"Technological development and eco-efficiency: Drivers of total factor productivity in OECD countries"

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TECHNOLOGICAL DEVELOPMENT AND ECO-EFFICIENCY: DRIVERS OF TOTAL FACTOR PRODUCTIVITY IN OECD COUNTRIES

Abstract

This study delves into the total factor productivity growth in OECD countries, focusing on the crucial role of technological advancement and environmental management. By utilizing the Malmquist-Luenberger index, the paper encompasses both positive and negative outputs, such as pollution, providing a comprehensive productivity analysis by breaking it down into efficiency and technical change. Data from 36 OECD countries from 2000 to 2021 were examined to uncover trends and patterns in productivity growth and its unintended environmental consequences. The results emphasize the dominant influence of technological progress, particularly after 2006, as the primary driver of productivity growth, surpassing improvements in technical efficiency. A significant increase in technical change (1.56 in 2021) compared to technical efficiency (1.05) underscores the importance of sustained investment in research and development (R&D), which correlates positively with patent generation and technological advancement. The study also illustrates that OECD countries have effectively integrated eco-efficient practices, aligning with global trends in environmentally conscious productivity analyses. By integrating environmental outputs such as PM2.5 pollution, the analysis demonstrates that countries mitigating these adverse effects achieve higher productivity growth. These findings challenge conventional productivity models, where productivity diminishes when environmental aspects are considered. The analysis emphasizes the necessity for tailored policy approaches to address disparities in R&D investments, technological adoption, and eco-efficiency among countries. Countries with more significant R&D investments consistently demonstrate superior technological advancement in patents (0.745). Policymakers are urged to prioritize long-term strategies that foster technological innovation and environmental sustainability to ensure sustained productivity growth and economic resilience.

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INTRODUCTION

Technological development drives systematic progress and the development of new technologies through research, experimentation, and innovation (Ciarli et al., 2021). These technological innovations affect every facet of life, from simple tasks like making coffee to complex global communications. While technology is indispensable for progress and can have positive societal impacts when used sustainably, it is crucial to monitor its effects on productivity and the unintended consequences that may arise.

Productivity, which measures the relationship between output and the inputs required for production, is a crucial indicator of an economy's ability to produce goods and services efficiently. Increased productivity leads to lower unit costs, benefiting consumers through reduced

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prices and improved living standards. This enhancement, achieved through the efficient use of resources, expands production possibilities and enhances global competitiveness. Productivity can be evaluated using partial indicators, such as labor or capital, or through total factor productivity (TFP), which captures the effects on total production beyond traditional inputs (Vallés-Giménez & Zárate-Marco, 2016).

However, while technological development generally boosts productivity, economic growth, and regional competitiveness, it also creates social disparities and significant environmental impacts, affecting public health (Bosworth & Snower, 2024; Halkos & Argyropoulou, 2021). Although several studies have assessed efficiency and productivity in OECD countries, the growth of TFP – including undesirable outputs – has not been adequately addressed. This omission is critical, as efficiency and productivity measurements overlooking the asymmetry between desirable and undesirable outputs provide an incomplete picture (Morales-Piñero et al., 2022; Oh, 2010).

Given the profound influence of technological development on productivity – both positively, through efficiency gains, and negatively, through environmental consequences – a comprehensive understanding of TFP requires an approach that integrates these dual aspects.

1. LITERATURE REVIEW AND HYPOTHESES

The literature on technological development and productivity is vast, spanning various sectors and regions, yet it often overlooks the complexities introduced by environmental factors. This review synthesizes key findings on the relationship between technology and productivity, focusing on the role of R&D investments, the differential impacts across regions, and the environmental externalities accompanying technological progress. Through this lens, the study situates itself within ongoing debates, highlighting the need for integrated approaches that consider both desirable and undesirable outputs in assessing productivity growth.

1.1. Impact of technology on productivity

Technological adoption has boosted efficiency in agriculture, manufacturing, and services, though unevenly across regions. Pine et al. (2020) highlight that technology has bridged social gaps by improving information access and promoting social mobility but has also widened income inequalities and the digital divide. Tamberi (2020) notes that productivity gaps between firms and sectors are more significant in poorer countries, suggesting a greater impact of technology on productivity in developing economies.

Hawash and Lang (2020) found that ICTs have a minor impact on total factor productivity (TFP) growth in developing countries. However, substantial ICT investments can boost TFP growth rates by 0.1% to 0.3% annually. In OECD countries, ICT advancements positively influence labor productivity growth (Fulgenzi et al., 2024), though not significantly improving overall productivity growth rates.

Modernizing farming techniques boosts productivity and farmer incomes. Fuglie and Echeverria (2024) show that adopting comprehensive technological packages, including investments in complementary assets and training, amplifies this effect.

Schiff and Wang (2023) emphasize that technology diffusion from G7 countries to Latin America and East Asia enhances productivity, measured by TFP. Education, trade, governance, and geographical proximity are critical. The results suggest that Latin America's TFP could double with East Asia's levels of education, trade, and governance. However, geographical distance from the US and Canada reduces TFP, underscoring the role of proximity to developed countries in productivity.

Herrero et al. (2023) indicate that robot imports in Latin America primarily enhance productivity for medium-skilled workers. Low-skilled workers remain unaffected due to low wages compared to the cost of robots. Automation improves efficiency, production precision, times, and product quality but requires significant investment, worker adaptation, job reconfiguration, and additional training (Nava, 2023).

1.2. Environmental externalities of technology

Environmental technologies enhance energy efficiency, yet technological changes can have significant environmental impacts, necessitating economic instruments like pollution taxes and emission trading permits. Despite addressing environmental challenges, technology can lead to resource overconsumption, CO_2 emissions, and electronic waste (Bampatsou & Halkos, 2017; Yilanci, 2023). PM2.5 pollution harms respiratory and cardiovascular health, reducing life expectancy (Zhang et al., 2019; Zhu et al., 2020). Industrial restructuring and technological progress can exacerbate PM2.5 pollution, though innovation-based progress can mitigate these impacts (Xu et al., 2021; Liang & Wang, 2023).

Bianchini et al. (2023) argue that local development of environmental technologies reduces greenhouse gas emissions, while digital technologies increase them, affecting life quality and health negatively (Halkos & Argyropoulou, 2021). Moreover, Vergès (2022) suggests that technological development, particularly automation and artificial intelligence, can exacerbate existing inequalities in Latin America, as low-skilled and low-wage jobs are the most affected. Automation and AI can worsen inequalities in Latin America by affecting low-skilled, low-wage jobs, leading to job losses, precarious employment, labor market polarization, and deteriorating working conditions through digital surveillance (Mao et al., 2020; Nava, 2023). Rivera (2019) argues that while automation displaces jobs in the short term, it creates long-term opportunities influenced by demographics and workforce skills.

As can be seen, various factors influence technology's impact on productivity growth. Technological change is the primary driver of stable productivity changes (Basu et al., 2001). European Central Bank et al. (2021) note that demand-driven cyclical effects and changes in labor and capital dominate short-term fluctuations, while technological and organizational changes determine long-term trends. Adoption and diffusion of innovation require changes in business models (Foster & He, 2022). AI has the potential for significant productivity impact, though its influence is minimal (Foster & He, 2022).

Education and continuous training are crucial for adopting technology and adapting to its changes (Vergès, 2022). The level of education and technological competence among the population determines the effective use of technology. Institutional context, including the regulatory environment and innovation ecosystem, is critical. Favorable legislation promoting competition, protecting intellectual property, and encouraging R&D, along with strengthening research institutions and academia-industry partnerships, drives effective technology use and productivity (Hawash & Lang, 2020).

Socioeconomic, cultural, and regulatory factors shape technology's impact on productivity. Tough internal competition, import and export penetration, R&D, ICT, and trade openness improve economic growth and reduce the gap between developed and developing countries (Misra et al., 2015; Pieri et al., 2018; Utku-İsmihan, 2019). Reviewing the literature reveals diverse concepts and results, highlighting ongoing efforts to expand the debate in this context.

This study aims to analyze the growth of total factor productivity (TFP) in OECD countries, emphasizing both the role of technological development and environmental factors in driving productivity growth. The study proposes four research hypotheses to achieve this objective:

H1: Technological development positively influences total factor productivity growth in OECD economies.

H2: Increased investments in R&D are positively correlated with patent generation, thereby contributing to total factor productivity growth.

H3: Including environmental impacts as undesirable outputs (e.g., PM2.5 pollution) significantly alters productivity measurement.

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H4: *Countries showing improvements in eco-efficiency experience more remarkable overall productivity growth.*

2. METHOD

This study followed a systematic approach to measure the growth of total factor productivity (TFP) driven by technological development in OECD economies, considering environmental factors. Recognizing that these environmental impacts can negatively affect productivity, the non-parametric Malmquist-Luenberger Productivity Index (ML) was employed, as proposed by Chung et al. (1997). The ML enables the inclusion of desirable and undesirable outputs, providing a more comprehensive estimation of productivity growth. The study encompassed 36 OECD countries with complete data for 2000–2021.

The selection of inputs and outputs in data envelopment analysis (DEA) is a crucial preliminary step. Previous studies evaluating productivity and environmental impact within OECD countries have used variables such as industry, taxes, population, GDP, R&D expenditure, knowledge capital, labor, capital, energy, PM2.5, and CO2 emissions (Yang et al., 2021; Zhu et al., 2020; Pieri et al., 2018; Bampatsou & Halkos, 2017; Emrouznejad et al., 2016; Oh, 2010).

Data for this study were sourced from OECD databases, focusing on science and technology indicators and major economic indicators (OECD, 2024a, 2024b). To ensure consistency and mitigate the effects of economies of scale, the variables BERD, GFCF, Patent, and Exports were normalized using the variable Labor. Normalizing these variables against the Labor variable allows for a more accurate comparison across countries with differing scales of economic activity and workforce sizes. This approach ensures that the size of the economy or labor force does not disproportionately influence productivity and technological development measures. Table 1 shows the description of variables.

The study utilized the non-parametric ML method developed by Aparicio et al. (2013) to assess TFP growth, mitigating inconsistencies identified by Chung et al. (1997). This approach takes into account both desirable and undesirable outputs when estimating productivity growth. By employing ML, the analysis disentangles efficiency and technical changes to pinpoint the drivers of TFP growth. The study also utilized the data envelopment analysis (DEA) toolbox for MATLAB (Álvarez et al., 2020) for the analysis. Additionally, a comparative analysis of productivity was conducted using both the Malmquist-Luenberger productivity index (ML) and the Malmquist productivity index (M). This dual-method approach allowed for the evaluation of the impact of undesirable outputs, such as pollution, on productivity measurements. While the Malmquist-Luenberger productivity index incorporates undesirable outputs, offering a comprehensive understanding of productivity changes accounting for environmental impacts, the Malmquist productivity index focuses solely on desirable outputs.

Table 1. Study variables

Symbol	Definition
Input Variables	
BERD	Business Enterprise Expenditure on R&D at current PPP $ millions per working-age population, measures investment in R&D.
Labor	The working-age population (15 and over) is in thousands, measuring labor.
GFCF	Gross fixed capital formation at current prices in $ millions per working-age population, measuring capital stock
Output Variables	
Patent	Number of triadic patent families per working age population, measuring R&D investment impact. Triadic patents protect the same invention in multiple countries.
GDPperHour	GDP per hour worked in US dollars measuring labor productivity.
Exports	Total exports in computer, electronic, and optical industries at current PPP $ millions per working-age population, measuring technological development.
Undesirable Output Variable	
PM2.5	Mean population exposure to PM2.5 in micrograms per cubic meter, a significant global health risk, and OECD Green Growth indicator.

The method's parameters include fixing the first period (2000) as the base period and using it as a reference for technological change. The standard ML is based on the directional efficiency score, requiring calculation of the mix period efficiency observed in two periods. Once calculated, the ML indices define productivity changes. If ML > 1, efficiency increases, allowing more desirable output with less undesirable production. If ML = 1, productivity remains unchanged, and ML < 1 signals a decline.

The index can be decomposed into efficiency change and technical change. MLTEC defines changes in technical efficiency, while frontier-shift effects corresponding to technical change are MLTC. If MLTEC or MLTC > 1, productivity change responds to both technical efficiency gains and technical improvements. Conversely, if MLTEC or MLTC < 1, productivity decreases with more significant inefficiency and technical regression.

3. RESULTS

The descriptive statistics analysis (Table 2) reveals significant disparities in R&D investment, labor force size, capital stock, and output indicators among OECD countries. GDP per hour worked (GDPperHour) averages $46.82, with a relatively lower standard deviation of $21.38, suggesting less variability in labor productivity. Mean population exposure to PM2.5 averages 14.43 μg/m³, with a standard deviation of 6.00 μg/m³, indicating variability in environmental health risks across countries.

Table 3 indicates that countries with high expenditure in R&D (BERD), such as Switzerland, Japan, and Sweden, also excel in patent production and technological exports, reinforcing the positive impact of R&D investment on innovation and economic output. The Pearson correlation is positive and significant at 0.745. For example, Japan (BERD 1.018, Patents 0.165) and Switzerland (BERD 1.294, Patents 0.170) demonstrate robust patent outputs relative to their R&D expenditure. Additionally, countries with substantial R&D investments tend to exhibit higher labor productivity. Noteworthy cases include Switzerland (BERD 1.294, GDP per hour 61.545) and Sweden (BERD 1.300, GDP per hour 62.623). However, variations in productivity and environmental health indicators highlight the need for targeted policies to address these disparities. This comprehensive understanding is crucial for policymakers to foster balanced and sustainable growth across the OECD region.

The PM2.5 variable deserves special attention. A review of its average trend over the past 20 years, reveals a decline from 18 μg/m³ in 2000 to 12 μg/m³ in 2021. The Pearson correlation demonstrates a significant negative relationship between PM2.5 and GDPperHour (–0.600), indicating that technological advancements have progressively mitigated their impact.

Following the descriptive statistics analysis, the Malmquist-Luenberger productivity index (ML) was calculated (refer to Figure 1). Table A1 provides detailed values of the productivity index, which highlights changes in productivity across the OECD countries analyzed.

This outcome is further illustrated in Figure 1, which shows that technical efficiency has remained relatively constant over time while technical change has been on the rise, aligning with the productivity increases reported by the Malmquist-Luenberger index.

The comparison of ML with its components, MLTEC and MLTC, reveals that technological change (MLTC) has been a more significant driver of productivity growth than efficiency change (MLTEC). The higher value of MLTC in 2021 for OECD (1.56) compared to MLTEC (1.05) suggests that innovations and technological advancements have had a more substantial impact on productivity than mere improvements in efficiency.

Table 2. Descriptive statistics

Statistics	BERD	LABOR	GFCF	Patent	GDPperHour	Exports	PM2.5
Mean	0.618	28105.8	10.58	0.039	46.82	1.32	14.43
Standard Deviation	0.526	44388.6	6.03	0.044	21.38	1.47	6.00

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Table 3. Average values by variable and country

Country	BERD	LABOR	GFCF	Patent	GDPperHour	Exports	PM2.5
Australia	0.562	18018.75	13.660	0.022	49.505	0.196	7.689
Austria	1.028	7041.71	12.853	0.054	59.327	1.290	15.289
Belgium	0.897	9017.09	11.838	0.050	64.895	1.300	15.414
Canada	0.510	27777.16	11.635	0.024	47.773	0.570	7.888
Colombia	0.014	31506.16	3.397	0.000	11.918	0.003	19.119
Czechia	0.343	8851.03	9.852	0.004	34.895	2.407	19.118
Denmark	0.990	4591.83	11.483	0.067	62.541	1.510	11.973
Estonia	0.226	1122.68	8.458	0.004	30.627	1.377	8.618
Finland	1.055	4451.74	11.271	0.069	54.959	1.806	6.603
France	0.680	50505.44	11.063	0.049	60.305	0.711	12.851
Germany	0.965	69894.97	10.286	0.079	58.982	1.581	14.553
Greece	0.110	9236.67	5.482	0.002	33.314	0.103	19.609
Hungary	0.233	8291.58	6.784	0.006	30.964	2.194	18.979
Iceland	0.931	224.74	13.916	0.025	53.905	0.144	7.083
Ireland	0.656	3557.01	23.940	0.025	73.773	5.798	10.068
Israel	1.728	5589.73	10.222	0.081	37.914	1.576	22.803
Italy	0.302	50738.42	8.231	0.016	49.982	0.323	19.392
Japan	1.018	110472.92	10.558	0.165	40.536	1.006	12.708
Korea	1.126	40978.56	12.034	0.059	28.699	2.892	25.179
Latvia	0.046	1761.05	6.108	0.003	28.509	0.476	17.147
Lithuania	0.093	2610.96	6.097	0.002	31.864	0.418	13.080
Luxembourg	1.070	418.33	21.823	0.055	86.418	2.202	11.610
Mexico	0.025	82246.74	5.058	0.000	18.232	0.740	20.707
The Netherlands	0.683	13600.97	12.138	0.088	62.095	4.916	14.979
New Zealand	0.268	3485.14	9.703	0.019	37.323	0.160	6.774
Norway	0.713	3774.58	17.402	0.032	78.177	0.702	7.801
Poland	0.144	30858.05	5.454	0.002	30.464	0.414	24.104
Portugal	0.201	8854.49	6.596	0.003	34.677	0.356	10.696
The Slovak Republic	0.104	4513.65	6.563	0.002	34.123	2.056	20.208
Slovenia	0.481	1740.13	7.840	0.008	38.691	0.539	18.585
Spain	0.260	38186.33	8.820	0.007	46.236	0.197	12.703
Sweden	1.300	7824.96	12.767	0.101	62.623	1.937	7.418
Switzerland	1.294	6639.07	17.949	0.170	61.545	3.875	12.818
Türkiye	0.128	53541.76	7.066	0.001	33.750	0.048	24.091
The United Kingdom	0.678	50281.40	8.503	0.037	53.495	0.821	12.379
The United States	1.377	239601.98	13.929	0.061	62.405	0.768	9.507

Note: Countries with higher capital stock investments (GFCF) often see an uptick in exports in technological industries. This trend is evident in nations like the Netherlands (GFCF 12.138, Exports 4.916) and Ireland (GFCF 23.940, Exports 5.798).

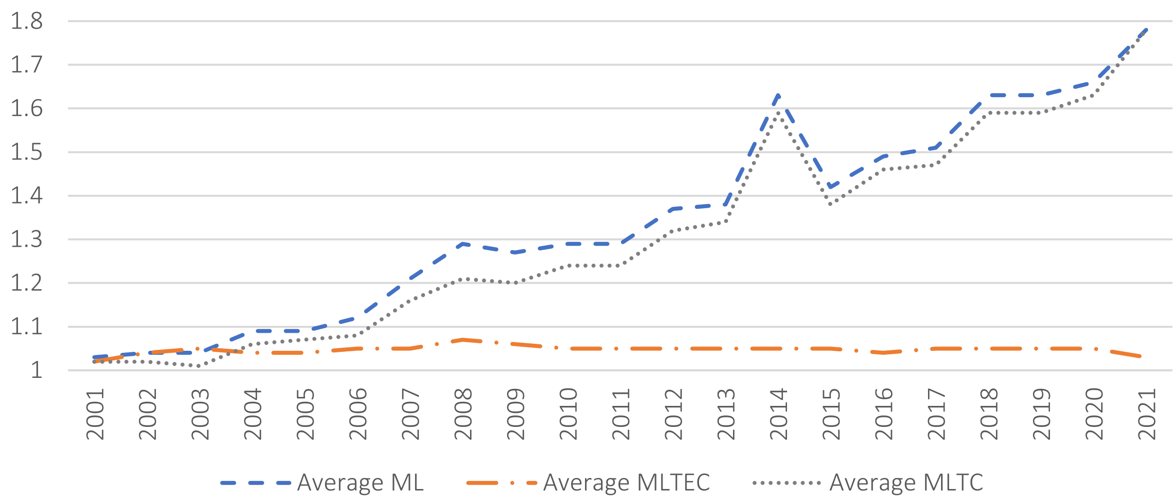

Figure 1. Decomposition of the ML index in OECD

Results show a general trend of productivity improvement over the period studied, with most countries exhibiting positive index values. Countries like Norway, Ireland, Latvia, Luxembourg, and the United States demonstrate significant productivity growth, suggesting the effective implementation of technological advancements and efficiency improvements (Table A1). However, a few countries, such as Colombia and Türkiye, show marginal declines or stagnation, indicating potential challenges in technological adoption or policy effectiveness.

The efficiency changes of the Malmquist-Luenberger index (MLTEC) measure how well countries have used their resources over time (Table A2). Efficiency changes more significant than 1 indicate substantial advances in operational efficiency, likely driven by successful policy frameworks or by more efficient use of production factors. On the contrary, values less than 1 indicate a reduction in efficiency, pointing to possible resource management inefficiencies or slower technological adaptation.

The average MLTEC value for the OECD is 1.01, indicating a modest 1% annual improvement in efficiency across OECD countries over the period analyzed. This result suggests that while countries have made progress in optimizing resource use, the efficiency gains are relatively modest compared to overall productivity improvements. Only Czechia, Korea, the Slovak Republic, Israel, Greece, and Portugal stood out in improving their technical efficiency of between 20% and 55% during the period. Likewise, countries such as Australia, New Zealand, and Türkiye present significant declines in their technical efficiency, reaching values of 0.83, 0.83, and 0.76, respectively, for the last period.

Table A3 breaks down the technological change component of the Malmquist-Luenberger index (MLTC). This component evaluates changes in the production frontier, reflecting technological advances. A value greater than 1 indicates increased productivity, suggesting good technology adoption, R&D activities, and vital innovation ecosystems. On the other hand, values of technological change less than 1 indicate a reduction in productivity caused by a technological setback, possibly due to barriers to innovation, including insufficient funding for R&D or limited industrial diversification.

The MLTC value added for 2021 is 1.56 compared to 1.01 in 2001, demonstrating a sustained annual growth rate in technology adoption and innovation. This underlines the critical role that technological progress has played in driving overall improvements in productivity. Countries such as Norway, Latvia, Ireland, Luxembourg, Iceland, Finland, Sweden, and the United States stand out for increases in their productivity driven by technical change that exceed the value of 2.0 points for 2021, indicating significant increases that can double their productivity.

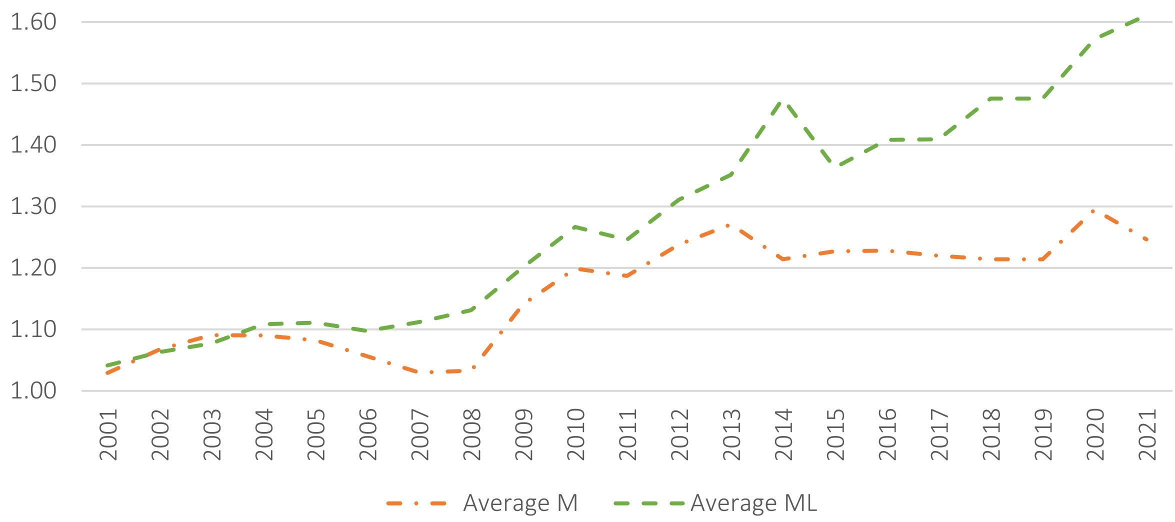

Figure 2. Comparison between M and ML index in OECD

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The Malmquist index without these variables was calculated better to understand the impact of undesirable outputs on productivity indices. Detailed results by country are provided in Table A4. Figure 2 compares the Malmquist index with undesirable outputs (ML) and without them (M). The ML index has consistently remained higher than the M index since 2004, indicating increased productivity when undesirable outputs are considered. Although DEA models typically reduce productivity when including such variables, this did not occur in this study due to the declining PM2.5 levels over the past 20 years. This finding confirms that reducing undesirable outputs over time positively influences productivity, as reflected in the index.

4. DISCUSSION

This study analyzes the growth of total factor productivity (TFP) in OECD countries, emphasizing both the role of technological development and environmental factors in driving productivity growth.

Technological advancements have been a primary driver of this productivity growth, as highlighted by Basu et al. (2001) and European Central Bank et al. (2021). The higher value of technical change in 2021 for OECD (1.56) compared to technical efficiency (1.05) shows that advancements in technology have significantly affected productivity rather than efficiency improvements. The significant productivity increase observed since 2006 is likely influenced by technological digitalization, as mentioned by Foster and He (2022). The study supports hypothesis 1, which posits that technological development drives total factor productivity (TFP) growth in OECD economies. Hypothesis 2 further refines this claim by emphasizing the critical role of R&D investments as a catalyst of technological development, showing a positive and significant correlation with patent generation (0.745). Findings align with Oh (2010), who similarly attributed productivity growth in OECD countries to technological progress.

The overall productivity growth observed in the study aligns with global trends in environmentally sensitive productivity analyses, suggesting that OECD countries have effectively integrated eco-efficiency practices into their economic policies. The modest efficiency gains identified are consistent with previous studies, such as Kumar (2006), who highlighted the challenges of achieving significant efficiency improvements in mature economies. This gradual improvement in technical efficiency reflects the incremental nature of such gains, supporting the findings of Emrouznejad and Yang (2016), who also reported steady efficiency improvements in environmentally conscious productivity measures.

When productivity is evaluated with and without environmental outputs, large differences in the results are observed. Typically, productivity indices decline when such variables are included; however, findings show the opposite. When the Malmquist Index was calculated without undesirable outputs, productivity appeared lower. This result stems from the declining trend in PM2.5 levels over the years, similar to Yang et al. (2021), demonstrating the model's capability to acknowledge countries' efforts in mitigating negative environmental impacts. This underscores the importance of incorporating environmental factors into efficiency assessments to achieve a more holistic and sustainable understanding of economic performance.

Moreover, hypothesis 3 introduces the idea that including environmental impacts, especially undesirable outputs like PM2.5 pollution, significantly alter productivity measurement. This concept is extended by hypothesis 4, which suggests that countries improving eco-efficiency – by mitigating undesirable outputs – experience greater productivity growth. The study demonstrates that technological development must be evaluated in conjunction with environmental factors, as these improvements are integral to maximizing productivity.

The heterogeneity observed in TFP growth across OECD countries can be attributed to variations in R&D investments, technological adoption, and eco-efficiency improvements. This suggests that the effectiveness of technological development and eco-efficiency initiatives varies significantly between countries, emphasizing the importance of tailored policy approaches.

This study highlights the necessity of fostering technological innovation to sustain productivity growth in OECD countries. Policymakers should prioritize investments in research and development to enhance technological capabilities further. However, it is crucial to recognize the study's limitations, including the use of aggregate data, which may obscure country-specific variations in productivity and efficiency improvements. Future research should explore specific technologies and innovations that significantly impact productivity and eco-efficiency. It is also vital to implement measures that enhance production factors to improve technical efficiency.

CONCLUSION

This study provides valuable insights into the drivers of total factor productivity (TFP) growth in OECD countries, with a particular focus on the role of technological development and environmental management. The findings confirm that technological advancements have played a dominant role in driving productivity growth over the past decades. The significant increase in technical change (1.56 in 2021) relative to technical efficiency (1.05) highlights that technological development, rather than improvements in efficiency, is responsible for much of the observed productivity growth. This underscores the importance of continuous investment in research and development (R&D) to sustain technological progress, as evidenced by the positive correlation between R&D investments and patent generation. Countries with higher investments in R&D and capital stock tend to exhibit better technological development.

The study also reveals that OECD countries have effectively integrated eco-efficiency practices into their economic policies, aligning with global trends in environmentally sensitive productivity analyses. Although efficiency improvements remain modest, they are consistent with the incremental nature of gains observed in mature economies. This finding reinforces the need for countries to adopt long-term strategies to gradually enhance technical efficiency. Moreover, the inclusion of undesirable outputs, such as PM2.5 pollution, in the productivity analysis further supports the argument that environmental management is an essential component of sustainable economic performance.

An essential contribution of this study is its demonstration of the substantial impact of environmental factors on productivity assessments. Contrary to traditional models where productivity indices tend to decline with the inclusion of environmental outputs, the results show that eco-efficiency measures, such as reducing PM2.5 pollution, have led to higher productivity levels. This highlights the importance of incorporating environmental metrics into productivity evaluations to provide a more comprehensive understanding of economic performance. Countries that successfully mitigate negative environmental impacts not only improve their eco-efficiency but also experience enhanced productivity growth.

Finally, the study points to the heterogeneity in TFP growth across OECD countries, driven by differences in R&D investment, technological adoption, and environmental management. This variability suggests that tailored policy approaches are necessary to address the unique challenges and opportunities faced by each country. These findings emphasize the need for policymakers to prioritize investments in R&D and foster both technological innovation and eco-efficiency policies to enhance productivity and ensure long-term economic sustainability.

AUTHOR CONTRIBUTIONS

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REFERENCES

1. Álvarez, I. C., Barbero, J., & Zofío, J. L. (2020). A data envelopment analysis toolbox for MATLAB. *Journal of Statistical Software, 95*(3), 1-49. https://doi.org/10.18637/JSS.V095.I03
2. Aparicio, J., Pastor, J. T., & Zofio, J. L. (2013). On the inconsistency of the Malmquist-Luenberger index. *European Journal of Operational Research, 229*(3), 738-742. https://doi.org/10.1016/J.EJOR.2013.03.031
3. Bampatsou, C., & Halkos, G. (2017). Energy and CO 2 emissions as the determinants of countries' productivity with different levels of economic development. *International Journal of Global Energy Issues, 40*(5), 277-293. Retrieved from https://ideas.repec.org/a/ids/ijgeni/v40y2017i5p277-293.html
4. Basu, S., Fernald, J. G., & Shapiro, M. D. (2001). *Productivity growth in the 1990s: Technology, utilization, or adjustment?* (NBER Working Paper Series No. 8359). Cambridge, MA: National Bureau of Economic Research. https://doi.org/10.3386/W8359
5. Bianchini, S., Damioli, G., & Ghisetti, C. (2023). The environmental effects of the "twin" green and digital transition in European regions. *Environmental and Resource Economics, 84*(4), 877-918. https://doi.org/10.1007/s10640-022-00741-7
6. Bosworth, S. J., & Snower, D. J. (2024). Technological advance, social fragmentation and welfare. *Social Choice and Welfare, 62*(2), 197-232. https://doi.org/10.1007/s00355-023-01484-0
7. Chung, Y. H., Färe, R., & Grosskopf, S. (1997). Productivity and undesirable outputs: A directional distance function approach. *Journal of Environmental Management, 51*(3), 229-240. https://doi.org/10.1006/JEMA.1997.0146
8. Ciarli, T., Kenney, M., Massini, S., & Piscitello, L. (2021). Digital technologies, innovation, and skills: Emerging trajectories and challenges. *Research Policy, 50*(7). https://doi.org/10.1016/J.RESPOL.2021.104289
9. Emrouznejad, A., & Yang, G.-l. (2016). A framework for measuring global Malmquist–Luenberger productivity index with CO2 emissions on Chinese manufacturing industries. *Energy, 115,* 840-856. https://doi.org/10.1016/J.ENERGY.2016.09.032
10. European Central Bank, Kindberg-Hanlon, G., Dieppe, A., & Francis, N. (2021). *Technology and demand drivers of productivity dynamics in developed and emerging market economies*. European Central Bank. https://doi.org/10.2866/691190
11. Foster, L., & He, A. (2022). Technology and productivity growth. *Business Economics, 57*(3), 111-119. https://doi.org/10.1057/S11369-022-00262-7
12. Fuglie, K. O., & Echeverria, R. G. (2024). The economic impact of CGIAR-related crop technologies on agricultural productivity in developing countries, 1961–2020. *World Development, 176,* Article 106523. https://doi.org/10.1016/J.WORLDDEV.2023.106523
13. Fulgenzi, R., Gitto, S., & Mancuso, P. (2024). Information and communication technology and labour productivity growth: A production-frontier approach. *Annals of Operations Research, 333*(1), 123-156. https://doi.org/10.1007/s10479-024-05818-8
14. Halkos, G., & Argyropoulou, G. (2021). Modeling energy and air pollution health damaging: A two-stage DEA approach. *Air Quality, Atmosphere and Health, 14*(8), 1221-1231. https://doi.org/10.1007/s11869-021-01012-y
15. Hawash, R., & Lang, G. (2020). Does the digital gap matter? Estimating the impact of ICT on productivity in developing countries. *Eurasian Economic Review, 10*(2), 189-209. https://doi.org/10.1007/S40822-019-00133-1
16. Herrero, S., Torrent, J., & Aguirre, K. (2023). *Robots and inequality in Latin America: Whose wages improve when automation is imported?* Research Square. https://doi.org/10.21203/RS.3.RS-3575772/V1
17. Kumar, S. (2006). Environmentally sensitive productivity growth: A global analysis using Malmquist–Luenberger index. *Ecological Economics, 56*(2), 280-293. https://doi.org/10.1016/J.ECOLECON.2005.02.004
18. Liang, C., & Wang, Q. (2023). The relationship between total factor productivity and environmental quality: A sustainable future with innovation input. *Technological Forecasting and Social Change, 191,* Article 122521. https://doi.org/10.1016/J.TECHFORE.2023.122521
19. Mao, C., Koide, R., Brem, A., & Akenji, L. (2020). Technology fore-

sight for social good: Social implications of technological innovation by 2050 from a Global Expert Survey. *Technological Forecasting and Social Change, 153,* Article 119914. https://doi.org/10.1016/J.TECHFORE.2020.119914

20. Misra, K., Memili, E., Welsh, D. H. B., Reddy, S., & Sype, G. E. (2015). Cross-country technology gap in Latin America Growth accounting and non-parametric approaches. *Cross Cultural Management: An International Journal, 22*(4), 630-648. https://doi.org/10.1108/CCM-04-2014-0043
21. Morales-Piñero, J., Niño-Muñoz, D., & Lesmes-Cardenas, D. (2022). Gestión pública o privada de las universidades: ¿Cuál es la opción más eficiente para una política pública en educación superior en Colombia? [Public or private management of universities: Which is the most efficient option for a public policy in higher education in Colombia?]. *Education Policy Analysis Archives, 30*(161). (In Spanish). https://doi.org/10.14507/epaa.30.7310
22. Nava, A. (2023). Nuevas tecnologías digitales y su impacto en el poder de negociación del mundo del trabajo: El caso de Argentina [New digital technologies and their impact on the bargaining power of the world of work. The case of Argentina]. *Revista de Sociologia, 108*(2), Article e3092. (In Spanish). https://doi.org/10.5565/rev/papers.3092
23. OECD. (2024a). *Main Economic Indicators – Complete database.* Main Economic Indicators (Database). https://doi.org/10.1787/data-00052-en
24. OECD. (2024b). *Main Science and Technology Indicators.* OECD Science, Technology and R&D Statistics (Database). https://doi.org/10.1787/data-00182-en
25. Oh, D. (2010). A global Malmquist-Luenberger productivity index. *Journal of Productivity Analysis, 34*(3), 183-197. https://doi.org/10.1007/s11123-010-0178-y
26. Pieri, F., Vecchi, M., & Venturini, F. (2018). Modelling the joint impact of R&D and ICT on productivity: A frontier analysis approach. *Research Policy, 47*(9), 1842-1852. https://doi.org/10.1016/J.RESPOL.2018.06.013
27. Pine, K. H., Hinrichs, M. M., Wang, J., Lewis, D., & Johnston, E. (2020). For impactful community engagement: Check your role. *Communications of the ACM, 63*(7), 26-28. https://doi.org/10.1145/3401720
28. Rivera, T. (2019). Efectos de la automatización en el empleo en Chile [Effects of automation on employment in Chile]. *Revista de Análisis Económico, 34*(1), 3-49. (In Spanish). https://doi.org/10.4067/S0718-88702019000100003
29. Schiff, M., & Wang, Y. (2023). North-south trade-related technology diffusion and the East Asia-Latin America productivity gap. *World Trade Review, 22*(3-4), 348-358. https://doi.org/10.1017/S1474745623000034
30. Tamberi, M. (2020). Productivity differentials along the development process: A "MESO" approach. *Structural Change and Economic Dynamics, 53,* 99-107. https://doi.org/10.1016/J.STRUECO.2020.01.006
31. Utku-İsmihan, F. M. (2019). Knowledge, technological convergence and economic growth: A dynamic panel data analysis of Middle East and North Africa and Latin America. *Quality & Quantity, 53*(2), 713-733. https://doi.org/10.1007/s11135-018-0785-7
32. Vallés-Giménez, J., & Zárate-Marco, A. (2016). Productivity and growth. In A. Marciano & G. Ramello (Eds.), *Encyclopedia of Law and Economics* (pp. 1-8). Springer. https://doi.org/10.1007/978-1-4614-7883-6_384-1
33. Vergès, C. (2022). Precarización laboral, desigualdad y nuevas tecnologías [Job insecurity, inequality and new technologies]. *Revista Colombiana de Bioética, 17*(1). (In Spanish). https://doi.org/10.18270/RCB.V17I1.3937
34. Xu, N., Zhang, F., & Xuan, X. (2021). Impacts of industrial restructuring and technological progress on PM2.5 pollution: Evidence from prefecture-level cities in China. *International Journal of Environmental Research and Public Health, 18*(10), Article 5283. https://doi.org/10.3390/IJERPH18105283
35. Yang, C., Li, T., & Albitar, K. (2021). Does energy efficiency affect ambient PM2.5? The moderating role of energy investment. *Frontiers in Environmental Science, 9.* https://doi.org/10.3389/fenvs.2021.707751
36. Yilanci, V. (2023). *Perspectives on Ecological Degradation and Technological Progress.* IGI Global. https://doi.org/10.4018/978-1-6684-6727-5
37. Zhang, Y., Shuai, C., Bian, J., Chen, X., Wu, Y., & Shen, L. (2019). Socioeconomic factors of PM2.5 concentrations in 152 Chinese cities: Decomposition analysis using LMDI. *Journal of Cleaner Production, 218,* 96-107. https://doi.org/10.1016/J.JCLEPRO.2019.01.322
38. Zhu, Q., Li, X., Li, F., Wu, J., & Zhou, D. (2020). Energy and environmental efficiency of China's transportation sectors under the constraints of energy consumption and environmental pollutions. *Energy Economics, 89,* Article 104817. https://doi.org/10.1016/J.ENECO.2020.104817

APPENDIX A

Table A1. Malmquist-Luenberger Index (ML)

DMU	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Australia	1.00	1.02	1.02	1.10	1.12	1.10	1.15	1.19	1.15	1.26	1.24	1.22	1.30	1.23	1.32	1.36	1.35	1.23	1.23	1.37	1.51
Austria	1.00	1.01	1.00	1.04	1.06	1.09	1.09	1.08	1.14	1.18	1.14	1.16	1.16	1.44	1.22	1.29	1.33	1.44	1.44	1.55	1.58
Belgium	1.02	1.08	1.09	1.09	1.08	1.04	1.03	1.02	1.07	1.10	1.06	1.08	1.13	1.29	1.12	1.14	1.13	1.29	1.29	1.35	1.40
Canada	0.99	1.00	1.00	1.03	1.04	1.08	1.12	1.15	1.23	1.26	1.28	1.27	1.34	1.61	1.37	1.51	1.46	1.61	1.61	1.65	1.83
Colombia	1.04	1.02	0.99	1.03	1.14	1.29	0.97	0.74	0.97	0.89	0.81	0.69	0.69	0.73	0.63	0.67	0.69	0.73	0.73	1.01	0.85
Czechia	1.04	1.08	1.11	1.16	1.15	1.18	1.17	1.20	1.25	1.27	1.28	1.30	1.32	1.48	1.28	1.31	1.32	1.48	1.48	1.53	1.50
Denmark	1.00	1.04	1.05	1.08	1.06	0.95	0.94	0.99	1.12	1.28	1.28	1.26	1.26	1.44	1.23	1.34	1.32	1.44	1.44	1.56	1.67
Estonia	1.03	1.16	1.21	1.27	1.29	1.29	1.38	1.38	1.46	1.41	1.00	1.14	1.45	1.55	1.58	1.68	1.74	1.55	1.55	1.55	1.54
Finland	1.06	1.06	1.05	1.14	1.14	1.11	1.26	1.33	1.29	1.30	1.34	1.43	1.50	1.85	1.60	1.72	1.84	1.85	1.85	2.06	2.16
France	1.01	1.06	1.04	1.06	1.06	1.04	1.03	1.03	1.09	1.10	1.09	1.11	1.14	1.40	1.22	1.23	1.25	1.40	1.40	1.46	1.50
Germany	1.04	1.11	1.14	1.17	1.19	1.09	1.06	1.06	1.12	1.07	1.05	1.08	1.12	1.27	1.12	1.15	1.15	1.27	1.27	1.33	1.36
Greece	1.03	1.06	1.00	1.04	1.13	1.03	0.97	1.03	1.16	1.39	1.55	1.78	1.83	1.84	1.94	1.86	1.76	1.84	1.84	1.86	1.62
Hungary	1.05	1.06	1.12	1.24	1.19	1.18	1.26	1.31	1.31	1.45	1.48	1.45	1.31	1.03	1.16	1.25	1.12	1.03	1.03	1.06	1.06
Iceland	1.07	1.23	1.12	1.14	1.17	1.19	1.26	1.28	1.61	1.77	1.61	1.54	1.80	1.99	1.68	1.84	1.74	1.99	1.99	2.10	2.28
Ireland	1.11	1.09	1.04	1.15	1.11	1.12	1.14	1.17	1.16	1.38	1.46	1.31	1.34	2.07	1.68	1.80	1.82	2.07	2.07	2.31	2.62
Israel	1.01	1.01	1.07	1.12	1.25	1.06	0.99	0.99	1.06	1.04	0.98	0.94	0.98	1.00	1.03	0.99	0.98	1.00	1.00	1.08	1.07
Italy	1.02	0.98	0.99	1.00	0.99	0.97	0.96	0.99	1.05	1.07	1.08	1.18	1.27	1.23	1.26	1.25	1.23	1.23	1.23	1.36	1.17
Japan	0.99	1.04	1.09	1.11	1.04	1.05	1.04	0.98	1.05	1.13	1.07	1.02	0.97	0.98	0.99	1.00	0.99	0.98	0.98	0.97	0.99
Korea	0.99	1.03	1.10	1.15	1.16	1.11	1.11	1.11	1.12	1.18	1.15	1.15	1.14	1.22	1.17	1.17	1.20	1.22	1.22	1.24	1.26
Latvia	0.95	1.03	1.06	1.00	0.99	1.18	1.18	1.31	1.43	1.64	1.57	2.07	1.80	2.59	2.03	2.26	2.36	2.59	2.59	2.52	2.67
Lithuania	1.05	1.07	1.08	1.02	1.03	0.81	0.93	1.01	1.37	1.50	1.43	1.27	1.42	1.47	1.33	1.35	1.44	1.47	1.47	1.47	1.55
Luxembourg	1.30	1.08	1.06	1.09	1.11	1.16	1.24	1.31	1.31	1.52	1.53	2.10	2.16	2.19	2.15	2.03	2.06	2.19	2.19	2.69	2.72
Mexico	1.03	0.94	0.94	0.92	0.88	0.87	0.87	0.88	0.88	0.92	0.88	0.94	0.98	1.42	1.13	1.01	1.19	1.42	1.42	1.49	1.11
The Netherlands	1.05	1.44	1.52	1.46	1.32	1.13	1.04	1.08	1.10	1.16	1.12	1.20	1.23	1.26	1.10	1.16	1.15	1.26	1.26	1.32	1.41
New Zealand	0.95	0.98	0.98	1.00	0.99	1.03	1.06	1.05	1.07	1.08	1.10	1.10	1.14	1.17	1.16	1.19	1.19	1.17	1.17	1.29	1.29
Norway	1.10	1.10	1.12	1.22	1.32	1.30	1.42	1.53	1.42	1.59	1.52	1.75	1.85	2.07	1.78	1.85	1.91	2.07	2.07	2.10	2.70
Poland	1.10			1.25	1.21	1.15	1.13	1.11	1.17	1.24	1.22	1.25	1.28	1.22	1.18	1.22	1.25	1.22	1.22	1.26	1.26
Portugal	1.01	1.07	1.16	1.18	1.21	1.21	1.19	1.18	1.28	1.34	1.48	1.74	1.90	1.52	1.80	1.78	1.63	1.52	1.52	1.56	1.55
The Slovak Republic	0.96	1.00	1.11	1.17	1.10	1.19	1.34	1.42	1.59	1.49	1.41	1.45	1.48	1.37	1.33	1.41	1.39	1.37	1.37	1.60	1.60
Slovenia	1.00	1.00	1.06	1.04	1.14	1.15	1.21	1.11	1.07	1.21	1.31	1.39	1.37	1.37	1.40	1.50	1.45	1.37	1.37	1.49	1.34
Spain	1.00	0.98	0.94	0.93	0.90	0.88	0.91	0.95	1.11	1.19	1.26	1.41	1.52	1.34	1.46	1.46	1.41	1.34	1.34	1.44	1.41
Sweden	1.07	1.08	1.07	1.16	1.14	1.12	1.26	1.33	1.31	1.35	1.35	1.53	1.55	1.89	1.65	1.79	1.76	1.89	1.89	2.06	2.24
Switzerland	1.22	1.11	1.07	1.07	1.07	1.06	1.02	0.98	0.96	1.02	1.01	1.07	1.10	1.42	1.16	1.24	1.32	1.42	1.42	1.49	1.59
Türkiye	1.13	1.08	1.15	1.03	1.01	0.98	1.00	1.04	1.17	1.09	0.99	1.01	0.98	1.04	0.93	0.94	0.92	1.04	1.04	1.16	0.98
The United Kingdom	1.04	1.05	1.04	1.09	1.08	1.09	1.08	1.13	1.23	1.27	1.27	1.30	1.29	1.21	1.21	1.18	1.18	1.21	1.21	1.36	1.36
The United States	1.04	1.07	1.10	1.16	1.15	1.21	1.21	1.29	1.39	1.46	1.44	1.49	1.54	1.93	1.65	1.78	1.75	1.93	1.93	1.90	2.21
Average OECD	1.04	1.06	1.08	1.11	1.11	1.10	1.11	1.13	1.20	1.27	1.25	1.31	1.35	1.48	1.36	1.41	1.41	1.48	1.48	1.57	1.61

Table A2. Technical Efficiency Change (MLTEC)

DMU	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Australia	0.99	0.97	0.99	0.93	0.89	0.89	0.87	0.85	0.86	0.85	0.87	0.80	0.81	0.89	0.85	0.89	0.89	0.89	0.89	0.87	0.83
Austria	1.02	0.97	0.94	0.97	1.02	1.06	1.11	1.10	1.02	1.01	0.98	0.97	0.96	0.99	1.01	1.02	1.03	0.99	0.99	1.04	1.02
Belgium	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.96	0.92	0.90	0.92	0.91	0.93	0.94	0.94	0.91	0.91	0.97	0.97
Canada	0.95	0.95	0.92	0.90	0.89	0.90	0.95	0.94	0.99	0.90	0.95	0.91	0.96	1.02	0.95	1.00	1.01	1.02	1.02	1.01	0.96
Colombia	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.71	0.64	0.64	0.83	0.71	0.71	1.00	1.00
Czechia	1.11	1.15	1.16	1.19	1.18	1.24	1.26	1.27	1.25	1.24	1.35	1.29	1.27	1.60	1.34	1.30	1.37	1.60	1.60	1.60	1.55
Denmark	0.99	1.00	1.00	1.00	1.00	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Estonia	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Finland	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.97	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
France	0.99	1.01	1.00	0.98	0.98	0.99	1.00	1.00	0.97	0.94	0.95	0.94	0.95	1.02	1.01	1.01	1.02	1.02	1.02	1.03	0.98
Germany	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.98	0.91	0.93	0.95	0.98	0.99	1.00	1.00	0.98	0.98	0.98	0.99
Greece	1.20	1.20	1.15	1.20	1.15	1.20	1.19	1.11	1.06	1.09	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20
Hungary	1.09	1.09	1.23	1.23	1.23	1.23	1.23	1.23	1.23	1.23	1.23	1.23	1.10	1.00	1.04	1.07	1.01	1.00	1.00	0.98	0.95
Iceland	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Ireland	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Israel	1.02	1.02	1.11	1.19	1.27	1.16	1.04	1.19	1.27	1.14	1.09	1.07	1.15	1.25	1.32	1.21	1.33	1.25	1.25	1.29	1.20
Italy	1.01	1.01	0.98	0.99	0.98	1.01	0.99	0.99	0.90	0.91	0.88	0.95	0.96	1.01	0.98	1.00	1.01	1.01	1.01	1.01	0.97
Japan	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Korea	0.99	1.05	1.12	1.13	1.16	1.17	1.18	1.15	1.20	1.29	1.20	1.16	1.15	1.49	1.37	1.18	1.34	1.49	1.49	1.44	1.41
Latvia	1.11	1.08	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11
Lithuania	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99
Luxembourg	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Mexico	1.15	1.15	1.15	1.05	1.01	0.92	0.86	0.94	0.86	1.00	0.98	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15
The Netherlands	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
New Zealand	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.82	1.00	0.94	0.91	0.82	0.82	0.79	0.76
Norway	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Poland	1.09	1.22	1.22	1.22	1.22	1.22	1.22	1.22	1.06	1.22	1.14	1.01	0.97	1.01	0.95	0.94	0.99	1.01	1.01	0.99	1.04
Portugal	1.32	1.32	1.32	1.32	1.32	1.32	1.28	1.23	1.18	1.19	1.18	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.27
The Slovak Republic	0.99	1.03	1.07	1.21	1.15	1.21	1.21	1.21	1.21	1.21	1.21	1.21	1.21	1.21	1.21	1.21	1.21	1.21	1.21	1.21	1.21
Slovenia	1.05	1.03	1.05	0.96	1.00	0.96	1.07	0.95	0.88	0.85	0.93	1.08	1.05	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08
Spain	1.08	1.07	1.05	1.01	0.99	0.98	0.98	1.00	1.04	1.08	1.05	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11
Sweden	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Switzerland	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Türkiye	1.11	1.10	1.11	1.11	1.02	1.11	1.08	1.11	0.98	0.91	0.84	0.89	0.84	0.87	0.83	0.81	0.81	0.87	0.87	0.95	0.83
The United Kingdom	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.98	0.99	1.00	1.00	1.00	1.00
The United States	0.98	1.01	1.06	1.01	0.98	1.03	1.02	1.07	1.11	1.13	1.13	1.09	1.08	1.10	1.06	1.08	1.08	1.10	1.10	1.09	1.10
Average OECD	1.03	1.04	1.05	1.05	1.04	1.05	1.05	1.05	1.03	1.03	1.03	1.04	1.03	1.05	1.04	1.03	1.05	1.05	1.05	1.06	1.05

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Table A3. Technical Change (MLTC)

DMU	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Australia	1.00	1.05	1.03	1.18	1.26	1.24	1.33	1.40	1.34	1.47	1.42	1.53	1.60	1.38	1.54	1.52	1.51	1.38	1.38	1.58	1.82
Austria	0.98	1.03	1.07	1.07	1.05	1.02	0.98	0.98	1.11	1.17	1.15	1.20	1.20	1.45	1.21	1.26	1.29	1.45	1.45	1.49	1.55
Belgium	1.02	1.08	1.09	1.09	1.08	1.04	1.03	1.02	1.08	1.14	1.15	1.19	1.23	1.41	1.21	1.21	1.20	1.41	1.41	1.38	1.45
Canada	1.04	1.05	1.09	1.15	1.16	1.20	1.18	1.22	1.23	1.40	1.35	1.40	1.39	1.58	1.44	1.51	1.44	1.58	1.58	1.64	1.90
Colombia	1.04	1.02	0.99	1.03	1.14	1.29	0.97	0.74	0.97	0.89	0.81	0.69	0.69	1.03	0.98	1.04	0.83	1.03	1.03	1.01	0.85
Czechia	0.94	0.94	0.95	0.97	0.98	0.95	0.93	0.94	1.00	1.03	0.95	1.01	1.04	0.93	0.96	1.01	0.96	0.93	0.93	0.95	0.97
Denmark	1.01	1.04	1.05	1.08	1.06	0.96	0.94	0.98	1.12	1.28	1.28	1.26	1.26	1.44	1.23	1.34	1.32	1.44	1.44	1.56	1.67
Estonia	1.03	1.16	1.21	1.27	1.29	1.29	1.38	1.38	1.46	1.41	1.00	1.14	1.45	1.55	1.58	1.68	1.74	1.55	1.55	1.55	1.54
Finland	1.06	1.06	1.05	1.14	1.14	1.11	1.26	1.33	1.29	1.34	1.34	1.43	1.50	1.85	1.60	1.72	1.84	1.85	1.85	2.06	2.16
France	1.03	1.05	1.04	1.08	1.08	1.06	1.02	1.03	1.12	1.17	1.14	1.17	1.20	1.37	1.20	1.22	1.23	1.37	1.37	1.42	1.53
Germany	1.04	1.11	1.14	1.17	1.19	1.09	1.06	1.06	1.12	1.09	1.15	1.17	1.17	1.30	1.14	1.15	1.15	1.30	1.30	1.35	1.37
Greece	0.86	0.88	0.87	0.87	0.98	0.86	0.82	0.93	1.09	1.27	1.30	1.49	1.53	1.54	1.62	1.55	1.47	1.54	1.54	1.55	1.36
Hungary	0.96	0.98	0.91	1.00	0.96	0.96	1.02	1.06	1.06	1.17	1.20	1.17	1.20	1.03	1.11	1.17	1.11	1.03	1.03	1.09	1.12
Iceland	1.07	1.23	1.12	1.14	1.17	1.19	1.26	1.28	1.61	1.77	1.61	1.54	1.80	1.99	1.68	1.84	1.74	1.99	1.99	2.10	2.28
Ireland	1.11	1.09	1.04	1.15	1.11	1.12	1.14	1.17	1.16	1.38	1.46	1.31	1.34	2.07	1.68	1.80	1.82	2.07	2.07	2.31	2.62
Israel	0.98	0.99	0.97	0.95	0.98	0.91	0.95	0.83	0.83	0.91	0.90	0.88	0.85	0.80	0.78	0.81	0.74	0.80	0.80	0.83	0.90
Italy	1.01	0.98	1.01	1.01	1.01	0.97	0.97	1.00	1.17	1.18	1.23	1.25	1.31	1.22	1.28	1.25	1.22	1.22	1.22	1.35	1.21
Japan	0.99	1.04	1.09	1.11	1.04	1.05	1.04	0.98	1.05	1.13	1.07	1.02	0.97	0.98	0.99	1.00	0.99	0.98	0.98	0.97	0.99
Korea	1.00	0.99	0.98	1.02	1.00	0.95	0.93	0.96	0.93	0.91	0.96	0.99	0.99	0.82	0.85	0.99	0.90	0.82	0.82	0.86	0.89
Latvia	0.86	0.95	0.95	0.89	0.89	1.06	1.05	1.18	1.28	1.47	1.41	1.86	1.61	2.32	1.82	2.03	2.11	2.32	2.32	2.26	2.40
Lithuania	1.05	1.07	1.08	1.02	1.03	0.81	0.93	1.01	1.37	1.50	1.43	1.27	1.42	1.47	1.33	1.35	1.44	1.47	1.47	1.47	1.56
Luxembourg	1.30	1.08	1.06	1.09	1.11	1.16	1.24	1.31	1.31	1.52	1.53	2.10	2.16	2.19	2.15	2.03	2.06	2.19	2.19	2.69	2.72
Mexico	0.90	0.82	0.82	0.87	0.87	0.95	1.01	0.94	1.02	0.92	0.90	0.81	0.85	1.24	0.99	0.88	1.03	1.24	1.24	1.29	0.97
The Netherlands	1.05	1.44	1.52	1.46	1.32	1.13	1.04	1.08	1.10	1.16	1.12	1.20	1.23	1.26	1.10	1.16	1.15	1.26	1.26	1.32	1.41
New Zealand	0.95	0.98	0.98	1.00	0.99	1.03	1.06	1.05	1.07	1.08	1.10	1.10	1.14	1.43	1.16	1.26	1.31	1.43	1.43	1.63	1.69
Norway	1.10	1.10	1.12	1.22	1.32	1.30	1.42	1.53	1.42	1.59	1.52	1.75	1.85	2.07	1.78	1.85	1.91	2.07	2.07	2.10	2.70
Poland	1.02			1.02	0.99	0.94	0.93	0.91	1.10	1.01	1.07	1.25	1.32	1.21	1.24	1.29	1.26	1.21	1.21	1.28	1.22
Portugal	0.77	0.81	0.88	0.90	0.92	0.92	0.93	0.96	1.08	1.12	1.25	1.33	1.45	1.16	1.37	1.36	1.24	1.16	1.16	1.19	1.22
The Slovak Republic	0.97	0.97	1.03	0.96	0.96	0.98	1.10	1.17	1.31	1.22	1.16	1.20	1.22	1.13	1.10	1.16	1.14	1.13	1.13	1.32	1.32
Slovenia	0.95	0.97	1.01	1.08	1.14	1.20	1.14	1.17	1.21	1.42	1.41	1.29	1.31	1.27	1.30	1.39	1.35	1.27	1.27	1.38	1.24
Spain	0.93	0.91	0.90	0.92	0.91	0.90	0.92	0.95	1.06	1.10	1.20	1.26	1.37	1.20	1.31	1.31	1.26	1.20	1.20	1.30	1.26
Sweden	1.07	1.08	1.07	1.16	1.14	1.12	1.26	1.33	1.31	1.35	1.35	1.53	1.55	1.89	1.65	1.79	1.76	1.89	1.89	2.06	2.24
Switzerland	1.22	1.11	1.07	1.07	1.07	1.06	1.02	0.98	0.96	1.02	1.01	1.07	1.10	1.42	1.16	1.24	1.32	1.42	1.42	1.49	1.59
Türkiye	1.01	0.98	1.03	0.93	0.98	0.88	0.93	0.93	1.20	1.20	1.18	1.14	1.17	1.19	1.12	1.16	1.14	1.19	1.19	1.22	1.19
The United Kingdom	1.04	1.05	1.04	1.09	1.08	1.09	1.08	1.13	1.23	1.27	1.27	1.30	1.29	1.21	1.22	1.21	1.19	1.21	1.21	1.36	1.36
The United States	1.06	1.06	1.04	1.15	1.18	1.17	1.19	1.21	1.25	1.30	1.27	1.37	1.42	1.75	1.56	1.64	1.62	1.75	1.75	1.73	2.01
Average OECD	1.01	1.03	1.04	1.06	1.07	1.05	1.07	1.09	1.17	1.23	1.21	1.27	1.31	1.42	1.32	1.37	1.35	1.42	1.42	1.50	1.56

Table A4. Malmquist Index (M)

DMU	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Australia	0.93	0.87	0.84	0.81	0.76	0.75	0.74	0.77	0.78	0.81	0.78	0.77	0.81	0.95	0.85	0.89	0.87	0.95	0.95	0.97	0.96
Austria	0.99	1.01	1.00	1.03	1.07	1.09	1.08	1.07	1.13	1.17	1.13	1.14	1.14	1.06	1.18	1.15	1.13	1.06	1.06	1.16	1.10
Belgium	1.00	1.07	1.08	1.06	1.04	1.03	0.99	0.97	1.02	1.05	1.00	1.01	1.05	0.98	1.04	1.03	1.01	0.98	0.98	1.07	1.02
Canada	0.96	0.98	0.97	0.92	0.88	0.84	0.81	0.81	0.89	0.83	0.83	0.79	0.80	0.86	0.82	0.87	0.86	0.86	0.86	0.95	0.85
Colombia	1.01	0.99	0.95	0.98	1.12	1.29	0.92	0.69	0.89	0.81	0.75	0.63	0.64	0.52	0.44	0.52	0.57	0.52	0.52	0.80	0.65
Czechia	1.08	1.16	1.20	1.25	1.26	1.31	1.30	1.33	1.40	1.44	1.51	1.54	1.57	1.51	1.52	1.57	1.58	1.51	1.51	1.65	1.65
Denmark	1.00	1.04	1.05	1.08	1.06	0.95	0.94	0.96	1.12	1.28	1.28	1.26	1.26	1.16	1.22	1.15	1.15	1.16	1.16	1.17	1.13
Estonia	1.03	1.16	1.21	1.27	1.29	1.29	1.38	1.38	1.46	1.41	1.00	1.12	1.44	1.55	1.58	1.68	1.74	1.55	1.55	1.55	1.49
Finland	1.00	1.04	1.05	1.04	1.03	1.03	0.97	0.95	1.01	1.03	1.02	1.00	1.06	0.99	1.11	1.05	1.03	0.99	0.99	1.01	1.02
France	0.98	1.02	1.03	1.01	0.99	0.96	0.91	0.89	0.96	0.95	0.93	0.93	0.96	0.89	1.00	0.98	0.95	0.89	0.89	0.98	0.86
Germany	1.04	1.11	1.14	1.17	1.19	1.08	1.02	0.98	1.06	0.99	0.93	0.93	0.96	0.86	0.94	0.92	0.91	0.86	0.86	0.89	0.89
Greece	0.96	1.00	0.97	1.01	1.07	1.03	0.98	1.04	1.12	1.40	1.74	2.11	2.17	2.09	2.29	2.15	2.01	2.09	2.09	2.09	1.75
Hungary	1.00	1.04	1.15	1.28	1.22	1.17	1.24	1.27	1.30	1.49	1.53	1.47	1.31	0.92	1.09	1.18	1.06	0.92	0.92	0.98	0.95
Iceland	1.04	1.23	1.12	1.14	1.15	1.17	1.18	1.17	1.61	1.77	1.61	1.54	1.80	1.55	1.42	1.46	1.47	1.55	1.55	1.52	1.54
Ireland	1.11	1.08	1.04	1.06	1.05	1.04	1.02	0.98	1.14	1.38	1.46	1.28	1.30	1.26	1.30	1.27	1.22	1.26	1.26	1.46	1.50
Israel	1.01	1.01	1.07	1.12	1.25	1.06	0.99	0.99	1.06	1.04	0.98	0.94	0.98	0.96	1.03	0.96	0.98	0.96	0.96	1.07	0.99
Italy	0.99	0.96	0.97	0.96	0.95	0.92	0.90	0.93	1.02	1.04	1.06	1.17	1.29	1.19	1.31	1.27	1.23	1.19	1.19	1.34	1.05
Japan	0.98	1.03	1.09	1.11	1.01	0.97	0.95	0.89	1.02	1.10	1.04	0.99	0.89	0.82	0.87	0.89	0.88	0.82	0.82	0.82	0.82
Korea	0.97	1.16	1.46	1.64	1.68	1.44	1.31	1.24	1.31	1.42	1.48	1.48	1.54	1.48	1.47	1.42	1.42	1.48	1.48	1.47	1.45
Latvia	0.95	1.03	1.06	1.00	0.99	1.18	1.17	1.31	1.43	1.64	1.57	2.07	1.80	2.59	2.03	2.26	2.36	2.59	2.59	2.52	2.67
Lithuania	1.05	1.07	1.08	1.02	1.03	0.81	0.91	1.00	1.37	1.50	1.43	1.27	1.42	1.47	1.32	1.31	1.41	1.47	1.47	1.47	1.55
Luxembourg	1.30	1.08	1.06	1.08	1.11	1.15	1.12	1.16	1.21	1.52	1.53	2.10	2.16	2.19	2.15	2.03	2.06	2.19	2.19	2.69	2.72
Mexico	1.03	0.95	0.93	0.87	0.81	0.81	0.79	0.81	0.78	0.82	0.79	0.87	0.92	1.38	1.10	0.97	1.15	1.38	1.38	1.45	1.07
The Netherlands	1.04	1.44	1.52	1.46	1.32	1.12	0.95	0.99	1.00	1.09	1.06	1.13	1.17	0.91	0.94	1.01	0.99	0.91	0.91	0.94	0.96
New Zealand	0.89	0.88	0.82	0.79	0.76	0.79	0.81	0.82	0.93	0.93	0.93	0.92	0.90	0.75	0.83	0.81	0.78	0.75	0.75	0.78	0.78
Norway	1.04	1.06	1.12	1.10	1.14	1.20	1.14	1.16	1.09	1.14	1.17	1.19	1.19	1.04	1.03	0.99	1.03	1.04	1.04	1.01	1.27
Poland	1.19	1.42	1.41	1.39	1.33	1.21	1.06	1.03	1.10	1.21	1.16	1.21	1.25	1.17	1.12	1.21	1.27	1.17	1.17	1.22	1.26
Portugal	1.02	1.07	1.17	1.20	1.24	1.30	1.31	1.31	1.41	1.47	1.66	2.02	2.20	1.72	2.01	1.98	1.82	1.72	1.72	1.80	1.69
The Slovak Republic	0.97	1.06	1.21	1.25	1.20	1.28	1.41	1.51	1.76	1.59	1.50	1.61	1.64	1.50	1.47	1.54	1.51	1.50	1.50	1.74	1.77
Slovenia	1.00	1.00	1.06	1.04	1.14	1.15	1.21	1.11	1.07	1.21	1.31	1.39	1.37	1.37	1.40	1.50	1.45	1.37	1.37	1.49	1.34
Spain	0.98	0.96	0.92	0.89	0.84	0.80	0.79	0.86	1.11	1.20	1.34	1.52	1.66	1.29	1.54	1.51	1.42	1.29	1.29	1.44	1.37
Sweden	0.98	1.02	1.05	1.05	1.06	1.00	0.96	0.94	1.03	1.02	1.00	1.01	1.02	0.93	0.96	0.93	0.90	0.93	0.93	0.94	0.92
Switzerland	1.22	1.11	1.07	1.01	1.00	1.01	0.92	0.86	0.89	0.91	0.90	0.89	0.88	0.82	0.85	0.83	0.84	0.82	0.82	0.84	0.84
Türkiye	1.26	1.19	1.24	1.06	0.92	0.85	0.89	0.94	1.15	1.00	0.86	0.87	0.83	0.93	0.78	0.79	0.77	0.93	0.93	1.04	0.87
The United Kingdom	0.99	1.00	1.01	1.00	0.99	0.98	0.95	0.98	1.11	1.13	1.15	1.13	1.11	0.91	0.99	0.94	0.92	0.91	0.91	1.08	0.98
The United States	1.04	1.11	1.12	1.08	1.03	1.00	1.03	1.10	1.33	1.37	1.33	1.27	1.26	1.12	1.18	1.18	1.16	1.12	1.12	1.19	1.15
Average OECD	1.03	1.07	1.09	1.09	1.08	1.06	1.03	1.03	1.14	1.20	1.19	1.24	1.27	1.21	1.23	1.23	1.22	1.21	1.21	1.29	1.25

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