm-level evidence suggests that digital technologies can foster environmental innovation (Montresor & Vezzani, 2023) and that complementary investments in green and digital technologies improve firms' economic performance (Marrocu, Paci, & Serafini, 2026). Yet, much less is known about whether firms simultaneously developing both green and digital technological capabilities also achieve superior employment, job quality, labour productivity, and industrial productivity. This gap is particularly relevant for understanding whether technological transformation can simultaneously strengthen firms' competitiveness and support the objectives of a just transition.

The automotive industry provides a particularly relevant setting in which to address this question. Electrification and digitalisation are fundamentally reshaping production technologies, supplier networks, and global value chains (Wittmann, 2017).

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Electrification reduces the technological complexity and labour intensity of several traditional internal combustion engine components, creating significant adjustment pressures for suppliers and raising concerns about employment, job quality, and regional industrial resilience (Galgóczi, 2020; Pichler et al., 2021; Novaresio, 2024). At the same time, digital technologies—including automation, artificial intelligence, advanced manufacturing, and data-driven production—offer new opportunities to improve productivity, innovation, and international competitiveness. Understanding whether firms can leverage these complementary technological transformations to generate gains for both industrial performance and workers is therefore central to assessing whether the twin transition also constitutes a just transition.

These challenges are especially pronounced in Italy, where the automotive industry has experienced a prolonged decline in domestic vehicle production and employment over the past two decades, raising concerns about the future competitiveness of one of the country's most important manufacturing ecosystems (Bubbico, 2023). Nevertheless, Italy remains one of Europe's largest and most diversified automotive supplier systems, characterised by a dense network of specialised firms whose exposure to the ongoing technological transformation is highly heterogeneous. In this context, innovation is becoming a key determinant of firms' resilience and adaptation to structural change. As argued by Novaresio (2025), innovation plays a central role in shaping employment dynamics during the transition to electric mobility, suggesting that investments in new technological capabilities may be crucial not only for firms' competitiveness but also for sustaining employment throughout the transition. Italy therefore represents a critical case for assessing whether complementarities between green and digital technological capabilities can simultaneously strengthen firms' competitiveness, enhance productivity, and support a more just industrial transition.

Against this background, this paper investigates whether firms simultaneously developing green and digital technological capabilities achieve superior labour and productivity outcomes than firms specialising in only one technological trajectory. Combining longitudinal balance-sheet information from AIDA with patent data from Google Patents for the population of Italian automotive firms over the period 2015–2024, the paper estimates the effects of green and digital technological capabilities on employment, job quality (proxied by average wages), labour productivity, and industrial productivity using fixed-effects panel models, dynamic event-study analysis, and causal forest methods. By integrating insights from the literature on directed technological change, the twin transition, and the just transition, the paper provides one of the first firm-level assessments of whether complementarities between green and digital technological capabilities generate outcomes consistent with both enhanced competitiveness and the objectives of a just transition.

Literature, Research Gap and Contribution

More fundamentally, this paper builds on the literature on directed technological change, which argues that the direction of firms' technological investments is a key determinant of productivity growth, competitiveness, and labour demand. Acemoglu (2002) shows that innovation is directed towards specific technological trajectories, while Acemoglu and Restrepo (2019, 2020) argue that the labour market consequences of technological change depend on whether new technologies primarily automate existing tasks or create new productive activities. This perspective suggests that the economic effects of technological change depend not only on the intensity of innovation but also on its direction and on the complementarities between different technological trajectories. Building on this theoretical framework, an expanding body of empirical research has examined how directed technological change is unfolding through two major and increasingly interconnected technological trajectories: digitalisation and decarbonisation. The literature has progressively moved from analysing their individual effects on firms and workers to investigating their interaction through the concept of the twin transition.

A first stream of literature examines the labour market implications of the green transition. Firm-level evidence suggests that environmental innovations and cleaner production can generate positive employment effects by creating new production opportunities and strengthening firms' competitiveness (Rennings & Zwick, 2002; Fernández et al., 2024). Environmental innovation has also been associated with higher labour productivity (Piekkola & Rahko, 2024), while recent evidence indicates that green re-industrialisation can contribute to employment growth, wage dynamics, and productivity improvements when accompanied by technological upgrading and complementary investments (Cella et al., 2022). Overall, this literature suggests that green technological investments can improve both labour and production outcomes, although their effects vary substantially across firms.

A second strand of research investigates the labour market implications of digital transformation. The diffusion of automation, artificial intelligence, advanced manufacturing technologies, and data-driven production has increased firms' productivity and innovative capacity while simultaneously altering skill requirements, work organisation, and labour demand. Empirical evidence shows that digital technologies may substitute for routine tasks while increasing demand for complementary skills, generating heterogeneous effects on employment, wages, and productivity depending on firms' technological capabilities and organisational characteristics (Autor, Levy, & Murnane, 2003; Acemoglu & Restrepo, 2019, 2020; Dauth et al., 2021). Overall, the literature suggests that digital transformation has the potential to enhance firms' productivity while reshaping both the quantity and quality of employment.

More recently, attention has shifted towards the interaction between digitalisation and decarbonisation through the concept of the twin transition. Firm-level evidence suggests that digital technologies complement environmental innovation (Montresor & Vezzani, 2023), while complementary investments in green and digital technologies improve firms' economic performance (Marrocu, Paci, & Serafini, 2026). Together, these studies suggest that complementarities between green and digital technological capabilities may generate economic benefits beyond the individual effects of each technological trajectory, although evidence on their labour market implications remains scarce.

These issues are particularly relevant in the automotive industry, where electrification and digitalisation are simultaneously transforming production technologies, supplier networks, and value chains (Wittmann, 2017). Existing studies highlight substantial employment and restructuring challenges associated with electrification, reflecting the lower component complexity and changing production architecture of electric vehicles (Galgóczi, 2020; Pichler et al., 2021; Novaresio, 2024). Novaresio (2025) further shows that innovation plays a central role in shaping employment dynamics during the transition to electric mobility. Moreover, Novaresio and Patrucco (2025) demonstrate that innovation, international competitiveness, and green technological change reinforce one another within the European automotive industry, suggesting that firms' technological capabilities are closely linked to their competitive performance. At the firm level, Novaresio, Moretti, and Zirpoli (2025) further highlight that supplier tier and regional location are key dimensions of firms' heterogeneous exposure to the transition, motivating their inclusion as control variables in the empirical analysis.

Alongside electrification, digital transformation is reshaping the automotive industry through both process and product innovation. On the production side, the adoption of Industry 4.0 technologies—including advanced automation, smart manufacturing, and data-driven production—has transformed manufacturing processes and supply-chain organisation, with important implications for productivity, firms' competitiveness, and workforce skill requirements (Calabrese & Falavigna, 2022). On the product side, increasing software content, vehicle connectivity, and digital functionalities are transforming automobiles into increasingly integrated digital products, where software-enabled services and connectivity have become important sources of value creation and competitive differentiation, reinforcing the complementarities between digitalisation and electrification (Wittmann, 2017; Carbonell, 2024). These developments suggest that digital transformation affects not only firms' productivity but also the composition of employment and the quality of jobs within the automotive industry (Calabrese & Falavigna, 2022; Carbonell, 2024).

Building on these developments, Carbonell (2024) argues that, within the European automotive industry, the green and digital transitions increasingly converge around product innovation—particularly through connected and electric vehicles—but that, in

the absence of a coherent industrial strategy, this convergence risks exacerbating regional disparities and uneven industrial restructuring. Consistent with this perspective, Krzywdzinski et al. (2026) show that the twin transition is reshaping the division of labour within the European automotive supplier industry, generating heterogeneous adjustment costs and opportunities across firms, supplier tiers, and regions.

Despite these advances, important empirical gaps remain. Existing studies primarily examine the labour market effects of digitalisation and decarbonisation separately, analyse the organisation of production under the twin transition, or focus on firms' competitiveness rather than jointly analysing labour and productivity outcomes. Much less is known about whether firms simultaneously developing green and digital technological capabilities achieve superior labour market and productivity outcomes than firms specialising in only one technological domain. In particular, there is little longitudinal firm-level evidence linking green and digital patenting activities to employment, wages—as a proxy for job quality—labour productivity, and industrial productivity.

By combining balance-sheet information from AIDA with patent data from Google Patents over the period 2015–2024, this paper provides one of the first longitudinal firm-level assessments of how complementarities between green and digital technological capabilities shape firms' labour and production outcomes in the automotive industry. Beyond advancing the literature on directed technological change and the economics of the twin transition, the analysis speaks directly to the broader debate on the just transition. In a country such as Italy—where the automotive industry is simultaneously facing technological disruption, industrial restructuring, and long-standing concerns over manufacturing competitiveness—the paper provides new evidence on whether the complementary development of green and digital technological capabilities can support both firms' competitiveness and workers' outcomes. More broadly, the findings will contribute to understanding under which conditions the twin transition can also become a just transition.

Research Questions and Hypotheses

This paper addresses the following research question: “How do firms' green and digital technological capabilities, individually and jointly, affect labour and productivity outcomes in the Italian automotive industry?”

To answer this question, the analysis tests four hypotheses.

H1 (Green technological capabilities). Green technological capabilities are associated with firms' labour and productivity outcomes, including employment, wages (used as a proxy for job quality), labour productivity, and industrial productivity.

H2 (Digital technological capabilities). Digital technological capabilities are associated with firms' labour and productivity outcomes, including employment, wages, labour productivity, and industrial productivity.

H3 (Complementarity hypothesis). The interaction between green and digital technological capabilities generates complementary effects, such that firms simultaneously developing both technological trajectories experience stronger labour and productivity gains than firms specialising in either green or digital technologies alone.

H4 (Heterogeneity hypothesis). The effects of green and digital technological capabilities vary systematically according to firms' supplier tier, export orientation, regional location, financial performance, and pre-existing technological capabilities.

Data and Empirical Strategy

The empirical analysis covers the period 2015–2024 and combines firm-level balance-sheet information from the AIDA (Bureau van Dijk/Orbis) database with patent data retrieved from Google Patents for firms operating in the Italian automotive industry (NACE Rev. 2 code 29). Green and digital innovation are measured using annual patenting activity, constructed as the combined count of patent applications and granted patents classified according to internationally recognised patent taxonomies. Green patents are identified using the OECD ENV-TECH classification (Hascic & Migotto, 2015), while digital patents follow the WIPO Digital Technologies taxonomy. Combining patent applications and granted patents allows the analysis to capture firms' innovative activity throughout the patenting process rather than focusing on a single stage. While patent applications provide an early signal of firms' technological investments and innovation efforts, granted patents identify inventions that have successfully completed the patent examination process. This combined measure therefore captures the overall intensity of firms' annual patenting activity, reflecting both the generation and formal recognition of technological innovation. Given the highly skewed distribution of patent counts and the prevalence of zero-valued observations, the baseline models employ the inverse hyperbolic sine (IHS, or asinh) transformation of patent counts, while the logarithmic transformation, $\log(x + 1)$, is used as a robustness check. In addition, Green Intelligence (GI) patents—defined as patents combining artificial intelligence and environmental technologies following the classification proposed by Biggi, Iori, Mazzei, and Mina (2025)—are included as a control variable to isolate the effects of AI-enabled green innovation from the broader complementarities between green and digital technological change.

Labour quantity is measured by the number of employees. Labour quality is proxied by average wages and personnel costs per employee, reflecting firms' demand for higher-skilled labour. Labour productivity is measured as value added per employee, while

industrial productivity is captured by firms' value of production. The empirical models further control for firms' innovation effort through research and development (R&D) expenditures and for the economic value of firms' intellectual property through patent royalties. Additional controls include export intensity (exports-to-sales ratio), supplier tier (OEMs versus suppliers), regional location, firm size, firm age, return on assets (ROA), return on equity (ROE), EBITDA, and year fixed effects.

The empirical strategy proceeds in three complementary stages.

First, descriptive statistics and regional maps provide an overview of the spatial distribution of employment, wages, productivity, export orientation, and green and digital innovation across the Italian automotive ecosystem.

Second, the main analysis estimates firm fixed-effects panel models using one-year lagged explanatory variables to mitigate concerns related to reverse causality and simultaneity. The baseline specification is:

$$Y_{it} = \beta 0 + \beta 1\ IHS(GreenPatents_{i,t-1}) + \beta 2\ IHS(DigitalPatents_{i,t-1}) + \beta 3[IHS(GreenPatents) \times IHS(DigitalPatents)]_{i,t-1} + \beta 4\ IHS(GI_{i,t-1}) + \beta 5\ IHS(R\&D_{i,t-1}) + \beta 6\ IHS(Royalties_{i,t-1}) + \gamma X_{it} + \alpha_i + \delta_t + \varepsilon_{it} \quad \text{Eq.1}$$

where Y_{it} alternatively denotes employment, average wages (used as a proxy for job quality), labour productivity, and industrial productivity. GreenPatents and DigitalPatents denote firms' annual green and digital patenting activity, measured as the combined number of patent applications and granted patents. GI captures annual Green Intelligence patenting activity. R&D measures firms' innovation effort, whereas Royalties capture the economic value generated from firms' intellectual property assets. X_{it} denotes the vector of additional firm-level controls, including export intensity, supplier tier, regional location, firm size, firm age, ROA, ROE, and EBITDA. Firm and year fixed effects are denoted by α_i and δ_t, respectively. Consistent with the theoretical framework, the interaction coefficient $\beta 3$ constitutes the main parameter of interest, testing whether the simultaneous development of green and digital innovation generates labour and productivity gains beyond the individual effects of each technological trajectory.

Third, dynamic event-study models analyse firms' performance before and after entering the twin technological trajectory. The treatment event is defined as the first year in which a firm has developed both green and digital patenting activity, regardless of the order in which the two technological trajectories were adopted. Accordingly, firms are considered treated once both technological capabilities are observed, allowing for sequential adoption over time. For expositional simplicity, the event-study specification is written as:

$$Y_{(it)}=\sum_{(k\neq -1)} \beta_k\ EventTime_{(it)}^k + \gamma X_{(it)} + \alpha_i + \delta_t + \varepsilon_{(it)}. \quad \text{Eq.2}$$

where EventTime_it^k denotes a set of leads and lags measuring the number of years before and after firms' entry into the twin technological trajectory. The year immediately preceding treatment (k = −1) is omitted as the reference category. Because firms enter the twin technological trajectory at different points in time, Equation (2) is estimated using the staggered difference-in-differences estimator proposed by Callaway and Sant'Anna (2021), which identifies cohort-specific average treatment effects and is robust to heterogeneous treatment timing, thereby avoiding the biases associated with conventional two-way fixed-effects event-study estimators. This specification enables testing for pre-treatment trends and estimating the dynamic evolution and persistence of labour and productivity outcomes following firms' entry into the twin technological trajectory.

Finally, causal forest methods (Wager & Athey, 2018) are employed to estimate heterogeneous treatment effects across firms according to supplier tier, export orientation, regional location, financial performance, firm size, and pre-existing firm characteristics. This complementary machine-learning approach allows the identification of heterogeneous effects that may remain hidden in average regression estimates, providing additional evidence on which firms benefit most from the twin transition.

Expected Contributions

This paper provides new longitudinal firm-level evidence on the relationship between green and digital technological innovation, employment, job quality, labour productivity, and industrial productivity in the automotive industry. By combining balance-sheet information from AIDA with patent data from Google Patents, the analysis contributes to the literature on directed technological change by examining whether complementarities between green and digital innovation are associated with labour and productivity outcomes beyond the individual effects of each technological trajectory.

More broadly, the paper contributes to the emerging literature on the twin transition by jointly analysing labour market and firm performance outcomes within a unified empirical framework. By documenting average, dynamic, and heterogeneous effects across firms, supplier tiers, and regions, the analysis sheds light on how different patterns of technological specialisation are associated with firms' adjustment to the ongoing industrial transformation.

Finally, the paper contributes to current academic and policy debates on the economic implications of the European twin transition by providing evidence on whether complementarities between green and digital innovation are associated with labour outcomes consistent with the objectives of a just transition. Rather than evaluating specific policy interventions, the study identifies the firm-level conditions under which the twin transition is associated with both stronger industrial performance and more favourable labour market outcomes, thereby contributing to a better understanding of one of the central economic questions surrounding Europe's industrial transformation.

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