

Digital Factory Governance and Innovation-Led Trade Reforms: Comparative Dynamics of Portugal and Brazil

Lucas Ferrante^{1*}, Arie Carneiro²

¹Department of Environmental Dynamics, National Institute for Research in Amazonia (INPA), Manaus, Amazonas Brazil

²Federal University of Amazonas (UFAM), Manaus, Amazonas Brazil

Abstract

The Fourth Industrial Revolution has significantly transformed the global industrial landscape by integrating digital technologies, automation, artificial intelligence, and smart manufacturing systems into economic activities. This study aims to examine the emerging dimensions of industrial, trade, and innovation policies within the context of Industry 4.0, with particular emphasis on the experiences of Portugal and Brazil. The research investigates the extent to which Industry 4.0 has influenced policy formulation, industrial competitiveness, technological advancement, and international trade performance in both countries. The study further explores the limitations and impacts of industrial modernization strategies, innovation frameworks, and trade policies under rapidly changing technological environments.

A descriptive research design was adopted using documentary analysis and secondary data sources collected from governmental reports, policy documents, industrial statistics, and international economic databases. The findings reveal that industrial, trade, and innovation policies in Portugal and Brazil were considerably influenced by economic crises, technological transformation pressures, and global market uncertainties during the period under analysis. The study also identifies structural limitations related to technological diffusion, industrial productivity, innovation capacity, and international trade integration. Moreover, both countries continue to face challenges in expanding their participation in global value chains outside the framework of regional economic integration, trade blocs, and free trade agreements.

The study concludes that Industry 4.0 requires comprehensive policy restructuring focused on digital transformation, technological investment, innovation ecosystems, and industrial competitiveness. Strengthening collaborative industrial strategies and improving technological capabilities are essential for Portugal and Brazil to achieve sustainable economic growth and stronger participation in the global digital economy.

Keywords: Industrial Policy, Trade Policy, Innovation Policy, Industry 4.0, Digital Transformation.

*Corresponding author:

Lucas Ferrante, Department of Environmental Dynamics, National Institute for Research in Amazonia (INPA), Manaus, Amazonas Brazil. E-mail: ferrante_lucas21@gmail.com

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Introduction

The beginning of the twenty-first century has been characterized by rapid technological transformation driven by advances in digital communication, automation, artificial intelligence, robotics, cloud computing, big data analytics, blockchain systems, and cyber-physical production networks. These

technological developments, commonly associated with the Fourth Industrial Revolution (Industry 4.0), have significantly reshaped industrial structures, trade relations, and innovation ecosystems across developed and developing economies [1-3]. The growing integration of intelligent manufacturing systems and digital technologies into production processes has generated new opportunities and challenges for governments,

industries, and firms operating within highly competitive global markets [4].

Industry 4.0 represents a paradigm shift in industrial development by combining digitalization, automation, and data-driven decision-making with advanced manufacturing systems. Technologies such as artificial intelligence, the Internet of Things (IoT), cloud computing, blockchain, 5G communication networks, additive manufacturing, and smart robotics are transforming the way firms produce goods, manage supply chains, and interact with consumers [5,6]. Consequently, governments are increasingly required to redesign industrial, trade, and innovation policies capable of supporting technological modernization, industrial competitiveness, and sustainable economic growth within this rapidly evolving environment [7].

The interaction between industrial policy, trade policy, and innovation policy has therefore become more significant in the context of Industry 4.0. Industrial policy is no longer limited to supporting manufacturing expansion; rather, it now encompasses digital transformation, innovation ecosystems, research and development (R&D), technological capability building, and integration into global value chains [8]. Similarly, trade policy increasingly focuses on digital commerce, international competitiveness, technological cooperation, and economic integration, while innovation policy seeks to strengthen knowledge transfer, technological diffusion, entrepreneurship, and collaborative networks among governments, universities, and industries [9,10].

Portugal provides an important example of policy adaptation toward Industry 4.0 through the implementation of the "Industry 4.0 Program" introduced in 2016 and operationalized in 2017. The initiative focused on multiple strategic pillars, including digital skills training, technological cooperation, startup development, investment incentives, financing support, internationalization, and legal modernization [11]. The program achieved substantial progress by supporting thousands of firms and workers through incentives financed largely by European Union structural funds. These efforts contributed to the formation of an innovation-oriented industrial ecosystem aimed at improving productivity, competitiveness, and technological modernization within the Portuguese economy [12].

In Brazil, the diffusion of Industry 4.0 technologies has also gained increasing attention among policymakers, business associations, and industrial sectors. However, the implementation process has progressed unevenly due to structural economic challenges, institutional limitations, and technological disparities among firms [13]. Studies indicate that larger firms are more advanced in adopting Industry 4.0 technologies compared to smaller enterprises, while automation and productivity improvements remain the primary motivations for digital transformation initiatives [14]. Despite investments in sectors such as information

technology, telecommunications, aerospace, agriculture, and advanced manufacturing, Brazil continues to face challenges related to innovation capacity, industrial competitiveness, and integration into global technological networks [15].

Both Portugal and Brazil have experienced the influence of economic crises, globalization pressures, and technological disruptions on their industrial and trade policies over the last decades. While Portugal benefited from European integration mechanisms and financial support following the 2008 economic crisis, Brazil encountered difficulties associated with policy inconsistency, limited industrial coordination, and slower technological diffusion [16,17]. In both countries, the shortage of digital skills, insufficient technological infrastructure, and weak innovation linkages have emerged as significant barriers to successful Industry 4.0 transformation [18].

Theoretical discussions surrounding industrial policy have evolved considerably in recent decades. Contemporary industrial policy is increasingly viewed as an institutionally coordinated process that integrates industrial development, innovation systems, knowledge transfer, and economic competitiveness [19]. Unlike traditional industrial policy approaches focused primarily on manufacturing expansion, modern industrial strategies emphasize horizontal coordination among governments, firms, universities, financial institutions, and research organizations [20]. These collaborative arrangements are essential for fostering innovation ecosystems capable of supporting digital industrial transformation [21].

Trade policy has also undergone substantial transformation due to globalization and the increasing importance of digital trade and global value chains. Services and digital commerce now constitute a significant proportion of global trade flows, while technological competition among nations has intensified [22]. The emergence of China as a major global technological and industrial power, combined with strategic trade tensions involving advanced economies such as the United States, has further complicated the international trade environment [23]. Additionally, the COVID-19 pandemic accelerated digitalization trends while exposing vulnerabilities in global supply chains and industrial systems [24].

Innovation policy plays a critical role in supporting Industry 4.0 transformation by encouraging research and development activities, technological learning, knowledge diffusion, and industrial upgrading. The concept of "policy mix" has gained prominence in innovation studies, referring to the combination of policy instruments designed to stimulate innovation performance and technological modernization [25]. Effective innovation policies require coordination between industrial objectives, educational systems, technological infrastructure, and international collaboration mechanisms [26].

Against this background, this study aims to examine the limits

and impacts of industrial, trade, and innovation policies from an Industry 4.0 perspective in Portugal and Brazil. The research seeks to provide a comparative analysis of the policy approaches adopted by both countries between 2008 and 2018, focusing on their capacity to promote industrial modernization, technological upgrading, and international competitiveness [27,28]. The study also contributes to the growing literature on Industry 4.0 by analyzing how industrial, trade, and innovation policies interact within different economic and institutional contexts [29,30].

The remainder of the article is organized as follows. Section Two presents the conceptual and theoretical framework related to industrial, trade, and innovation policies within the context of Industry 4.0. Section Three describes the research methodology and data sources used in the study. Section Four discusses the comparative analysis and findings related to Portugal and Brazil. Section Five presents the conclusion, policy implications, limitations, and recommendations for future research.

Materials and Methods

This section presents the methodological procedures adopted in the study. Regarding the objectives, the research is classified as descriptive because it seeks to observe, record, analyze, and interpret the dynamics of industrial, trade, and innovation policies within the context of Industry 4.0 without manipulating the variables under investigation [30]. Descriptive studies are appropriate for examining contemporary economic and technological phenomena and for identifying relationships among institutional, industrial, and innovation-related transformations [31].

With respect to the nature of the research, the study follows a qualitative approach due to its emphasis on interpretation, contextual analysis, and examination of policy frameworks rather than the application of statistical or econometric techniques [32]. The qualitative method allows a broader understanding of the institutional and structural changes associated with Industry 4.0 policies in Portugal and Brazil. The research is also characterized as applied research because it seeks to contribute to policy discussions related to industrial modernization, technological upgrading, and innovation governance [33].

The investigation was conducted through documentary research using secondary data collected from official reports, institutional publications, policy documents, industrial statistics, and international databases. Documentary research was considered appropriate because it provides reliable and comprehensive information regarding industrial, trade, and innovation policy developments in both countries during the selected period [34]. Secondary data also enabled the comparative analysis of technological transformation indicators, industrial competitiveness, innovation capacity, and trade performance.

The period selected for the analysis covers the years from

2008 to 2018. The choice of this timeframe was based on the significant economic and institutional transformations experienced by Portugal and Brazil following the global financial crisis of 2007-2008 [35]. During this period, Portugal experienced sovereign debt challenges, economic restructuring, and recovery supported by European Union initiatives, while Brazil faced fiscal instability, industrial slowdown, and structural economic constraints [36]. The selected timeframe also coincides with the growing international diffusion of Industry 4.0 concepts, digital transformation strategies, and innovation-oriented industrial policies.

The study focused on analyzing the interaction between industrial policy, trade policy, and innovation policy within the context of technological modernization and digital industrial transformation. The comparative approach adopted in the research allows the identification of similarities, differences, opportunities, and limitations in the policy frameworks implemented in Portugal and Brazil [37]. This comparative perspective contributes to understanding how countries with different economic structures and institutional conditions respond to the challenges imposed by Industry 4.0.

To construct the empirical analysis, several official databases and institutional sources were consulted. For Portugal, the primary data sources included the National Institute of Statistics (INE), the Directorate-General for Education and Science Statistics (DGEEC), the Ministry of Economy, and the Bank of Portugal [38]. These institutions provided statistical information related to industrial production, innovation indicators, technological investments, labor qualification, and international trade performance.

For Brazil, the study utilized databases from the Institute of Applied Economic Research (IPEA), the Brazilian Institute of Geography and Statistics (IBGE), and the Ministry of Science, Technology, Innovation and Communications (MCTIC) [39]. Additional information was obtained from policy reports, industrial surveys, and governmental publications concerning technological innovation, industrial productivity, trade dynamics, and digital transformation initiatives.

The collected data were analyzed through comparative and interpretative techniques, focusing on the evolution of industrial modernization policies, technological adoption strategies, innovation systems, and trade integration mechanisms in both countries [40]. This methodological approach enabled a comprehensive understanding of the impacts and limitations of Industry 4.0-oriented policies within different economic and institutional environments.

Results

The comparative analysis between Portugal and Brazil demonstrates that industrial, trade, and innovation policies under the industry 4.0 framework have evolved differently due

to variations in institutional capacity, economic stability, and technological readiness [39]. Portugal achieved relatively better progress in digital transformation because of stronger integration with the European Union, structured innovation programs, and continuous support for technological modernization. The implementation of the Portugal Industry 4.0 Program encouraged digital skills development, investment incentives, and technological cooperation among firms and research institutions.

The Portuguese case also highlights the importance of coordinated policy alignment between industrial modernization and trade integration [35]. Although the country still faces limitations regarding low technological intensity and dependence on SMEs, the integration of innovation policies with European funding mechanisms improved R&D investment and export competitiveness. The increase in patent applications and technological services exports reflects gradual progress toward a knowledge-based economy.

Brazil experienced greater structural and economic difficulties during the analyzed period [38]. Industrial recovery after the 2014–2016 recession remained weak and inconsistent, negatively affecting industrial productivity and innovation capacity [39]. Although scientific production expanded considerably, innovation indicators such as patent applications, private R&D investment, and technological modernization remained below expectations [40]. The lack of policy continuity and insufficient coordination between industrial and innovation strategies limited the advancement of Industry 4.0 initiatives [41].

The findings also indicate that both countries continue to face barriers in technological diffusion, digital qualification, and integration into global value chains [42] (Figure 1). Small and medium-sized enterprises remain less prepared for the transition toward intelligent manufacturing systems due to financial restrictions, outdated infrastructure, and limited access

to advanced technologies [43]. In Brazil, the aging industrial equipment and low automation levels demonstrate the need for stronger industrial renewal policies [44].

Trade policies also played a significant role in shaping industrial competitiveness [45]. Portugal benefited from participation in the European Single Market and regional economic integration, while Brazil remained more dependent on domestic market conditions and faced challenges related to external competitiveness [46]. The expansion of digital trade and service-based economic activities under Industry 4.0 requires stronger international cooperation, innovation ecosystems, and institutional support mechanisms [47].

The study further reveals that Industry 4.0 policies are not restricted to technological adoption alone but also involve workforce qualification, institutional coordination, and innovation governance [48]. Digital transformation requires long-term public and private investments in research, education, infrastructure, and technological capability development [49].

The comparative evidence suggests that Portugal advanced more consistently in creating an innovation-oriented industrial ecosystem, while Brazil still struggles with structural instability and fragmented policy implementation [50]. Despite these differences, both countries demonstrate that industrial, trade, and innovation policies remain fundamental instruments for improving competitiveness and adapting economies to the digital transformation associated with the Fourth Industrial Revolution [51].

Discussions

The analysis of Portugal and Brazil demonstrates that industrial, trade, and innovation policies within the industry 4.0 environment are strongly influenced by economic structure, institutional coordination, and technological capability [52,53]. Portugal

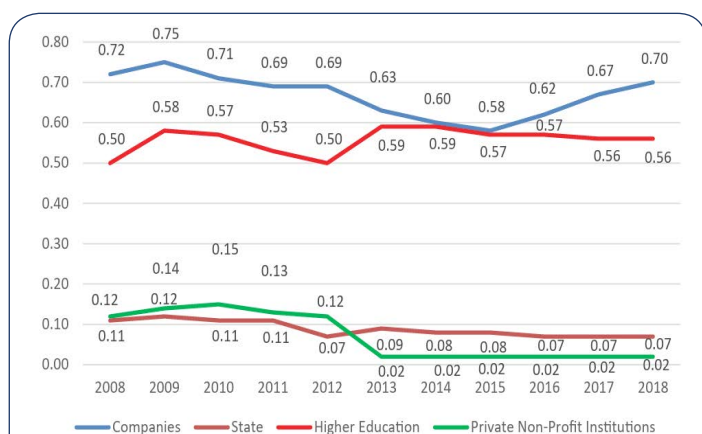


Figure 1 National expenditure on science and technology (S&T) in relation to GDP, by institutional sector, 2008-2018 Portugal. (Source: Own elaboration from PORDATA/ INE data).

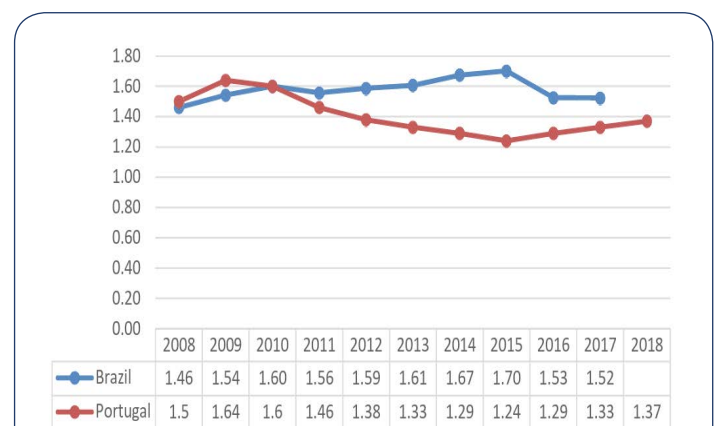


Figure 2 National S&T expenditure (%) relative to GDP, 2008-2017. (Sources: Own elaboration based on INE-Annual National Accounts/PORDATA/Coordination of Indicators and Information (COIND)-Ministry of Science, Technology, Innovations and Communications).

achieved relatively better progress in technological modernization due to European Union integration, innovation funding, and digital transformation programs focused on industrial competitiveness [54]. The country experienced manufacturing decline after the adoption of the euro and exposure to global competition (Figure 2), particularly following China's accession to the WTO and the expansion of the European Union to Eastern Europe [55]. Despite these challenges, Portugal improved the technological sophistication of some industries and strengthened its scientific and innovation ecosystem through European structural support [56].

The Portuguese recovery after 2015 was associated with export growth, improvements in education, and increased investment in research and innovation activities [57]. However, structural weaknesses remained visible, particularly the dependence on SMEs, low public investment, and the persistence of low-skilled labor in several sectors [58]. The industry 4.0 strategy in Portugal contributed to digital transformation through support for startups, technological cooperation, workforce training, and industrial modernization policies [59].

Brazil followed a different trajectory due to its historical dependence on import substitution industrialization and recurring macroeconomic instability [60]. Industrial policies such as the Industrial, Technological and Foreign Trade Policy, the Productive Development Policy, and the Brazil Bigger Plan attempted to increase industrial competitiveness and innovation capacity, but policy discontinuity and weak institutional coordination limited their effectiveness [61-63]. Economic crises, political instability, exchange rate volatility, and high production costs negatively affected industrial productivity and export competitiveness [64].

The Brazilian case also reveals that local content policies and state intervention generated mixed outcomes [65]. While some sectors benefited from employment creation and industrial expansion, these policies also reduced international competitiveness and technological integration [66]. The persistence of high taxation, bureaucratic complexity, and infrastructure deficiencies weakened the capacity of Brazilian industries to compete globally [67]. In addition, the low participation of private firms in R&D investment and the limited modernization of industrial equipment delayed the transition toward Industry 4.0 technologies [68].

Both countries continue to face challenges in digital transformation, technological diffusion, and innovation performance [69]. The findings suggest that successful Industry 4.0 implementation requires long-term industrial strategies, institutional stability, skilled human capital, and stronger integration between industrial, trade, and innovation policies [70-72].

Conclusion

Industrial, trade, and innovation policies from the industry 4.0 perspective in Brazil and Portugal revealed important

technological and structural challenges between 2008 and 2018. Portugal achieved noticeable progress through European Union support, innovation funding, and digital transformation initiatives, while Brazil continued to face limitations related to low investment in innovation and weak participation in global value chains. Economic crises and the COVID-19 pandemic further exposed industrial vulnerabilities and emphasized the importance of strengthening technological capability, innovation systems, education, and digital infrastructure for sustainable economic competitiveness.

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