Title: FROM ADOPTION TO IMPACT: EFFECTS OF ARTIFICIAL INTELLIGENCE ON PRODUCTIVITY AND HETEROGENEITY IN THE SPANISH MANUFACTURING SECTOR

Extended Abstract

Introduction

The adoption of Artificial Intelligence (AI) technologies has been accelerating in recent years, reshaping the dynamics of firm productivity and competitiveness. Among the multiple branches of AI, predictive AI—understood as the deployment of advanced data analytics, cloud computing, and algorithm-based forecasting tools—has played a central role in transforming firm-level decision-making processes and operational efficiency. The COVID-19 pandemic further amplified these transformations, serving both as a catalyst and a stress test for firms' technological capabilities. Yet, while digitalization advanced broadly across industries, a critical empirical question remains: who actually benefits from predictive AI adoption in terms of productivity gains?

The present paper seeks to explore the heterogeneous impact of predictive AI adoption on total factor productivity (TFP) among Spanish manufacturing firms. Specifically, we investigate whether the effects of predictive AI adoption differ across firms with varying levels of productivity, how these effects evolved before and after the pandemic, and to what extent firm-specific capabilities and regional factors mediate these relationships.

Research Questions and Contributions

We address the following research questions:

(1) Which firms benefit the most from predictive AI adoption?

(2) How does the impact of predictive AI vary across the TFP distribution?

(3) Has the pandemic amplified or altered the productivity effects of predictive AI?

To answer these questions, we leverage unique firm-level data from the *Encuesta sobre Estrategias Empresariales* (ESEE) for the years 2018 (pre-COVID) and 2022 (post-COVID). We apply quantile regression models to capture heterogeneity across the productivity distribution, complemented with Two-Stage Least Squares (2SLS) estimation to address potential endogeneity concerns. Our contribution to the literature is threefold: (i) we provide novel evidence on how the productivity returns to AI have

evolved after the pandemic; (ii) we incorporate both firm-level capabilities and regional-level economic factors into our analysis; and (iii) we identify differential effects across firm sizes.

Our findings reveal an increasing and more generalized positive effect of predictive AI adoption on TFP after the pandemic, particularly benefiting firms located at the upper end of the productivity distribution. Firm-level factors such as training expenditure, market internationalization, and process innovation remain consistently significant determinants of productivity, while regional capital stock fosters TFP growth and localization economies appear to have negative spillovers on firm productivity.

Literature Review

The paper connects to several strands of literature:

AI, Digitalization and Productivity:

A growing body of research explores the effects of AI and digital technologies on productivity growth, highlighting self-selection mechanisms whereby more capable firms are better positioned to adopt and leverage these technologies (Brynjolfsson & McAfee, 2014; Aghion et al., 2019). Predictive AI technologies—such as big data analytics, cloud platforms, and algorithmic forecasting—enhance firms' capacity to optimize production, customize offerings, and reduce uncertainties (Cockburn et al., 2018).

Heterogeneity in Productivity Effects:

Recent empirical work underscores the non-linear and heterogeneous nature of productivity effects from technology adoption (Bloom et al., 2021). Quantile regression models offer a suitable framework for examining how AI's impact differs across firms with different baseline productivity levels (Koenker & Bassett, 1978; Andrews et al., 2016). Moreover, the pandemic-induced shock may have reconfigured these dynamics, altering both the pace and depth of AI diffusion (DeStefano et al., 2022).

Firm Capabilities and Absorptive Capacity:

Consistent with Cohen and Levinthal's (1990) absorptive capacity theory, firm capabilities such as human capital development, market internationalization, and process innovation mediate the productivity returns to AI adoption. Firms with greater training

efforts, wider market exposure, and ongoing innovation activities are better equipped to integrate AI into their production processes (Aral et al., 2021).

Regional Contexts and Spatial Spillovers:

Finally, regional economic structures exert a meaningful influence on firm productivity. While capital-intensive regions may provide complementary infrastructure and knowledge spillovers, localization economies may also generate negative externalities such as competition for resources, congestion, or diminishing marginal returns (Glaeser et al., 1992; Rosenthal & Strange, 2004).

Hypotheses

Based on this literature, we formulate the following hypotheses:

- H1: The adoption of predictive AI technologies has a positive impact on firm-level total factor productivity, particularly for firms with higher baseline productivity levels.
- H2: The effect of predictive AI adoption on TFP has become stronger and more widespread after the COVID-19 pandemic.
- H3: Firm-level characteristics such as training expenditure, international market scope, and process innovation are positively associated with TFP, regardless of AI adoption.
- H4: Regional characteristics influence TFP: capital-intensive regions foster higher productivity, while strong localization economies may crowd out firm-level efficiency gains.

Methodology and Data

We use microdata from the ESEE for 2018 and 2022, focusing on Spanish manufacturing firms. The ESEE provides rich firm-level information on technology adoption, workforce composition, market orientation, and innovation activities. Our final sample includes both small and large firms, classified according to the 200-worker threshold.

To complement firm-level data, we incorporate provincial-level indicators from Spanish national statistics (INE), including gross capital investment and capital stock for the industrial sector, as well as measures of localization economies (number of sector-related firms within the province).

The dependent variable, TFP, is estimated through an OLS production function controlling for capital inputs. The key independent variable, predictive AI adoption, is operationalized as a binary indicator capturing the use of advanced digital technologies such as cloud computing, big data analytics, and other forecasting tools. Control variables include firm age (and age squared), training expenditure, international market scope, and process innovation.

Our empirical strategy relies on quantile regression models to capture heterogeneity in the productivity effects of predictive AI across the TFP distribution. We estimate models separately for 2018 and 2022 to capture temporal dynamics. To address potential endogeneity between AI adoption and TFP, we use workforce educational attainment as an instrumental variable in 2SLS regressions, assuming that workforce education affects AI adoption but not TFP directly.

Results and Discussion

Our analysis yields several key findings:

First, the impact of predictive AI on TFP becomes substantially more pronounced and consistent in 2022 compared to 2018. In 2018, predictive AI adoption was positively associated with TFP only at the lower (10%) and upper (90%) tails of the distribution, with weaker statistical significance. By contrast, in 2022, significant positive effects emerge across almost the entire productivity distribution, with increasing magnitudes for higher quantiles. This suggests that predictive AI adoption has matured and diffused more effectively in the post-pandemic context.

Second, the average effect estimated through 2SLS indicates a clear shift: from 1.18 in 2018 to 2.82 in 2022, reflecting more robust and generalized productivity returns to AI adoption after COVID-19.

Third, firm-level capabilities consistently mediate productivity outcomes. Training expenditure, international market participation, and process innovation exhibit positive and significant associations with TFP across all quantiles and both years, supporting H3. These capabilities likely enhance firms' absorptive capacity and their ability to translate predictive AI adoption into productivity gains.

Fourth, regional factors display mixed effects. Capital-intensive regions positively contribute to firm productivity, particularly in 2022, while localization economies exert a negative influence on TFP. These negative spillovers may reflect intensified competition, labor market congestion, or diminishing returns from sectoral agglomeration.

Finally, disaggregating results by firm size reveals additional heterogeneity. For small firms (<200 employees), predictive AI adoption has particularly strong effects at the upper quantiles (90th and 95th), suggesting that smaller firms with already high TFP levels are best positioned to leverage predictive AI tools. For larger firms, AI impacts are more evenly distributed but slightly concentrated at central quantiles.

Taken together, these findings confirm hypotheses H1 through H3, while providing partial confirmation of H4. Predictive AI adoption indeed enhances TFP, especially after COVID-19, and firm capabilities consistently strengthen these gains. However, regional spillovers show that localization effects may hinder firm-level efficiency, particularly in highly agglomerated areas.

Conclusions and Policy Implications

Our results underscore several important conclusions:

- The productivity returns to predictive AI adoption have grown stronger and more generalized in the post-pandemic period.
- Firm-level capabilities such as workforce training, process innovation, and global market engagement are key enablers of successful AI adoption.
- Regional capital intensity supports productivity growth, but excessive sectoral concentration may generate negative localization effects.

From a policy perspective, these findings highlight the need for differentiated and targeted strategies. Policymakers should promote training programs that build firm-level absorptive capacities, particularly among smaller firms that can achieve significant gains through AI adoption. Industrial policies should carefully balance regional specialization with diversification to avoid agglomeration diseconomies. Finally, public support for digitalization initiatives should consider both firm-specific characteristics and regional economic structures to maximize productivity benefits across the entire business ecosystem.

Limitations and Future Research

This study has several limitations. Our data rely on cross-sectional observations and may not fully capture dynamic or causal relationships. While instrumental variable techniques help address endogeneity concerns, panel data methods or matched firm samples could provide stronger identification. Additionally, future research could extend this analysis to other sectors beyond manufacturing and explore the long-term evolution of AI-related productivity gains as AI technologies continue to evolve.

Keywords: Predictive Artificial Intelligence, Total Factor Productivity, Quantile Regression, COVID-19, Regional Economic Factors

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