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Robotizing to Compete? Firm-level Evidence

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Robotizing to compete? Firm-level evidence *

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Abstract

We investigate the impact of product market competition on firms' automation investments. We use a rich combination of micro-data on Portuguese exporters and exploit a novel source of variation in the degree of competition they face – a tariff liberalization between the European Union and Central and Eastern European countries in the 1990s. We find that firms facing greater competition in export markets tend to reduce investments in automation technologies. These average negative effects are driven by the least productive firms, while the most efficient exporters in industries that are more prone to automation tend to robotize in order to compete. These findings suggest that an increase in the degree of product market competition widens disparities between firms.

JEL classification: D22, F16, J23, L25, O33.
Keywords: automation, product market competition, firm heterogeneity, trade liberalization, workers, multi-product firms.

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1 Introduction

The use of automation technologies has increased dramatically in recent decades, especially in high and middle-income countries. The widely accepted explanation for this development is that advances in engineering have radically improved the capabilities of these technologies, while lowering their relative prices. The ensuing automation of industrial production caused significant productivity growth, but had adverse consequences for the labor market prospects of low-skilled workers (Acemoglu and Restrepo, 2020; Graetz and Michaels, 2018). In light of these impacts of automation technologies, it is important to understand the causes of their adoption. While differences in the relative price of labor and demographics provide a natural explanation for broad cross-country differences in automation (Acemoglu and Restrepo, 2021; Artuc et al., 2023), more recent studies based on micro-level data point to large differences in robot adoption across firms, industries and regions within countries (Brynjolfsson et al., 2023; Cheng et al., 2019; Deng et al., 2021).

How does product market competition impact firms' investments in automation technologies? Models of robot adoption commonly used in the literature suggest that a decrease in the market share of incumbents due to entry of new competitors hinders firms' ability to pay the large fixed cost of adopting automation technologies (Humlum, 2019; Koch et al., 2021). At the same time, foreign competition from both low- and high-wage countries may incentivize firms to engage in "defensive skill-biased innovation", increasing the sophistication of their products and production processes to make it harder to be imitated and leapfrogged by foreign competitors (Thoenig and Verdier, 2003). While previous research suggests that product market competition matters for firm-level investments in other innovation inputs and outputs, the direction and the magnitude of the effects differs across studies (Autor, Dorn, et al., 2020; Bloom et al., 2013; Coelli et al., 2022, e.g.). Relative to other types of investment, robots are characterized by a significantly higher labor substitutability, which is vital for cost reduction, but they also involve substantial fixed costs of adoption (Acemoglu and Restrepo, 2020; Bessen et al., 2023). Hence, the available evidence provides limited guidance on how firms' automation investments would react to increased competition.

In this paper, we study empirically the impact of product market competition on firms' investments in automation. We bring together rich and comprehensive administrative micro data from Portugal, including employer-employee data, firm-level exports and imports, and firm-level imports of automation technologies. For causal identification, we use a large and so far unexploited tariff liberalization between the European Union (EU) and Central and Eastern European Countries (CEECs) in the 1990s. This event was a major shock for Portuguese exporters, who heavily depended on the European market. We find that firms more exposed to product market competition responded by reducing investments in automation on average, while only the most productive firms in highly automating industries exhibited a positive response. At the same time, the shock led to adjustments in several product and worker margins of the firm. Our results indicate that stronger competition leads to an increase in concentration both within and between Portuguese firms.

Our identification strategy leverages a previously unexploited source of variation in the degree of competition stemming from a large tariff liberalization between the EU and CEECs between 1993 and 2001. While the average tariff for industrial goods fell from 6.5 to 0 percent, some products experienced tariff reductions of up to 35 percentage points, substantially lowering the prices of goods from CEECs in the EU market. The liberalization had a significant impact on the degree of competition faced by Portuguese exporters, which were highly reliant on the EU market.[1] We measure the degree of exposure of Portuguese firms to this competition shock by combining firm-product-level data on the initial composition of firms' export portfolios with product-level data on EU tariffs with respect to CEECs. Our identifying assumption is that the variation in tariff reductions across products is exclusively determined by the EU's initial level of most-favored-nation tariff rates, which Portugal could not influence when joining the European Economic Community in 1986.

Our main outcome of interest – investments in automation equipment by Portuguese

[1]In the year 1993, 80% of Portuguese manufacturing exports were destined for Western European countries.

firms – is traceable via import statistics at the firm-product level. Using specific product codes in the harmonized system nomenclature, we are able to identify imports of automation equipment, including industrial robots and numerically controlled machinery. As there was little domestic supply of automation equipment in Portugal in the 1990s, firm-level imports are a reliable indicator of investments in automation. The data reveal a continuous increase in automation equipment imports and in the number of automation equipment importers during the 1990s, which provide large variation to estimate the causes of robot adoption.

We start the empirical analysis by illustrating the relevance of this negative shock on firm outcomes. To achieve this, we provide evidence of the significant impact of tariff liberalization on firms' export performance. Specifically, we document that more exposed firms experienced a sharp decline in total sales growth, driven by a sizable reduction in exports to the EU markets, while domestic and extra-EU sales remained unaffected. In addition, we find evidence for adjustment at the product margin: firms reduce the number of products exported to the EU, while exports to other destinations remain unaffected. Finally, we document a reduction in export prices for more exposed firms, which is likely to reflect a reduction in markups in the EU market. Thereby, we provide robust evidence for mounting competitive pressure resulting from the tariff liberalization. Reassuringly, we find no evidence of pre-trends and can show that our results are not driven by changes in exposure to competition from China in the EU market.

We extend the analysis of firm outcomes to the worker dimension, where we establish that firms respond to increased competitive pressures by lowering labor costs, thereby emphasizing the importance of the negative shock. We observe a notable decline in employment growth at more exposed firms, particularly among low-skilled workers. This reduction in employment growth is compounded by a decrease in work hours for incumbent workers, resulting in substantial reductions in the total wage bill, while hourly wages remain unaffected. These findings suggest that the tariff liberalization led firms to constrain new hires and adjust work hours for incumbent workers, indicating a strategic response that reduces labor costs and has the potential to enhance labor productivity.

In our main results, we show that greater exposure to the tariff liberalization is linked to reduced levels of automation. We find that a one-standard-deviation increase in exposure leads to a substantial 25 percent reduction in automation at the intensive margin, as well as a 3-percentage-point decrease in the likelihood of firms adopting automation at the extensive margin. Despite the apparent need for firms to curb labor cost in the face of intensified competitive pressure, this evidence indicates that, on average, heightened competition diminishes the incentive for automation. However, when scrutinizing more productive firms within industries that are highly prone to automation, we find evidence of heterogeneous treatment effects. Using differences in labor productivity across firms as a proxy, we observe that initially more productive firms respond by increasing their automation levels compared to less productive firms. This observation implies that within industries where automation is most prevalent, heightened competition tends to discourage substantial automation investments among less competitive firms while simultaneously fostering automation among the industry leaders.

Our paper contributes to the literature on trade and innovation (Chen and Steinwender, 2019). We exploit a novel source of variation in competition in foreign markets, the tariff liberalization between the EU and CEECs in the 1990s and provide new firm-level evidence for automation investments. By combining data on firms' ex-ante product portfolio with information on product-level tariff changes, we can compute firm-specific exposure to policy-induced changes in competition. This allows us to leverage variation in tariff exposure across firms within the same industry, offering a more precise approach compared to prior studies that primarily focused on tariff reductions or import competition at a more aggregated industry level (Autor, Dorn, et al., 2020; Chen and Steinwender, 2021; Coelli et al., 2022). We also expand the literature by considering imports of automation equipment as part of process innovation and technology upgrading. While previous studies mainly focused on corporate research and development, technology adoption through imports of machinery are especially relevant to countries that may not be at the forefront of technology development, helping them to maintain competitiveness in the global market place (Hoekman and Javorcik, 2006). Finally, we study the effect of competition in the destination country of exports, while existing research has primarily focused on the impact of foreign competition on domestic markets. The heterogeneous results among firms that we observe can be reconciled through the lens of models from the industrial organization literature. On the one hand, Schumpeterian models show that competition could reduce potential rents from innovation, leading to a decrease in innovation (Schumpeter, 1942). On the other hand, higher competition could reduce pre-innovation rents and increase pressure to overtake competitors (Arrow 1962), implying a positive impact on innovation. Hence, the contrasting results we find may reflect firms' position as laggards or leaders. As initially more productive firms are the leaders in their industry, they have stronger incentives to innovate to escape competition, whereas the opposite holds for the laggers - decreased returns to innovation and profit margins lead less productive firms to decrease investments in innovation.[2]

Our paper also relates to the literature that studies the determinants of automation at the firm level. We contribute to this literature by empirically studying the role of competition in product markets, for which the literature has so far lacked a clear prediction. We show that competition has a heterogeneous impact on firm's automation depending on firms' initial competitiveness. This finding provides a novel explanation for the stark differences in automation adoption across firms within the same industries observed in recent micro-level studies (Brynjolfsson et al., 2023; Deng et al., 2021). So far, the heterogeneity of automation adoption has been explained by differences in factor markets conditions, such as changes in minimum wage, immigration, and labor and capital taxation (Acemoglu, Manera, et al.,

[2]Aghion et al. (2005)'s model shows that differences in pre- and post-innovation rents determine the direction of responses to increased competition. Previous empirical studies reveal contrasting results of competition on innovation for different countries - for instance negative for US firms (Autor et al. 2020) and positive for European firms (Bloom et al. 2016). As argued by Autor et al. (2020), the negative impact of foreign competition on innovation they find for the US could be explained by the fact that US industries are further away from the technology frontier, whereas European industries investigated by Bloom et al. (2016) are closer to the technology frontier. We show large heterogeneity within the same industry in a country.

2020; Danzer et al., 2020; Fan et al., 2020; Nain and Wang, 2021).

Finally, our paper also relates to the literature that investigates the impact of robot adoption on labour market outcomes. Several papers suggest that advanced automation technologies such as industrial robots and numerically controlled machinery increase the demand for skilled workers and may in this way contribute to an increase in wage inequality (Acemoglu and Autor, 2011; Acemoglu and Restrepo, 2020; Akerman et al., 2015; Autor, Levy, et al., 2003; Koch et al., 2021; Michaels et al., 2014). However, this is not necessarily the case: using firm-level data for Finnland, Hirvonen et al. (2022) show that the adoption of advanced technologies increased employment without leading to skill-biased technological change. In our paper, firms that are more severely hit by the competition shock react by decreasing investments in both robots and employment, in particular of low-skilled workers. Hence, our results are not explained by a substitution between capital and labor, but could be rather a result from product-level reallocations within the firm, as we discuss in the paper.

The remainder of this manuscript is structured as follows: In Section 2, we provide background information on the tariff liberalization between the EU and CEECs in the 1990s. Section 3 presents the data used in this study, while Section 4 explains our empirical strategy. We summarize and discuss our findings in Section 5 and conclude with an outlook in Section 6.

2 Background

This section provides a description of the event of tariff liberalization between the EU and the CEECs in the 1990s. It emphasizes the characteristics that make this policy change exogenous from the perspective of the Portuguese economy, making it an ideal event to evaluate changes in competition faced by Portuguese exporters in the EU market. The following features characterized this period of tariff liberalization.[3]

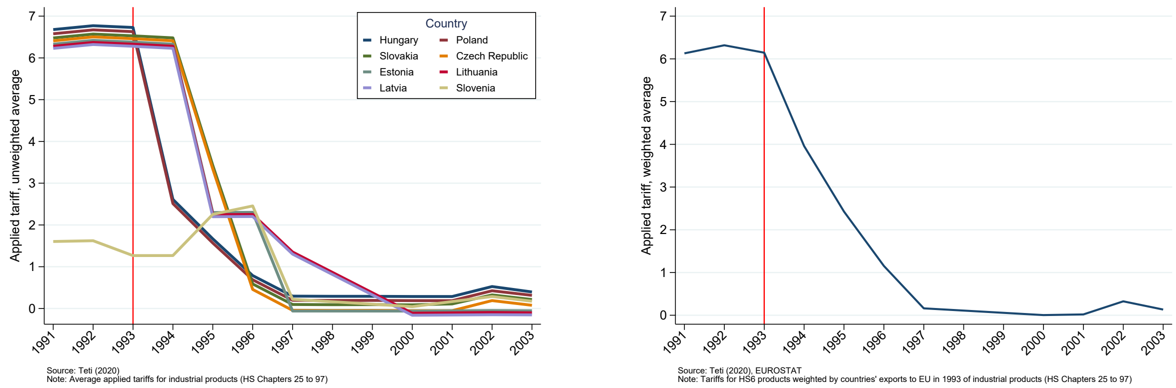
[3] In terms of identification, one important advantage of this period, in comparison to the event of the Eastern European Enlargement in 2004, is the fact that the 2004 enlargement is characterized by a bundle

Association agreements and *de facto* customs union Whereas the literature on the Eastern European Enlargmeent focuses on the event of 2004, the process of integration in the EU started already in the 1990's. After the dissolution of the Soviet Union and the Council for Mutual Economic Assistance in 1991, the EU and the CEECs concluded a series of association agreements to strengthen economic and political ties and set up the legal framework for the later accession. The EU concluded association agreements with Hungary and Poland in 1991, with the Czechia and Slovakia in 1992, with Estonia, Latvia and Lithuania in 1993 and with Slovenia in 1995. The main part of these association agreements was a comprehensive liberalization of trade in goods and services.[4] While the EU had charged non-preferential Most-Favourite-Nation tariffs on imports from the CEECs before, the agreements set a time schedule for abolishing tariffs for industrial goods and substantially reducing tariffs for all remaining goods within the following years. Figure 1 shows that the large share of tariff changes happened in the beginning of the liberalization period between 1993 to 1998. By January 1, 2002, industrial tariffs had been abolished on both sides, creating a *de facto* customs union before many CEECs formally joined the EU in 2004. The EU's tariff liberalization with the CEECs had several implications for the Portuguese exporters, as we discuss below.

The EU's tariff liberalization with the CEECs in the 1990s boosted their firms' competitiveness in the EU market. Figure 1 shows that the average tariff for industrial goods fell from 6.5 to 0 percent between 1993 and 2001. During that period, some products experienced a tariff reduction of up to 70 percentage points. This tariff liberalization substantially lowered goods prices and facilitated market entry of exporters from the CEECs. Figure 2 illustrates that manufacturing exports from the CEECs increased 20 % yearly, and their

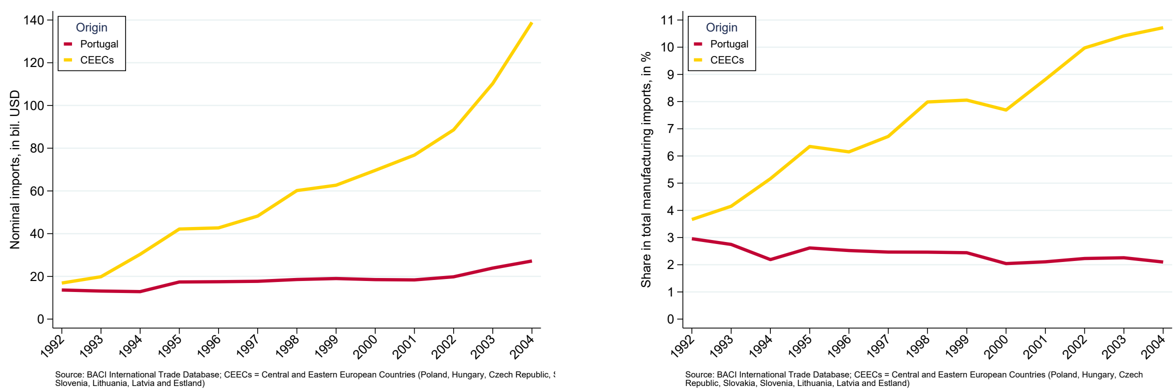
of policy changes, including changes in non-tariff barriers and migration policies, as well as other changes in the environment, such as the rise of China after entry into the World Trade Organization in 2001 and its penetration in the EU market. In our period of analysis, we can be less concerned about these potential confounding factors that affect firms' competitiveness.

[4]Beyond liberalizing trade, the agreements also set the basis for new institutions that facilitated political dialogue, financial co-operation and technical assistance for the restructuring of the Central and Eastern European economies. (see European Econonic Communities, 1992).



(a) By country (b) Average

Figure 1: EU import tariffs towards CEECs (1991-2003)



(a) Import volumes (b) Share in total manufacturing imports

Figure 2: EU manufacturing imports (1992-2004), by origin

share of total EU manufacturing imports rose from 1.5% to 9% from 1993 to 2004. The increasing market share of CEECs producers resulted in heightened competitive pressure on other exporters of low-value-added industrial goods to the EU market, including Portugal.

Relevance of the competition shock for Portuguese exporters In the early 1990s, the EU market was of great importance to Portuguese manufacturing firms. Figure 3 indicates that the EU was the destination of over 80% of Portuguese manufacturing exports, accounting for more than 30 % of total manufacturing output of Portuguese firms. This reliance on the EU market made Portuguese firms vulnerable to economic fluctuations within the EU, as well as changes in EU trade policies. This implies that the rise of competi-

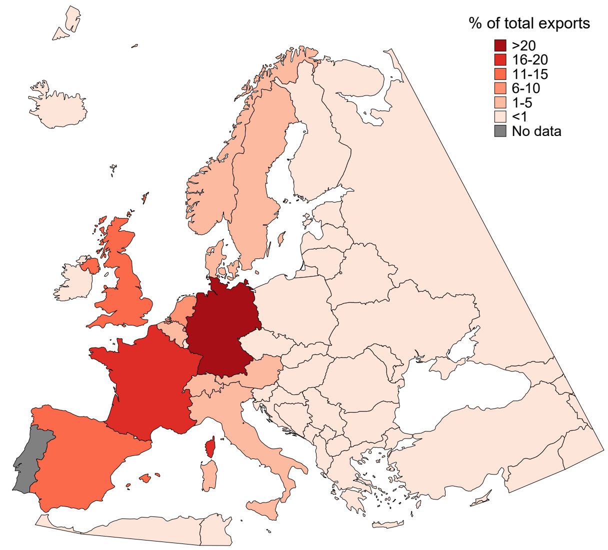


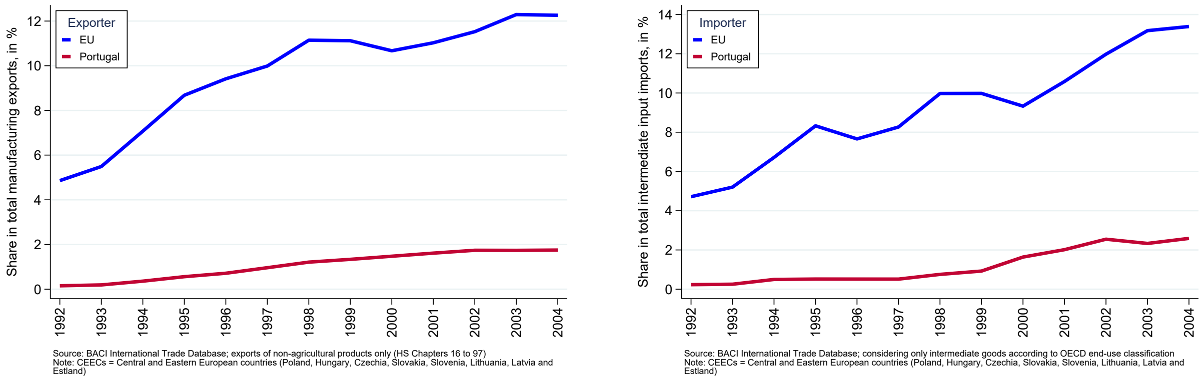
Figure 3: Main export destinations of Portuguese manufacturing exports in 1993

tion from the CEECs companies in the EU market was a significant competitive challenge for Portuguese exporters. The documents of the association agreements demonstrate that the Portuguese government made efforts to protect the domestic economy from increased competition, notably by incorporating exceptions that postponed tariff liberalization and temporarily retained quantitative restrictions on certain goods for the Portuguese market.[5] However, the government was unable to protect local companies from competition with CEECs firms in the rest of the EU market.

As a result of these developments, Portugal's share in the EU market fell throughout the 1990s. Figure 2 illustrates that Portugal's share of EU manufacturing imports dropped from 3% in 1992 to 2% in 2004. Although Portuguese manufacturing imports kept growing in absolute terms, Portugal became less important as supplier of industrial goods to the EU market relative to its competitors from the CEECs.

Integration of Portugal versus rest of the EU with CEECs At the same time, for reasons such as geographical location, the Portuguese economy integrated less strongly

[5] See for instance *Europe Agreement establishing an association between the European Communities and their Member States, of the one part, and the Republic of Poland, of the other*, Protocol 5, Chapter II, Article 10.



(a) Manufacturing exports to CEECs (b) Intermediate goods imports from CEECs

Figure 4: Trade integration with CEECs (1992-2004)

with the CEECs than the rest of the EU. Although Portuguese manufacturing exports to the CEECs grew steadily over the 1990s, Figure 4a shows that they still only accounted for about 2% of all Portuguese manufacturing exports in 2004. In contrast, CEECs had become an important destination for EU manufacturing exports receiving more than 12% of all EU manufacturing exports by 2004. Similarly, Portugal experienced relatively lower integration into value chains with the CEECs compared to the rest of the EU. According to Figure 4b, in 2004, Portugal's import share of intermediate goods from the CEECs was only 2.5%, whereas the rest of the EU had surpassed this figure by importing over 13%. By 2004, only 1% of all Portuguese manufacturing firms directly imported intermediate inputs from CEECs.

The rise of competition in the European export market was likely the most important channel through which the trade liberalization between the EU and the CEECs affected the Portuguese economy in the 1990s. This conclusion is also supported by Reis (2013) who relates the weak economic performance of Portugal in the late 1990s to the fierce competition in global markets for low value-added products that Portugal had specialized in. The historical evidence suggests that trade liberalization and the process of integration of the European Union were largely outside of the influence of the Portuguese government. As such, this period of tariff liberalization is a well-suited setting to study the effect of increasing

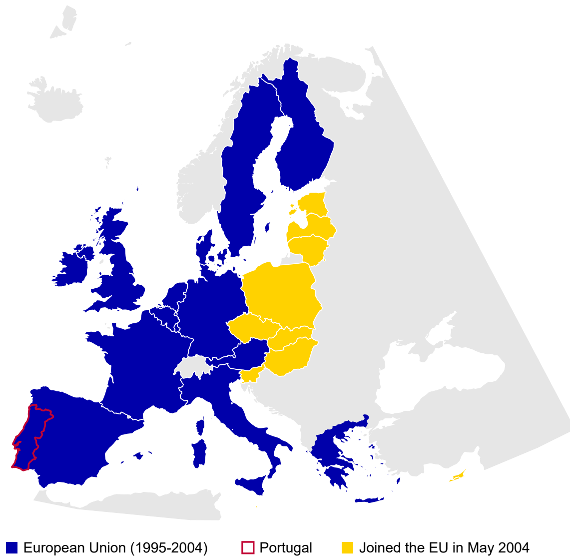


Figure 5: Map of Eastern enlargement of the European Union

competition in foreign markets on firms' technology investments.

3 Data

3.1 Data sources

To assess the impact of the tariff liberalization with CEECs on Portuguese firms, we combine tariff data with rich administrative data from the National Statistics Institute of Portugal (INE).

Tariff data: To proxy changes in competition in the context of the EU's tariff liberalization with CEECs, we leverage granular data on applied tariffs provided by Teti (2020). Specifically, this database provides information on applied tariffs of the EU for more than 5000 products at the HS 6-digit level. Its strength lies in its comprehensive tariff coverage based on a rigourous methodology that rectifies common issues such as misreporting and the resulting false tariff imputation, which results in large measurement error in other official tariff databases.[6] To assess the level of tariff protection for specific products, we calculate

[6]Teti (2020) introduces a new database that is built using a new interpolation algorithm taking the misreporting into account.

the average applied tariff imposed by the EU on the eight CEECs that joined the EU in 2004. This includes Poland, Hungary, Czechia, Slovakia, Latvia, Lithuania, Estonia, and Slovenia.[7]

Employer-employee data: We utilize data on the universe of firms and workers in Portugal from the dataset *Quadros de Pessoal (QP)* [Personnel Records] provided by INE. This database is the product of a high-quality compulsory census run by the Ministry of Employment covering the population of firms with wage earners in manufacturing and services. Each firm is required by law to provide information on an annual basis about its characteristics and those of each individual that comprises its workforce, ensuring high compliance with reporting. Firm-level information includes annual sales, number of employees, industry code, geographical location, date of constitution and share of capital that is foreign-owned. The set of worker characteristics includes wages, gender, age, schooling, date of starting, detailed occupation and hours worked. A worker may also be matched to the firm where she is employed. We use this data to build our controls and merge it to other administrative data-sets using a common firm identifier provided by INE.

Customs data: In addition, we use administrative data on firms' import and export transactions from the database *Estatísticas do Comércio Internacional (ECI)* [Foreign Trade Statistics] provided by INE. This database is the country's official information source on imports and exports. It comprises all import and export transactions of firms, and provides detailed information on the product exported (imported) at the 8-digit level, the destination (source) market, and the value and quantity exported (imported). Export values reported in the data are free-on-board, thus excluding any duties or shipping charges, while import values are CIF. This data can be merged to the *Quadros de Pessoal* dataset using a common identifier. This feature allows us to identify firms that export among manufacturing firms, and hence are exposed to competition in the European market in the context of the tariff liberalization. Overall, we use the customs data to build our explanatory variable leveraging

[7]While Cyprus and Malta were part of EU's 2004 enlargement, we do not considered them in this context as they had already established preferential trade relations with the EU in the early 1970s.

information on firms product portfolios, various outcome variables as well as control variables.

We leverage the customs data to measure firms' investments in industrial automation technology. Specifically, we trace firms' imports of industrial robots as well as numerically controlled machinery by means of detailed product codes listed in EU's classification of goods, the Combined Nomenclature (CN).[8] As most automation technology is produced outside Portugal and must be imported, tracing investments in automation technology through imports is a good proxy for major automation investments in Portuguese manufacturing firms.

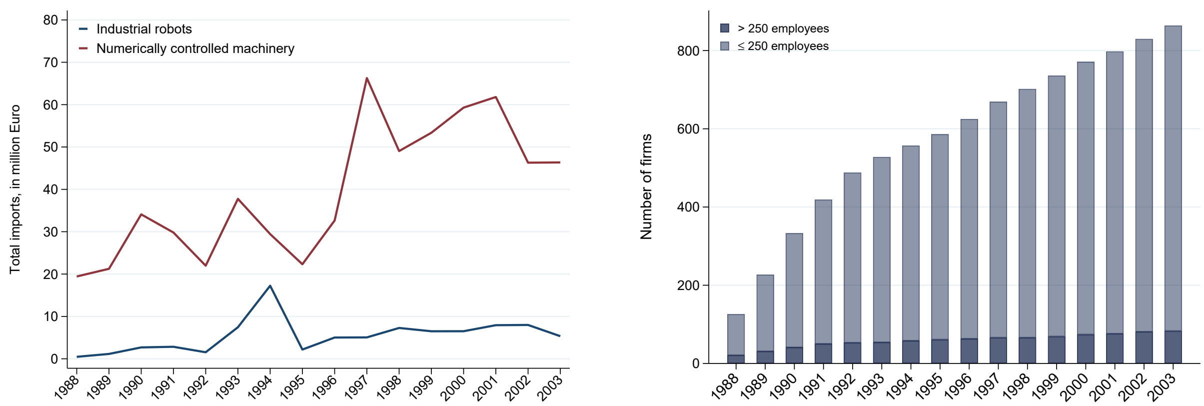
3.2 Description of trends in automation imports

When looking at the imports of automation equipment and the adoption of such technologies by firms, we observe that Portugal underwent a process of increasing automation in the 1990s.[9] Figure 6a provides a compelling illustration of this evolution. Notably, it reveals a consistent upward trend in annual imports of automation equipment by manufacturing firms, with numerically controlled machinery imports nearly tripling from 1988 to the early 2000s. A similar trajectory is observed for industrial robots, which, starting from zero in 1988, surged to over 8 million EUR at the turn of the millennium. An important insight is that imports of numerically controlled machinery are in volumes by far the more important part of industrial automation.

Figure 6b shows that the overall increase in imports of automation equipment coincides with an increase in the number of importing firms, suggesting a diffusion of automation

[8]The Combined Nomenclature (CN) is the EU's eight-digit coding system, comprising the Harmonised System (HS) codes with further EU subdivisions. The nomenclature includes industrial robots categorized under the following codes: "84798950 - Multi-purpose industrial robots" (1987-1995) and "84795000 - Industrial Robots, not elsewhere classified" (since 1996). For a wide class of machine tools (4-digit headings 8456 to 8468), the Combined Nomenclature also distinguishes between "numerically controlled" and "other than numerically controlled" vintages or tools "for working with the hand". Similar to Acemoglu and Restrepo (2018), we leverage this distinction to trace further imports of automation equipment.

[9]Given the lack of domestic suppliers in the 90's, import data provide a good proxy for automation investments in Portugal. Moreover, firms in Portugal exhibit lower levels of investment in R&D and patent activity when compared to their counterparts in other EU countries. This highlights the importance of investing in technology adoption and automation as avenues to enhance the competitiveness for these firms.



(a) Total automation imports (b) Number of automation adopters

Figure 6: Automation between 1988 and 2003

technology across firms. While the early observation period witnessed a rapid surge in the number of firms importing automation equipment, a notable turning point occurs in 1993, marked by a persistent slowdown in growth at the extensive margin. This intriguing trend shift is attributed to firms with fewer than 250 employees, which appear to decelerate their adoption post-1992. By 2003, over 800 manufacturing firms had imported automation equipment at least once, with small and medium-sized enterprises constituting the majority of adopters. Figure 7 provides further nuance to the general trend towards automation showing the share of adopters among the group of manufacturing exporters when broken up by 2-digit industries. While the median of diffusion lies at 7.4 percent in the furniture industry, adoption rates reach more than 30 percent for the top three industries (Machinery and equipment: 42%; Basic metals 36% and Motor vehicles: 35 %).

This initial examination of the data reveals a general trend towards increased automation adoption in Portuguese manufacturing, characterized by both higher volumes of imports and a growing number of firms adopting automation technology. This trend, however, exhibits variations in the pace of adoption over time and across different industries.

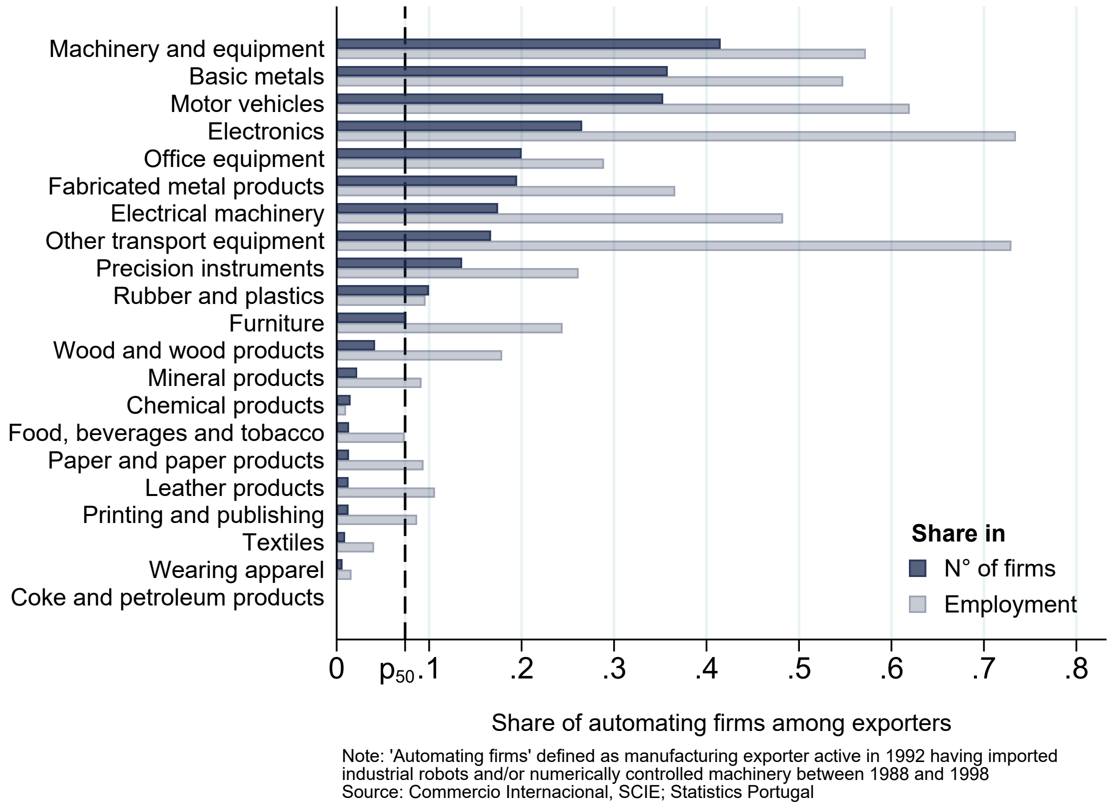


Figure 7: Diffusion within industries

4 Empirical Strategy

4.1 Measuring firms' exposure to foreign competition

To gauge the extent to which firms were exposed to increasing competition from Central and Eastern European firms in the EU market, we leverage information on the firms' initial export portfolio and information on product-specific reductions in EU tariffs vis-à-vis the CEECs. This information allows us to compute the firm-specific tariff reduction as the average tariff reduction weighted by the importance of each product in a firm's initial sales as given by

$$\Delta FC_i = -\sum_{p}^{1241} \phi_{i,p,1992} \times \Delta\tau_p \tag{1}$$

where the ϕ stands for the share of exports of the 4-digit product p to the EU in total sales of firm i in 1992 and $\Delta\tau$ is the difference between the applied tariff of the EU with respect to CEECs in 1992 and the zero tariff at the end of the liberalization.

$$\phi_{i,p,1992} = \frac{X^{EU}_{i,p,1992}}{S_{i,1992}}$$

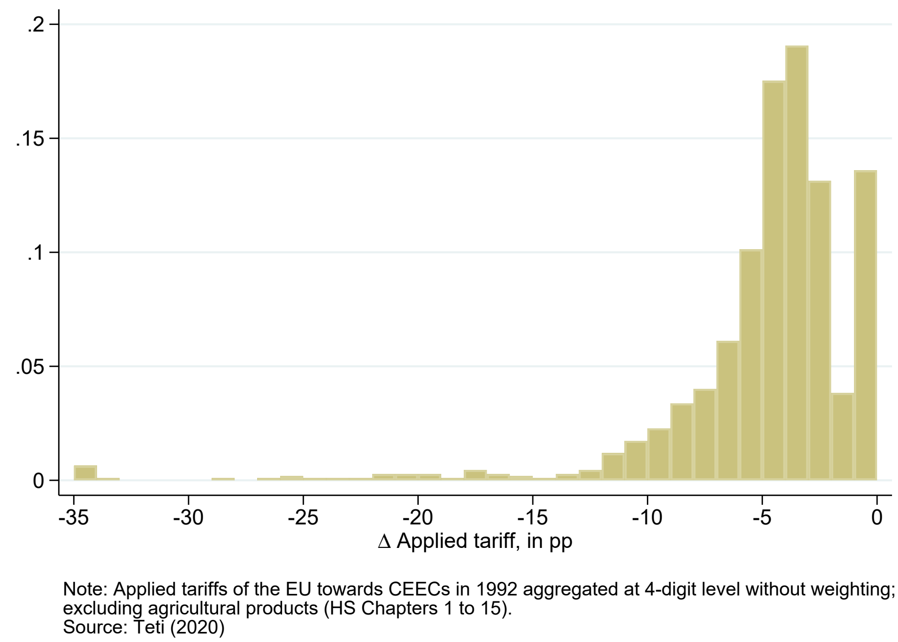
To ease the interpretation of coefficients in the regression analysis, we multiply the summation by -1. Thereby, we obtain an exposure measure which is larger for stronger reductions in tariffs.

An important advantage of the proposed measure is that it leverages variation in tariff reductions across products. Figure 8a and 8b show significant variation in tariff reductions across all 4-digit products. As each firm exports a different portfolio of products, this variation in tariff reductions across products results in varying treatment intensity across firms – even within the same industry. This is an improvement over prior studies that leveraged tariff reductions or increasing import competition at the level of a firm's industry (e.g. Autor, Dorn, et al., 2020; Chen and Steinwender, 2021) and allows for more stringent industry controls in our regression analysis. Figure 8b shows that tariff reductions varied widely across product classes and are not concentrated on specific goods.

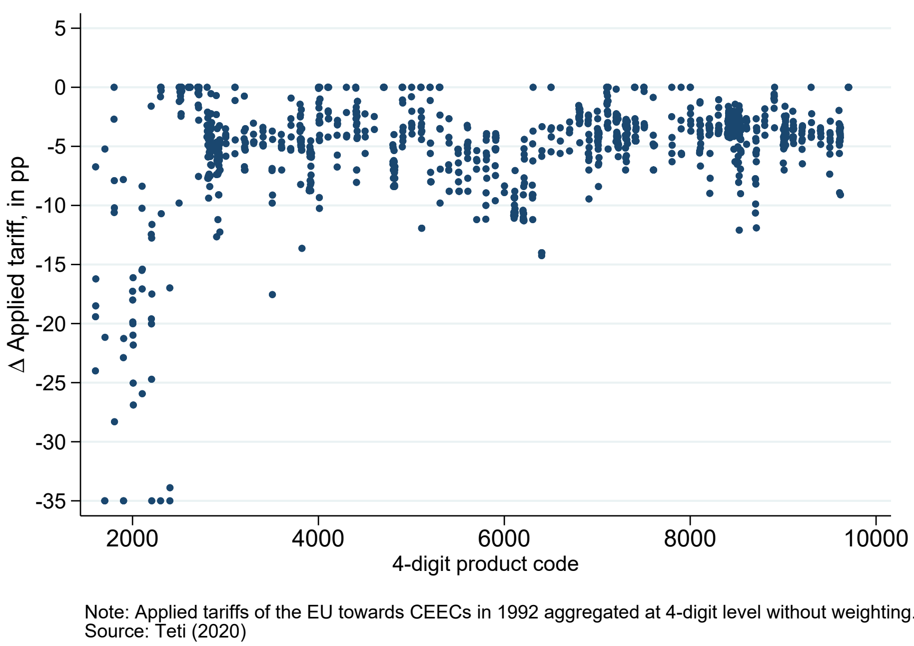
Our identifying assumption is that the variation of tariff reductions across products is orthogonal to the competitiveness of Portuguese exporters and, consequently, unrelated to trends in the adoption of automation technology. If initial tariff barriers were strategically designed to shield firms specializing in non-competitive products, we would confound the extent of tariff reductions with unobserved differences in the competitiveness of firms. In such a scenario, we would anticipate a negative relationship between applied tariffs prior to liberalization and product-specific competitiveness indicators, such as the revealed comparative advantage (RCA).[10] Figure 9 depicts the relationship between EU tariffs and revealed comparative advantage of Portugal for each 4-digit product. Our analysis reveals no sub-

[10] Values above unity indicate a comparative advantage in a given product relative to the rest of the world.

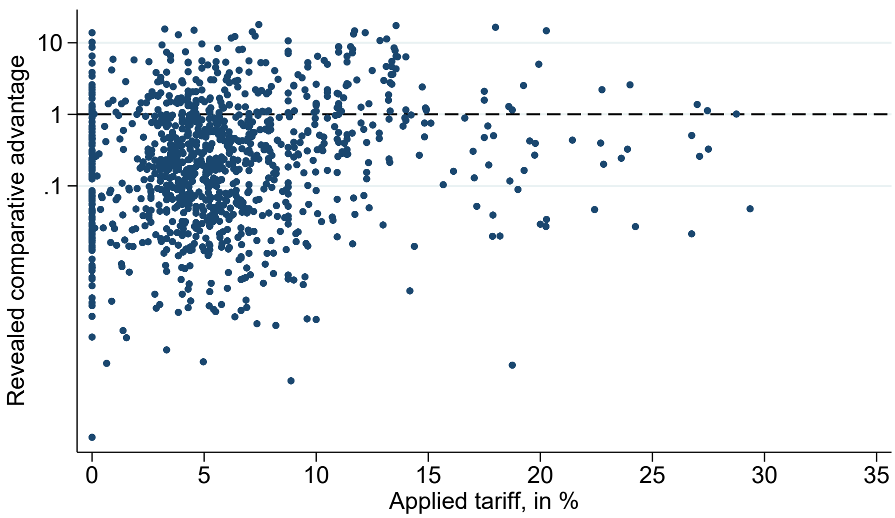
Figure 8: Product-level variation in EU tariff reductions



(a) Distribution of tariff reductions



(b) Tariff reductions across HS4 product classes



Note: Applied tariffs of the EU towards CEECs in 1992 aggregated at 4-digit level without weighting; excluding agricultural products (HS Chapters 1 to 15). Revealed comparative advantage computed as $RCA_{i,PRT} = (X_{i,PRT}/X_{total,PRT}) / (X_{i,WORLD}/X_{total,WORLD})$; graph windsorizes 21 products with RCA above 20 and tariffs above 30 percent.
Source: BACI, Teti (2020)

Figure 9: EU applied tariffs and Portuguese export specialization in 1992

stantial association between EU tariffs and Portugal's RCA. This finding suggests that the tariff schedule of the EU's customs union was not aligned with Portugal's export strengths. Consequently, it supports our assumption that tariff reductions were equally important for both firms specializing in more and less competitive products.

4.2 Empirical specification

To evaluate the importance of the tariff liberalization for the growth of Portuguese exporters, we start our analysis by estimating regressions in long differences:

$$\Delta\log\left(\mathrm{Y}_i\right) = \beta\Delta\mathrm{FC}_i + \mathbf{X}'_{i,1992}\gamma + \mathrm{industry}_j + \mathrm{region}_n + \varepsilon_i \tag{2}$$

where Y_i stands for different measures of firm performance, in particular sales, employment and export product characteristics. Specifically, we examine long differences in a measure of firm performance between 1992 and 1998, covering the year leading up to the liberalization and extending to the point when most of the goods trade with the CEECs was liberalized (see

Figure 1b). We account for differential trends by controlling for firms' baseline characteristics in 1992 and including dummies for NUTS 2 regions and 2-digit ISIC industries.

In the main part of our analysis, we study the effect of increasing competition on automation by estimating the following equation:

$$\text{asinh}\left(\text{Y}_i\right) = \beta \Delta \text{FC}_i + \mathbf{X}'_{i,1992}\gamma + \text{industry}_j \times \text{size bracket}_s + \text{region}_n + \varepsilon_i \quad (3)$$

where Y_i is the automation variable defined as the sum of imports of industrial robots and numerically controlled machinery by firm i between 1992 and 1998 scaled by the number of production workers in 1992. This measure of automation is close to the widely used concept of robot density, defined as the number of industrial robots per employees or hours worked (Graetz and Michaels, 2018). Looking at imports over the entire period of liberalization allows us to capture the firms' automation response to the full reduction in tariffs and without imposing restrictive timing assumptions. In our main analysis, we account for the skewed outcome distribution and the large share of zeros by appling an inverse hyperbolic sine transformation of the outcome variable.

In our main specification, we control for several baseline characteristics $\mathbf{X}'_{i,1992}$ that likely affect the propensity to adopt automation technology. First, we control for firm sales as larger firms tend to be more productive and are more likely to shoulder the fixed cost involved in automation adoption. Second, we account for differences in firm age as we expect younger firms to be more flexible in the re-organization of their production process. Third, we control for foreign ownership as this might affect access to foreign technology and knowledge. Finally, we include dummies for NUTS 2 regions as well as dummies for 2-digit ISIC industry by size bracket cells.[11] Thereby, we account for different trends in adoption and will only compare firms within the same industry and size class.

We also account for contemporaneous factors in trade that we expect to affect firms'

[11] We group firms into size brackets by number of employees in 1992 (10-49, 50-249, 250-499, 500-999 or $\geq$1000).

incentives to automate. To account for potential improvements in market access for Portuguese firms exporting to CEECs, we include dummies that indicate whether firms were already exporting to CEECs in 1992 and whether they started exporting to CEECs over ther period until 1998. In addition, we want to ensure that both the tariff shock and firm-level automation are not confounded by rising competition from China in the EU in the decade leading up to China's accession to the the World Trade Organization in 2001. For this reason, we compute for each firm a measure of exposure to rising Chinese import penetration in 4-digit product markets in the EU, following Branstetter et al. (2019) which is analogous to our measure of exposure to the tariff liberalization. [12]

Finally, we control for the sum of product shares $\phi_{i,p}$ of each firm which corresponds to the share of exports to the EU in total sales. As most firms sell also products domestically or outside of the EU market, the sum of exposure shares is often smaller than unity. According to recent work on shift-share designs by Borusyak et al. (2022), such "incomplete shares" lead to biased estimates as they induce differences in the treatment intensity that do not come from exogenous variation in the shock and can potentially be correlated with the outcome variable. In our case, this could be a concern if firms with higher exposure to the EU export market are more productive and are also more likely to adopt advanced production technology. For this reason, we follow Borusyak et al. (ibid.) and correct for the non-random exposure of firms to the European export market by controlling for the sum of product shares $\phi_{i,p}$ of each firm in 1992.

[12] To compute a measure of firm-level exposure to Chinese import penetration in the European market, we average increases in Chinese import penetration across 4-digit product markets weighted by the importance of products p in a firm's total sales: $\Delta \mathrm{FC}_i^{China} = \sum_p^{1241} \frac{X_{i,p,1992}}{S_{i,1992}} \times \frac{IMP_{p,1998}^{China} - IMP_{p,1992}^{China}}{IMP_{p,1992}^{Total}}$.

5 Results

This section presents our main results. Section 5.1 documents that the exposure to tariff reductions reduced firms' sales growth highlighting the economic significance of the tariff liberalization for Portuguese exporters. Sections 5.2 and 5.3 explore different margins of adjustment showing that more exposed firms specialized in the most competitive products and significantly reduced their labor demand. Section 5.4 unpacks the effect of tariff reductions on automation, showing a negative average effect with strong heterogeneity by initial labor productivity and industry exposure to automation. Finally, Section 5.5 performs a variety of robustness checks.

5.1 Firm sales and exports

Table 1 presents the results of long-difference regressions from 1992 to 1998, shedding light on the first-order impact of exposure to tariff reductions on firms' sales by destination. The estimation reveals that exposure to tariff reductions is associated with a substantial reduction in total sales, which is primarily driven by a decline in exports to the EU market, while domestic and extra-EU sales remain largely unaffected. Accordingly, the first column shows that a standard deviation increase in the exposure to tariff reductions is associated with a 20.5 percent decrease in total sales growth. Further unpacking total sales, columns 2 and 3 show that the sizable negative effect on total sales growths stems from a decline in foreign sales, while domestic sales do not exhibit any significant reduction. More specifically, columns 4 and 5 show that the negative effect on total exports can be attributed to exports to the EU market, while extra-EU exports are less affected. These results show that the tariff liberalization between the EU and CEECs had a significantly negative effect on the sales growth of Portuguese firms in the EU market and is highly suggestive of declining market shares due to increasing competition from CEECs. If declining market shares were indeed of economic relevance for Portuguese exporters, we would expect firms to adjust their export

Table 1: Effect of exposure to tariff reductions on sales by destination: long difference regressions, 1992-1998 (OLS)

	Δ log(x) $\times$ 100 from 1992 to 1998				
	Total Sales	Domestic Sales	Total Exports	Intra-EU Exports	Extra-EU Exports
	(1)	(2)	(3)	(4)	(5)
Δ FC	-20.50***	-9.51	-11.92**	-13.41**	-10.01
	(6.60)	(27.96)	(4.90)	(6.33)	(9.57)
Observations	4,186	4,186	3,352	2,614	1,982
R-squared	0.07	0.12	0.05	0.14	0.02
Industry FE	YES	YES	YES	YES	YES
Region FE	YES	YES	YES	YES	YES

Note: The dependent variable is the change in the log of a given sales variable between 1992 and 1998 multiplied by 100. The explanatory variable is normalized to have a mean of 0 and a standard deviation of 1. All regressions include dummies for 2-digit ISIC industries and 2-digit NUTS regions and control for the sum of product shares. Standard errors are robust to heteroskedasticity and allow for clustering at the 3-digit industry-level (99 industries). Coefficients with ***, **, and * are significant at the 1%, 5% and 10% confidence level, respectively.

strategies and the organization of production in response, as demonstrated in the following section.

5.2 Export strategies

Table 2 provides evidence that firms adjusted their export strategies in terms of the variety and prices of goods exported to the EU market. The first two columns report that a one-standard-deviation increase in exposure to tariff reductions resulted in a significant 23-percentage-point decrease in the growth in the number of product varieties exported to the EU. Remarkably, this effect does not extend to exports to destinations outside the EU.[13] Similarly, columns 3 and 4 reveal that firms decreased average product prices for EU exports by more than 2 percentage points, while prices for exports to other destinations remained

[13]The number of products is defined as the number of HS 8-digit products exported by the firm to a destination country.

Table 2: Effect of exposure to tariff reductions on firm product scope: long difference regressions, 1992-1998

	Δlog(#Products)		Δlog(Price)		ΔQuality	
	Intra-EU	Extra-EU	Intra-EU	Extra-EU	Intra-EU	Extra-EU
	(1)	(2)	(3)	(4)	(5)	(6)
ΔFC	-0.236***	-0.006	-0.027**	0.013	0.011	0.016
	(0.021)	(0.025)	(0.010)	(0.020)	(0.025)	(0.031)
Observations	2,614	1,998	4,588	3,010	2,089	1,644
R-squared	0.141	0.019	0.023	0.015	0.010	0.017
Industry FE	YES	YES	YES	YES	YES	YES
Region FE	YES	YES	YES	YES	YES	YES

Note: The explanatory variable is normalized to have a mean of 0 and a standard deviation of 1. All regressions include dummies for 2-digit ISIC industries and 2-digit NUTS regions and control for the sum of product shares. Standard errors are robust to heteroskedasticity and allow for clustering at the 3-digit industry-level (99 industries). Coefficients with ***, **, and * are significant at the 1%, 5% and 10% confidence level, respectively.

unaffected. The reduction in prices could be driven by a reduction in the average quality of products exported to the EU. However, as shown in column 5, these adjustments did not impact the overall quality of the products exported by the firm, as defined by Khandelwal (2010). These findings combined indicate that firms adapted their export strategy specifically for the EU market by price reductions and a focus on a narrower range of products. In contrast, their pricing and product mix strategies for exports to the rest of the world remained unchanged. This supports the hypothesis that increased competitive pressure in the EU market in the context of the tariff liberalization prompted significant changes in firms' strategies, in particular for sales to the EU.

5.3 Employment and wages

Meanwhile, as shown in Table 3, tariff liberalization also had substantial ramifications for firms' production organization, particularly concerning labor demand. To establish this, we first look at the first two columns, which reveal that a one-standard-deviation increase

Table 3: Effect of exposure to tariff reductions on employment and wages: long difference regressions, 1992-1998 (OLS)

	Δ log(x) $\times$ 100 from 1992 to 1998				
	Total employment	Total wage bill	Total workhours	Monthly wage	Hourly wage
	(1)	(2)	(3)	(4)	(5)
Δ FC	-7.27***	-9.82***	-9.44***	-2.45**	-0.39
	(2.66)	(3.27)	(2.80)	(1.00)	(0.81)
Observations	4,064	4,064	4,064	4,064	4,064
R-squared	0.04	0.03	0.03	0.03	0.02
Industry FE	YES	YES	YES	YES	YES
Region FE	YES	YES	YES	YES	YES

Note: The dependent variable is the change in the log of a given employment or wage variables between 1992 and 1998 multiplied by 100. Explanatory variable is normalized to have a mean of 0 and a standard deviation of 1. All regressions include dummies for 2-digit ISIC industries and 2-digit NUTS regions. Standard errors are robust to heteroskedasticity and allow for clustering at the 3-digit industry-level (99 industries). Coefficients with ***, **, and * are significant at the 1%, 5% and 10% confidence level, respectively.

in exposure to tariff reductions corresponds to a significant 7-percentage-point decrease in employment growth and a substantial 9-percentage-point reduction in wage bill growth. Delving deeper into the data, columns 4 and 5 provide insights into the specific effects on wages. Here, we show a drop of over 2 percentage points in monthly wages while hourly wages remain unchanged. This suggests a multifaceted response by firms to heightened competitive pressure. They adapt by both limiting new hires and reducing the work hours of incumbent workers, a strategy that has the potential to enhance labor productivity. These findings further corroborate the hypothesis that the tariff liberalization between the EU and CEECs induced significant competitive pressure, prompting firms to alter both strategy and the organization of production.[14]

[14] We present additional findings on employment and wage effects by skill type in Appendix Table A.7. It is important to note that Table 3 shows baseline effects without adjusting for firm characteristics. We find consistent effects in the fully specified model, as detailed in Appendix Table ??.

5.4 Automation

The evidence so far suggests that firms reacted to increasing competition in the EU market by trying to curb labor costs and potentially increase productivity. Given firms' attempts to reduce labor costs, we could expect that they may strategically invest in technology capable of automating various aspects of their operations. Nevertheless, firms may also scale back investments in automation in response to the negative shock. This section provides empirical evidence using the exogenous tariff shock.

Table 4 presents our main result showing that firms more exposed to the tariff liberalization tend to automate less during the period of observation. Column 1 reports our baseline estimate indicating that a standard deviation increase in the exposure to tariff reductions decreases automation imports per production worker by about 57 percent. Colum 2 show that this estimate is robust to controlling for confounding firm characteristics such as sales, firm age and foreign ownership. Adding further contemporaneous controls for firms' exports to CEECs and Chinese import penetration in the EU market does not alter the estimate significantly. Once we introduce region and industry dummies, our main estimate observes a reduction by more than half. Yet, it still stands significant at 25 percent, shedding light on the impact of geographical and industry-specific factors.

In column 5, we further sharpen our analysis by incorporating industry-by-size bracket dummies. These more restrictive controls account for size-related adoption patterns across industries as revealed in Table A.3. Thereby, the model controls for the fact that firms of larger size in certain industries are potentially more suited for automation than others. In addition, this model only leverages variation in exposure to tariff reductions across firms within the same size class of a given industry. Despite this more stringent specification, the coefficient estimate experiences only a slight reduction to 23 percent. Contrary to our initial hypothesis that firms might increase automation to reduce labor costs, Table 4 therefore tells a different story: firms more exposed to the tariff liberalization, on average, engaged in less automation.

Table 4: Effect of exposure to tariff reductions on automation: 1992-1998 (OLS)

	asinh(Automation per worker) from 1992 to 1998				
	(1)	(2)	(3)	(4)	(5)
Δ FC	-0.57***	-0.57***	-0.57***	-0.25***	-0.23***
	(0.18)	(0.18)	(0.20)	(0.08)	(0.08)
Sales		0.00	0.00	0.01**	0.00
		(0.00)	(0.00)	(0.00)	(0.00)
Firm age		0.00	-0.00	0.00	-0.00
		(0.00)	(0.00)	(0.00)	(0.00)
Foreign ownership		0.46*	0.41*	0.17	-0.07
		(0.27)	(0.25)	(0.19)	(0.15)
Exporting to CEECs			0.17	0.20	0.11
			(0.12)	(0.13)	(0.14)
Export entry to CEECs			0.67***	0.49**	0.37**
			(0.24)	(0.19)	(0.18)
Δ FC^{China}			-0.02	-0.01	-0.02
			(0.06)	(0.03)	(0.04)
Observations	3,991	3,964	3,964	3,964	3,953
R-squared	0.03	0.03	0.04	0.18	0.23
Region FE	NO	NO	NO	YES	YES
Industry FE	NO	NO	NO	YES	YES
Industry x Size FE	NO	NO	NO	NO	YES

Note: The dependent variable is the inverse hyperbolic sine of the sum of firm-level imports of industrial robots and numerically controlled machinery from 1992 to 1998, deflated to 1990 prices, and divided by the number of production workers in 1992. Explanatory variable is normalized to have a mean of 0 and a standard deviation of 1. Specification (4) include dummies for 2-digit NUTS regions and 2-digit ISIC industries. Specification (5) includes a dummy variable for each 2-digit industry by employment size category (10-49,50-249,250-499, 500-999,$\geq$1000). Standard errors are robust to heteroskedasticity and allow for clustering at the 3-digit industry-level (99 industries). Coefficients with ***, **, and * are significant at the 1%, 5% and 10% confidence level, respectively.

Table 5: Effect of exposure to tariff reductions on automation: 1992-1998 (OLS)

	Automation adoption from 1992 to 1998				
	(1)	(2)	(3)	(4)	(5)
Δ FC	-0.07***	-0.07***	-0.07***	-0.03***	-0.03***
	(0.02)	(0.02)	(0.02)	(0.01)	(0.01)
Sales		0.00	0.00	0.00**	0.00
		(0.00)	(0.00)	(0.00)	(0.00)
Firm age		0.00	0.00	0.00	-0.00
		(0.00)	(0.00)	(0.00)	(0.00)
Foreign ownership		0.06*	0.06*	0.03	0.00
		(0.03)	(0.03)	(0.03)	(0.02)
Exporting to CEECs			0.02	0.02	0.01
			(0.01)	(0.01)	(0.02)
Export entry to CEECs			0.08***	0.06***	0.05**
			(0.03)	(0.02)	(0.02)
Δ FC^{China}			-0.00	-0.00	-0.00
			(0.01)	(0.00)	(0.00)
Observations	3,991	3,964	3,964	3,964	3,953
R-squared	0.03	0.03	0.04	0.18	0.24
Region FE	NO	NO	NO	YES	YES
Industry FE	NO	NO	NO	YES	YES
Industry x Size FE	NO	NO	NO	NO	YES

Note: The dependent variable is a dummy indicating whether the firm has imported industrial robots or numerically controlled machinery between 1992 and 1998. Explanatory variable is normalized to have a mean of 0 and a standard deviation of 1. Specification (4) include dummies for 2-digit NUTS regions and 2-digit ISIC industries. Specification (5) includes a dummy variable for each 2-digit industry by employment size category (10-49,50-249,250-499, 500-999,≥1000). Standard errors are robust to heteroskedasticity and allow for clustering at the 3-digit industry-level (99 industries). Coefficients with ***, **, and * are significant at the 1%, 5% and 10% confidence level, respectively.

The stark negative association between exposure to tariff reductions and automation is also mirrored by the extensive margin of automation adoption. Table 5 shows estimation results of linear probability models using automation adoption between 1992 and 1998 as a binary outcome variable. The first column reports that standard deviation increase in exposure reduced the likelihood of automation adoption by 7 percentage points. When controlling for firms baseline characteristics, contemporaneous factors and as well as region and industry dummies, the estimate drops to 3 percentage points, but remains significant, even in the fully saturated model in column 5. This effect is sizable given the average adoption rate of 5.2 percent in our sample over the period of observation. As such, Tables 5 confirms our previous finding showing that the tariff liberalization also decreased automation at the extensive margin.

Building on the insights from Aghion et al. (2005) regarding the impact of the competitive position on firms' responses to competition, we further examine whether tariff reductions prompt varying automation strategies based on firms' initial competitiveness. Specifically, investing in cutting-edge automation technology might not help cope with the increased competition, and constitute a risky investment with uncertain payoff, if the competitive disadvantage of certain firms is too large. However, if firms are highly competitive and close to the technological frontier, we could expect that investing in automation might be within reach and sufficient to close the competitive gap. To test this hypothesis, we introduce an interaction term in Equation 3, involving firms' initial labor productivity (sales per worker) as an indicator of competitiveness. Acknowledging the strong assumption of the linear nature of the moderating effect, this approach nevertheless enables a more detailed examination of the connection between automation and competition, offering insights into the role of firms' competitiveness.

Table 6 points into the direction of our hypothesis: the moderating influence of initial labor productivity on the impact of tariff reductions is positive. In the fully specified model, column 2 illustrates a statistically significant coefficient amounting to 28 percent. However,

Table 6: Heterogeneous effect of exposure to tariff reductions on automation: 1992-1998 (OLS)

	asinh(Automation per worker)		Automation adoption	
	(1)	(2)	(3)	(4)
Δ FC	-0.60***	-0.24***	-0.07***	-0.03***
	(0.19)	(0.08)	(0.02)	(0.01)
Labor productivity	0.19	0.22	0.02	0.03
	(0.31)	(0.58)	(0.03)	(0.06)
Δ FC × labor prod.	0.58**	0.28*	0.06**	0.03
	(0.27)	(0.16)	(0.03)	(0.02)
Observations	3,991	3,953	3,991	3,953
R-squared	0.03	0.23	0.03	0.24
Firm characteristics	NO	YES	NO	YES
Contemporaneous controls	NO	YES	NO	YES
Region FE	NO	YES	NO	YES
Industry FE	NO	YES	NO	YES
Industry x Size FE	NO	YES	NO	YES

Note: The dependent variable is the inverse hyperbolic sine of the sum of firm-level imports of industrial robots and numerically controlled machinery from 1992 to 1998, deflated to 1990 prices, and divided by the number of production workers in 1992. Explanatory variable is normalized to have a mean of 0 and a standard deviation of 1. Specifications (2) and (4) incorporate all control variables included in the fully specified model detailed in column (5) of Table 4. Standard errors are robust to heteroskedasticity and allow for clustering at the 3-digit industry-level (99 industries). Coefficients with ***, **, and * are significant at the 1%, 5% and 10% confidence level, respectively.

considering an interdecile range of 0.062 Million Euros per worker, this finding implies that transitioning from the 10th to the 90th decile would marginally mitigate the negative effect on automation, by a mere 1.7 percentage points, insufficient to reverse the underlying negative baseline effect of -24 percent. Columns 3 and 4 replicate this positive interaction when automation adoption is the dependent variable. Yet again, the magnitudes observed fail to reach substantial economic significance, as the negative impact on automation adoption is only dampened. Consequently, our preliminary conclusion is that initial competitiveness exhibits only a mild moderating role in this context.

Table 7: Heterogeneous effect of exposure to tariff reductions on automation for High adoption sectors: 1992-1998 (OLS)

	asinh(Automation per worker)		Automation adoption	
	(1)	(2)	(3)	(4)
Δ FC × Low	-0.44***	-0.21***	-0.05***	-0.02***
	(0.15)	(0.07)	(0.02)	(0.01)
Δ FC × High	-1.77***	-0.52**	-0.19***	-0.06*
	(0.48)	(0.24)	(0.05)	(0.03)
Labor productivity × Low	-0.83	0.04	-0.10*	0.01
	(0.50)	(0.45)	(0.06)	(0.05)
Labor productivity × High	28.12***	11.54***	3.19***	1.29***
	(5.82)	(4.14)	(0.62)	(0.43)
Δ FC × Labor prod. × Low	0.28	0.14	0.03	0.01
	(0.21)	(0.09)	(0.02)	(0.01)
Δ FC × Labor prod. × High	47.08***	22.67***	5.20***	2.49***
	(10.68)	(8.20)	(1.16)	(0.90)
Observations	3,991	3,953	4,186	4,150
R-squared	0.11	0.24	0.10	0.24
Firm characteristics	NO	YES	NO	YES
Contemporaneous controls	NO	YES	NO	YES
Region FE	NO	YES	NO	YES
Industry FE	NO	YES	NO	YES
Industry x Size FE	NO	YES	NO	YES

Note: Explanatory variable is normalized to have a mean of 0 and a standard deviation of 1. Specifications (2) and (4) incorporate all control variables included in the fully specified model detailed in column (5) of Table 4. Standard errors are robust to heteroskedasticity and allow for clustering at the 3-digit industry-level (99 industries). Coefficients with ***, **, and * are significant at the 1%, 5% and 10% confidence level, respectively.

In our final test, we explore the possibility that our current heterogeneity analysis might obscure distinctions among industries with varying inclinations towards automation. Given the noticeable disparities in adoption rates across industries, as shown in Table A.3, it is plausible that certain sectors could be inherently more conducive to automation adoption. Consequently, the moderating influence of initial productivity could vary across industries. To address this, we categorize industries based on their adoption rates, grouping those falling below the median of 7 percent as "low adoption industries," and categorizing the rest as "high adoption industries." We then conduct a refined heterogeneity analysis, introducing interactions with a dummy variable denoting industries with above-median adoption rates.

Our findings in Table 7 highlight a striking disparity: the positive interaction effect is significantly more pronounced for firms operating in high adoption industries. In the fully specified model, as demonstrated in column 2, the estimates for firms within high adoption industries suggest that transitioning from the 10th to the 90th decile would not only mitigate the negative effect on automation but do so by an impressive 140 percent, effectively reversing the initial negative baseline effect of -52 percent. Column 4 further reports a similar pattern, indicating that, at the extensive margin, a change in productivity spanning the interdecile range in high adoption industries yields a substantial positive impact, increasing the likelihood of automation by approximately 9 percent. These results imply that while the baseline effect remains negative, it is overturned for the most productive firms operating in industries particularly exposed to automation. This finding bears potential implications for their survival and the overall concentration of industries in the long run.

In summary, our analysis reveals that, on average, rising competition deterred firms from automation. However, a noteworthy exception emerged: the most productive firms in industries prone to automation exhibited a positive response that offset the negative impact, resulting in increased automation among the top firms in highly automating industries. This suggests that within industries, heightened competition dissuades substantial automation investments among average firms, while primarily encouraging automation at the largest firms.

This phenomenon could potentially reinforce patterns favoring industry-leading "superstar" firms. Thereby, increased competition may lead to a scenario where top firms become more automated, further accentuating concentration within the industry.

5.5 Robustness

A potential threat to our identification strategy is the possibility that firms exposed to greater tariff reductions may have experienced lower export growth even before the treatment period. This scenario could arise if tariffs acted as protective measures for less competitive firms. In this case, more exposed firms would likely have automated less even in the absence of tariff liberalization, given their downward trend in export performance. In such a scenario, the impact of tariff reductions on automation would be confounded with the influence of low competitiveness, leading to an upward bias in our coefficient estimate.

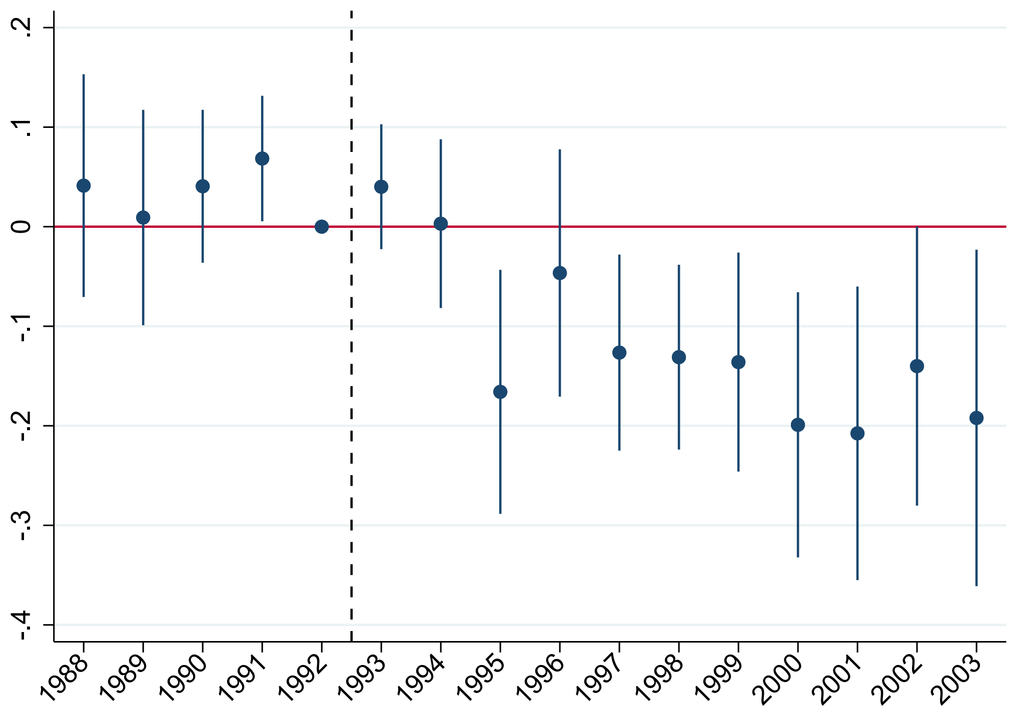
To address this concern, we extend the period of analysis and conduct an event study to investigate differences in exports between more and less exposed firms before and after the start of the tariff liberalization in 1992. Specifically, we estimate the following two-way linear fixed effects regression:

$$\log\left(\mathrm{Y}_{i,t}\right) = \alpha + \sum_{k \neq 1992} \beta_k \left(\Delta\mathrm{FC}_i \times 1_{t=k}\right) + \gamma_i + \delta_{j,t} + \Phi_i \times \delta_t + \varepsilon_{i,t} \tag{4}$$

where Y represents the total exports of firm i in year t, γ_i denotes firm-specific fixed effects that help account for time-invariant unobservable factors, while $\delta_{j,t}$ represents industry-by-year fixed effects to address contemporaneous factors that may confound the estimation. We further control for the sum of exposure shares Φ interacted with year dummies to obtain robust estimates following the methodology by Borusyak et al. (2022). We estimate the regression using data from 1988, which marks the start of our dataset, through 2003, one year prior to the Eastern enlargement of the EU.

Figure 10 depicts the coefficient estimates derived from Equation 4. It illustrates the

Figure 10: Dynamic effects of exposure to tariff reductions on total exports



Note: This figure plots regression coefficients β_k from Equation 4. The explanatory variable is normalized to have a mean of 0 and a standard deviation of 1. The plot reports 95% confidence intervals based on clustered standard errors at the 3-digit industry level.

absence of a differential trend in exports between firms more and less exposed to the tariff liberalization in the period leading up to tariff liberalization. This result supports the assumption that the treatment intensity was not correlated with prior export performance, serving as a proxy for firms' competitiveness. Furthermore, Figure 10 substantiates the impact of the tariff liberalization on exports showing persistent and statistically significant negative differences in exports from 1995 onwards. In 1998, firms that were a standard deviation more exposed to the tariff reductions had 12 percentage point lower export growth since 1992, which is in line with our estimate of 11.5 percentage points from Table 1. In sum, Figure 10 supports the assumption that the treatment intensity was uncorrelated with prior export performance, while confirming the persistently negative effect of the tariff liberalization on exports. We interpret this pattern as indicative of an exogenous increase in competition within the EU market, a pivotal assumption in our study.

Finally, our identification strategy could be threatened if more exposed firms had anticipated the increase in competition by investing in automation in advance. In this case, the negative coefficient in our main result could be due the fact that more exposed firms automate less because they had already automated in the pre-period. To address this potential concern we test how important automation investments prior to the tariff liberalization over the years 1988 to 1991 are in explaining automation in the main period of analysis.

In Table 8, we observe that while automation in the pre-period serves as a positive predictor for automation in the primary analysis period, factoring in pre-period automation only marginally reduces the effect estimate. Specifically, in Column 1, the coefficient is -0.18, compared to -0.23 obtained in the fully saturated model in Column 5 of Table 4, our primary result. Similarly, considering adoption in the pre-period trims the effect estimate at the extensive margin from -0.03 (as seen in Column 5 of Table 5) to -0.02. Importantly, both effect estimates, at both the intensive and extensive margins, retain their statistical significance. At the same time, including the pre-trend eliminates the statistical significance of the interaction with labor productivity, which was already weakly significant and of modest size in Table 6. In summary, Table 8 reaffirms our primary finding even when accounting for anticipatory effects, bolstering the robustness of our results.

Table 8: Effect of exposure to tariff reductions robust to pre-trends: 1992-1998 (OLS)

	asinh(Automation per worker)		Automation adoption	
	(1)	(2)	(3)	(4)
Δ FC	-0.18***	-0.19***	-0.02***	-0.02***
	(0.06)	(0.06)	(0.01)	(0.01)
Labor productivity		0.48		0.05
		(0.59)		(0.07)
Δ FC $\times$ Labor prod.		0.23		0.02
		(0.17)		(0.02)
asinh(Automation	0.28***	0.28***		
per worker)$_{1988-1991}$	(0.04)	(0.04)		
Automation			0.26***	0.26***
adoption$_{1988-1991}$			(0.04)	(0.04)
Observations	3,953	3,953	3,953	3,953
R-squared	0.28	0.28	0.29	0.29
Firm characteristics	YES	YES	YES	YES
Contemp. controls	YES	YES	YES	YES
Region FE	YES	YES	YES	YES
Industry FE	YES	YES	YES	YES
Industry x Size FE	YES	YES	YES	YES

Note: Explanatory variable is normalized to have a mean of 0 and a standard deviation of 1. Specification (4) include dummies for 2-digit NUTS regions and 2-digit ISIC industries. Specification (5) includes a dummy variable for each 2-digit industry by employment size category (10-49,50-249,250-499, 500-999,≥1000). Standard errors are robust to heteroskedasticity and allow for clustering at the 3-digit industry-level (99 industries). Coefficients with ***, **, and * are significant at the 1%, 5% and 10% confidence level, respectively.

6 Conclusion

We bring together a rich set of administrative micro-data including employer-employee data and customs data to assemble a novel dataset of firm-level imports of automation technologies in Portugal. We exploit a large tariff liberalization between the EU and CEECs in the 1990s to investigate how increased product market competition affects firms' automation investments and performance. We first find that firms that are more exposed to the tariff liberalization experience significant reductions in sales, driven by exports to the EU, and adjust their export strategy by reducing the number of exported product varieties and lowering prices of exports to the EU. Second, we show that more exposed firms significantly reduce labor costs by hiring fewer employees and reducing workhours of incumbent workers. We then assess the consequences of increased competition on firm-level automation. In our setting, we find that a one-standard-deviation increase in exposure leads to a substantial 25 percent reduction in automation at the intensive margin, as well as a 3-percentage-point decrease in the likelihood of firms adopting automation at the extensive margin. Despite the apparent need for firms to curb labor costs in the face of increased competition, we find that heightened competition diminishes the incentive for automation. However, when scrutinizing firms within industries that are highly prone to automation, we observe that firms that are initially more productive respond by increasing their automation levels compared to less productive firms.

Our results have important implications for the economic development of a large set of middle-income countries for which the acquisition of advanced manufacturing tools presents an opportunity to catch up, particularly if they are not technology innovators themselves. Our study suggests that an increasingly competitive global market place decreases technology investments in automation equipment on average and increases incentives to invest only for the most productive firms. This can result in a technology adoption pattern that further favors the most productive firms, resulting in concentrated adoption by superstar firms and limited diffusion, hindering industrial catch-up efforts.

Future work could extend the empirical analysis by collecting data on other forms of automation, such as software development, which might have important implications for firms operating across all sectors of the economy. Whereas the use of industrial robots and numerically controlled machinery imports as proxies for automation has the important advantage of measurability, it narrows the focus of our study to a specific type of industrial automation in the manufacturing sector. This form of automation often comes with substantial fixed cost investments in hardware and requires a significant reorganization of the production process (Bessen et al., 2023). Other less costly and scalable forms of automation such as software automation (including generative artificial intelligence) are increasingly deployed to creative cognitive tasks across all sectors of the economy (Eloundou et al., 2023). Hence, the empirical analysis of the effect of competition on other forms of automation presents a promising avenue for future research.

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A Appendix

Table A.1: Summary statistics: manufacturing exporters in 1992 (at least 10 employees)

	Mean	SD	p25	p75	p99	Sum
Number of employees	94.01	188.76	22.00	90.00	800.00	497,602
Sales, in Million EUR	4.56	40.41	0.41	2.92	49.63	24,116
Total exports, in Million EUR	1.43	7.06	0.02	0.97	17.10	7,583
Number of establishments	1.29	1.46	1.00	1.00	6.00	6,848
Foreign ownership	0.04	0.20	0.00	0.00	1.00	211
Firm age	17.17	16.79	6.00	22.00	73.00	
Export intensity	0.41	0.40	0.03	0.88	1.00	
Sales, in Million EUR/employee	0.05	1.09	0.01	0.04	0.30	
Sum of product shares	0.34	0.38	0.01	0.70	1.00	
Exporting to CEECs	0.06	0.23	0.00	0.00	1.00	292
Export entry to CEECs	0.06	0.23	0.00	0.00	1.00	304
Observations	5293					

Table A.2: Summary statistics of manufacturing exporters in 1992 (at least 10 employees): automation adopters vs. non-adopters between 1992-1998

	Non-Adopters			Adopters		
	Mean	SD	Sum	Mean	SD	Sum
Number of employees	89.54	174.18	450,118	181.96	361.97	47,310
Sales, in Million EUR	4.43	41.30	22,247	7.13	15.69	1,854
Total exports, in Million EUR	1.31	6.77	6,592	3.80	11.04	989
Number of establishments	1.29	1.47	6,498	1.31	1.41	340
Foreign ownership	0.04	0.19	184	0.10	0.31	27
Firm age	17.09	16.84		18.13	15.21	
Export intensity	0.40	0.40		0.43	0.37	
Sales, in Million EUR/employee	0.05	1.12		0.04	0.05	
Sum of product shares	0.34	0.38		0.35	0.34	
Exporting to CEECs	0.05	0.23	271	0.08	0.27	21
Export entry to CEECs	0.05	0.22	262	0.16	0.37	42
Observations	5027			260		

Table A.3: Share of exporting firms with automation by industry and employment size

		By number of employees					
	Total	1-9	10-49	50-249	250-499	500-999	$\geq$ 1000
Food and beverages	0.01	0.00	0.01	0.00	0.10	0.00	0.33
Tobacco products	0.33	.	.	0.00	.	.	1.00
Textiles	0.01	0.00	0.01	0.01	0.02	0.00	0.13
Wearing apparel	0.01	0.00	0.00	0.01	0.02	0.08	0.00
Leather products	0.01	0.00	0.00	0.01	0.05	0.14	1.00
Wood and wood products	0.04	0.01	0.02	0.13	0.13	0.75	.
Paper and paper products	0.01	0.00	0.00	0.00	0.00	0.20	.
Printing and publishing	0.01	0.00	0.00	0.02	0.43	0.00	.
Coke and petroleum products	0.00	.	0.00	.	.	.	0.00
Chemical products	0.01	0.00	0.02	0.02	0.00	0.00	0.00
Rubber and plastics	0.10	0.03	0.09	0.15	0.00	0.00	.
Mineral products	0.02	0.00	0.01	0.05	0.10	0.27	0.00
Basic metals	0.36	0.00	0.35	0.48	0.17	0.33	1.00
Fabricated metal products	0.19	0.04	0.15	0.34	0.57	0.00	.
Machinery and equipment	0.42	0.09	0.40	0.58	0.50	0.80	.
Office equipment	0.20	.	0.00	0.33	.	.	.
Electrical machinery	0.17	0.04	0.07	0.29	0.14	0.75	0.60
Electronics	0.27	0.10	0.17	0.15	0.75	1.00	1.00
Precision instruments	0.14	0.00	0.13	0.25	0.00	1.00	.
Motor vehicles	0.35	0.00	0.20	0.53	0.50	0.75	.
Other transport equipment	0.17	0.00	0.00	0.38	0.33	.	1.00
Furniture	0.07	0.01	0.03	0.26	0.50	1.00	.
Total	0.07	0.01	0.06	0.11	0.13	0.20	0.47

Table A.4: Effect of exposure to tariff reductions on sales by destination: long difference regressions, 1992-1998 (OLS)

	Δ log(x) $\times$ 100 from 1992 to 1998				
	Total Sales	Domestic Sales	Total Exports	Intra-EU Exports	Extra-EU Exports
Δ FC	-21.57***	-12.71	-12.67**	-12.84*	-6.55
	(7.02)	(28.68)	(5.38)	(7.22)	(10.52)
Sales, in Million EUR	-1.43***	-2.81**	-0.02	-0.38	0.27
	(0.25)	(1.11)	(0.29)	(0.30)	(0.31)
Firm age	-0.53***	-1.16*	-1.06***	-1.45***	-0.36
	(0.15)	(0.64)	(0.25)	(0.33)	(0.27)
Foreign ownership	7.13	-55.88	18.44	21.42	47.29**
	(7.07)	(58.88)	(12.93)	(13.48)	(20.13)
Exporting to CEECs	0.62	12.97	-11.47	-19.46*	0.17
	(5.23)	(47.97)	(10.86)	(10.83)	(13.67)
Export entry to CEECs	33.85***	-75.90**	63.08***	48.31***	94.13***
	(7.10)	(33.92)	(11.87)	(12.33)	(11.75)
Δ FC^{China}	-3.93	-14.12	-3.52	-2.71	-2.08
	(2.49)	(11.71)	(2.62)	(2.14)	(3.31)
Observations	4,150	4,150	3,307	2,580	1,945
R-squared	0.12	0.15	0.09	0.20	0.07
Region FE	YES	YES	YES	YES	YES
Industry FE	YES	YES	YES	YES	YES
Industry x Size FE	YES	YES	YES	YES	YES

Note: The dependent variable is the change in the log of a given sales variable between 1992 and 1998 multiplied by 100.Explanatory variable is normalized to have a mean of 0 and a standard deviation of 1. All regressions include dummies for 2-digit industry by employment size cells and 2-digit NUT regions. Standard errors are robust to heteroskedasticity and allow for clustering at the 3-digit industry-level (99 industries). Coefficients with ***, **, and * are significant at the 1%, 5% and 10% confidence level, respectively.

Table A.5: Effect of exposure to tariff reductions on automation: 1992-1998 (OLS)

	Automation per worker from 1992 to 1998				
	(1)	(2)	(3)	(4)	(5)
Δ FC	-564.86***	-549.18***	-557.73**	-168.98	-195.55
	(192.98)	(189.82)	(215.01)	(128.66)	(126.11)
Sales		2.61	1.64	1.09	2.85
		(3.79)	(3.63)	(3.27)	(5.03)
Firm age		-9.58*	-10.54**	-9.21**	-8.08**
		(4.91)	(5.17)	(4.18)	(4.04)
Foreign ownership		664.41	623.69	0.09	-460.33
		(567.59)	(546.37)	(447.50)	(368.28)
Exporting to CEECs			198.07	232.21	120.46
			(211.75)	(220.84)	(303.41)
Export entry to CEECs			698.38	322.49	33.50
			(468.39)	(444.03)	(446.62)
Δ FC^{China}			-40.23	-39.22	-42.47
			(74.11)	(45.81)	(42.47)
Observations	3,991	3,964	3,964	3,964	3,953
R-squared	0.00	0.01	0.01	0.05	0.09
Region FE	NO	NO	NO	YES	YES
Industry FE	NO	NO	NO	YES	YES
Industry x Size FE	NO	NO	NO	NO	YES

*Note:*The dependent variable is the sum of firm-level imports of industrial robots and numerically controlled machinery from 1992 to 1998, deflated to 1990 prices, and divided by the number of production workers in 1992. Explanatory variable is normalized to have a mean of 0 and a standard deviation of 1. Specification (4) include dummies for 2-digit NUTS regions and 2-digit ISIC industries. Specification (5) includes a dummy variable for each 2-digit industry by employment size category (10-49,50-249,250-499, 500-999,≥1000). Standard errors are robust to heteroskedasticity and allow for clustering at the 3-digit industry-level (99 industries). Coefficients with ***, **, and * are significant at the 1%, 5% and 10% confidence level, respectively.

Table A.6: Heterogeneous effect of exposure to tariff reductions on automation: 1992-1998 (OLS)

	Automation per worker from 1992 to 1998			
	(1)	(2)	(3)	(4)
Δ FC	-607.31***	-237.05*		
	(204.02)	(126.25)		
Labor productivity	67.83	-695.35		
	(540.06)	(932.48)		
Δ FC × labor prod.	997.78*	863.89*		
	(524.83)	(460.84)		
Δ FC × Low			-379.08**	-194.56
			(175.75)	(128.08)
Δ FC × High			-2,391.24***	-1,068.91**
			(774.82)	(424.91)
Labor productivity × Low			-584.00	-329.33
			(567.86)	(714.33)
Labor productivity × High			38,709.63***	19,157.21*
			(11,310.41)	(10,490.42)
Δ FC × Labor prod. × Low			255.59	410.72*
			(183.05)	(214.39)
Δ FC × Labor prod. × High			77,377.88***	47,267.07**
			(24,255.46)	(22,880.90)
Observations	3,991	3,953	3,991	3,953
R-squared	0.00	0.09	0.03	0.09
Firm characteristics	NO	YES	NO	YES
Contemporaneous controls	NO	YES	NO	YES
Region FE	NO	YES	NO	YES
Industry FE	NO	YES	NO	YES
Industry x Size FE	NO	YES	NO	YES

Note: Explanatory variable is normalized to have a mean of 0 and a standard deviation of 1. Specifications (2) and (4) incorporate all control variables included in the fully specified model detailed in column (5) of Table 4. Standard errors are robust to heteroskedasticity and allow for clustering at the 3-digit industry-level (99 industries). Coefficients with ***, **, and * are significant at the 1%, 5% and 10% confidence level, respectively.

Table A.7: Effect of exposure to tariff reductions on employment and wages by skill type: long difference regressions, 1992-1998 (OLS)

	Δ log(x) × 100 from 1992 to 1998			
	Total employment	Total wage bill	Total workhours	Average hourly wage
Panel A. Low-skilled workers	(1)	(2)	(3)	(4)
Δ FC	-6.95**	-10.73***	-9.75***	-0.98
	(2.86)	(3.38)	(3.15)	(0.79)
Observations	4,009	3,921	3,921	3,921
R-squared	0.06	0.06	0.05	0.04
Panel B. High-skilled workers	(5)	(6)	(7)	(8)
Δ FC	-4.76	-0.84	-9.07	8.24***
	(6.11)	(6.09)	(6.36)	(2.28)
Observations	1,888	1,506	1,506	1,506
R-squared	0.04	0.04	0.04	0.03
Firm characteristics	YES	YES	YES	YES
Contemp. controls	YES	YES	YES	YES
Industry FE	YES	YES	YES	YES
Region FE	YES	YES	YES	YES

Note: The dependent variables are defined as the change in the log of employment, wage bill, workhours or the average hourly wage between 1992 and 1998 multiplied by 100, respectively. Highly skilled workers are defined as workers with more than 12 years of formal education. The explanatory variable is normalized to have a mean of 0 and a standard deviation of 1. All regressions control for the following firm characteristics in 1992: sales, firm age, foreign ownership, CEEC exporter status as well as the sum of product shares. All regressions account for the following contemporaneous changes: a dummy for entry into the CEEC market and exposure to Chinese imports. Regressions also include dummies for 2-digit ISIC industries and 2-digit NUTS regions. Standard errors are robust to heteroskedasticity and allow for clustering at the 3-digit industry-level (99 industries). Coefficients with ***, **, and * are significant at the 1%, 5% and 10% confidence level, respectively.

Table A.8: Balance check: firm-level controls and tariff shock

	Sales	Firm age	Foreign ownership	Export to CEECs in 1992	Export entry to CEECs by 1998	Chinese imports
	(1)	(2)	(3)	(4)	(5)	(6)
Δ FC	-1.22	1.44	-0.02*	-0.01	0.01	-0.02***
	(0.99)	(0.95)	(0.01)	(0.01)	(0.01)	(0.01)
Observations	5,277	5,277	5,277	5,277	5,277	5,277
R-squared	0.05	0.27	0.11	0.08	0.13	0.29
Ind. x Size FE	YES	YES	YES	YES	YES	YES
Region FE	YES	YES	YES	YES	YES	YES

Note: Explanatory variable is normalized to have a mean of 0 and a standard deviation of 1. Regressions control for the sum of shares of product exports to EU in total sales in 1992, region and industry by employment size bracket dummies. Standard errors are robust to heteroskedasticity and allow for clustering at the 3-digit industry-level (99 industries). Regressions are unweighted. Coefficients with ***, **, and * are significant at the 1%, 5% and 10% confidence level, respectively.