The Determinants of Long-Run Economic Growth: An Empirical Analysis of OECD Economies using the Solow Growth Model and the Penn World Table.

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Abstract

This study addresses three primary objectives: (i) to examine the determinants of long-run economic growth (the 'what' question), (ii) to provide evidence for why certain countries outpace others in terms of growth rates (the 'why' question), and (iii) to analyse the contributions of various factors influencing economic growth (the 'how' question). Our findings demonstrate that an augmented Solow Growth Model serves as a valuable paradigm for describing economic growth patterns across thirty-eight OECD countries from 1996 to 2019. Through empirical analysis, we highlight the utility of this model in understanding the dynamics of economic growth and its application within diverse economic contexts. We conducted two distinct analyses that individually and collectively reinforce the assumptions of the Solow Model. First, using a regression approach, we found that the proximate causes of growth – input factors and productivity – demonstrate strong predictive power over the growth process of countries over time. Our analysis reveals that a 1 percent increase in the logged growth rate of total factor productivity (TFP) corresponds to a 1.47 percent increase in the logged growth rate of GDP per capita. Similarly, human capital contributes to growth, albeit with a slightly smaller magnitude (1.05 percent). These results corroborate findings from Abu-Qarn and Abu-Bader (2007), emphasising the significant predictive power of these variables in economic growth. Abu-Qarn and Abu-Bader also underscore the importance of incorporating human capital as a direct input factor under the assumption of constant returns to scale, a methodological approach that we adopted in our analysis. Second, the growth accounting method revealed consistent results: all factors positively impact growth, with TFP once again emerging as the primary driver of growth, followed by human capital, corroborating findings by Klenow and Rodríguez-Clare (1997). Additionally, our analysis supports convergence hypothesis amongst OECD countries, where poorer nations are closing the gap with their richer counterparts by growing at a faster rate, as demonstrated by Kremer, Willis, and You (2001). Other significant findings of our research include: (i) small differences in growth rates lead to pronounced differences in income levels over time, and (ii) longer time horizons are associated with more stable, higher growth rates.

Acknowledgements

I dedicate this dissertation to my beloved mother, who departed to eternity in 1996. Most importantly, all praise be to Jesus Christ, my Lord and my God, Who has carried me through four arduous years, being the guiding Light when I needed it most.

1 Introduction

Why do certain countries grow faster than others? *What* are the determinants of long-run economic growth, and *how* is this growth achieved? This paper examines the factors influencing economic growth measured by *GDP*[1] *per capita* using an augmented version of the Solow Growth Model. We introduce new data, timelines, and assumptions that uniquely combine to shed light on these questions. Whilst existing literature extensively discusses the role of the Solow Model in OECD[2] countries, our objective is to contribute new empirical evidence by affirming its *usefulness* in understanding countries' long-run growth patterns. The *'why'*, *'what'*, and *'how'* questions posed above represent the three primary objectives of this paper. We aim to answer these questions, which embody the core objectives of our study.

This dissertation draws on the following theoretical frameworks:

i) *Neo-Classical Growth Theory* – which attributes growth to supply-side components such as labour productivity, employment (workforce) size, and production factors.

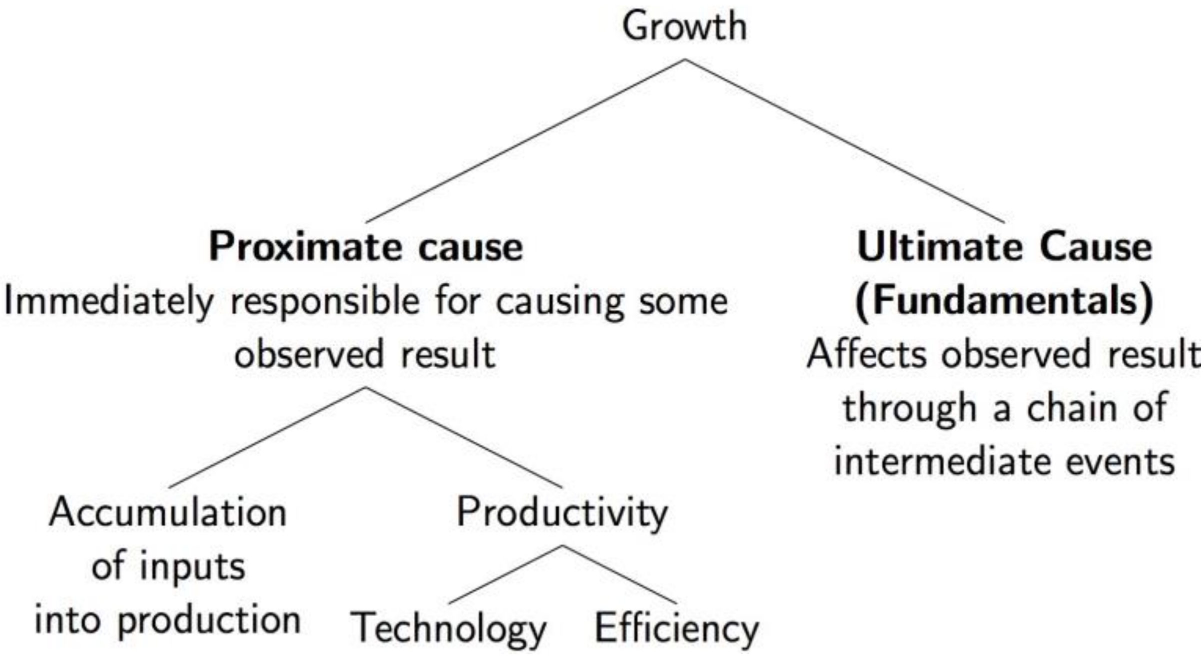
ii) *Endogenous Growth Theory* – which emphasises the significance of human capital and technological advancement.

As such, this paper focuses solely on the economic determinants of growth, known as *'proximate' causes*, whilst omitting consideration of *'ultimate' sources* such as non-economic factors including culture, geography, institutions, or luck hypotheses (Acemoglu, 2009). The structure of this economic paper aligns with the principles outlined by Neugeboren (2005) and Greenlaw (2006).

[1] Gross Domestic Product

[2] The Organisation for Economic Co-operation and Development

Figure 1



Source: University of Kent, ECOX6001 Economic Growth module

2 Literature Review

2.1 Economic Theory of Growth

Five established theories explain the growth process of countries over time. *Mercantilism*, which emerged between the 16th and 18th centuries in Western Europe, was characterised by the accumulation of gold and treasures, alongside export-intensive policies aimed at increasing net exports. Mercantilism employed a dual approach: it sought to keep production costs low on the supply side whilst leveraging favourable trade balances to address low wages on the demand side.

Adam Smith (1776) critiqued mercantilists for their protectionist zealotry and reliance on monopolistic interests. Instead, Smith proposed the *Classical Theory*, emphasising specialisation, division of labour, and economies of scale, which fostered capital accumulation and reinvestment of profits. A strength of this theory was its acknowledgement of certain limits, encompassing various domains such as demographic, environmental, social, and political factors, thus reflecting empirical realism. Importantly, *Classical Theory* attributes major shortcomings to the *Neo-Classical Theory*, including the exclusion of *'soft' variables* – complex and difficult-to-quantify factors – resulting in bias in its postulates (Saeed, 2008).

In the 20th century, *Keynesian Theory* (Keynes, 1936) delineated the role of aggregate demand in growth during the short and medium runs. In the long run, equilibrium in aggregate demand is achieved through labour and asset markets (the invisible hand) and government macroeconomic policies (the visible hand of government intervention) (Dutt, 2010). A caveat of this theory lies in its tendency to heavily rely on fiscal policy, whilst at the opposite end of the spectrum, placing extreme emphasis on monetary measures (Vickrey, 1948).

Despite its limitations, *Keynesian Theory* finds significant applicability in the field of macrodynamic economics, where mathematical principles support its validity. For instance, *Keynesian Theory* demonstrates mathematically that the propensity to invest can either surpass or fall short of the inducement to save, representing two unrelated groups of people with distinct sets of motives. This undermines *Say's Law*, which posits that supply creates its own demand. The implication is crucial because it suggests that mass overproduction and significant unemployment are theoretically impossible concepts (Kurihara, 1969).

Neo-Classical Theory, pioneered by Solow (1956), proposed the Solow Growth Model, where long-run growth results from constant returns to scale in output functions and capital formation. Main features of the Solow Model encompass a favourable association between capital and GDP, and concepts regarding capital stock depreciation, diminishing marginal returns, and steady state. The Solow Model has been widely debated, refuted, and contested on multiple grounds, including the assumption of exogenous and constant technological progress across countries (McQuinn and Whelan, 2006). Despite criticisms, the Solow Model remains fundamental to our analysis, and we focus on key aspects of Solow theory to avoid unnecessary complexity.

Lucas (1988) emphasises the crucial importance of human capital and technological change in propelling economic growth. However, a critique of Lucas's model arises from two conflicting interpretations regarding the role of knowledge at both *aggregate* and *individual* levels. Whilst accumulating human capital infinitely without diminishing returns seems illogical at an *individual* level, the optimisation problem in Lucas's model primarily reflects returns at the *individual* level, posing challenges in influencing *aggregated* knowledge.

Mankiw, Romer, and Weil (1992) demonstrate that, under the assumption of constant population growth and capital accumulation, poor countries tend to experience faster economic growth compared to rich countries, eventually converging in terms of standards of living. Their analysis underscores the critical role of human capital: incorporating human capital into the regression significantly enhances their results, aligning more closely with observed realism. Conversely, excluding human capital leads to findings that are inconsistent with Solow's predictions.

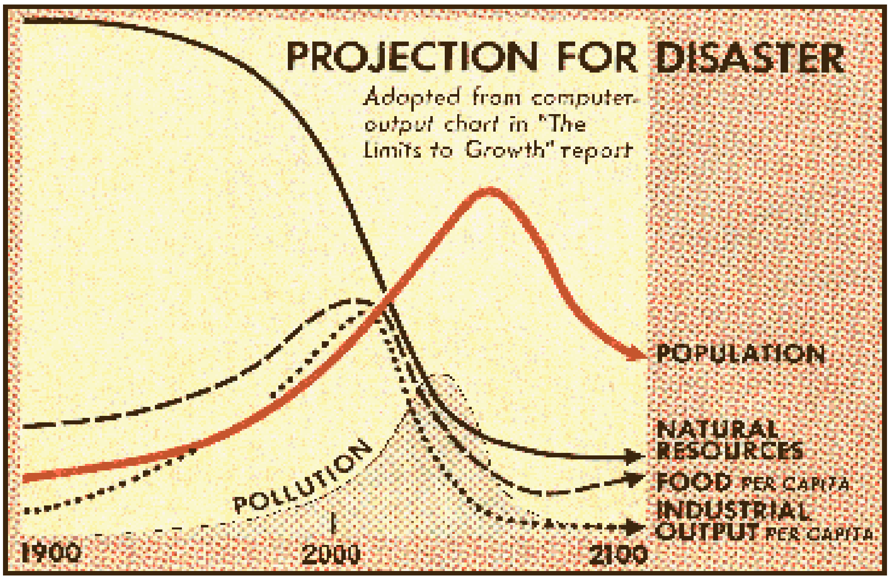
This is supported by evidence from Klenow and Rodríguez-Clare (1997), who show that education, as an independent component in the growth process, augments labour, physical capital, and TFP. The intuition behind this is that an educated labour force enhances efficiency by generating and implementing innovative ideas and technologies.

“Knowledge flows […] are invisible; they leave no paper trail by which they may be measured and tracked.” (Paul R. Krugman, 1991, p. 53)

Endogenous Theory, popularised by Romer (1986; 1990; 1994), posits that knowledge and technology are endogenous factors in the growth process, with innovation being the primary driver of growth. According to this theory, the *creation of new ideas* leads to higher productivity because these *ideas are non-rival* across space and time, and *innovation is only partially excludable* since its creator cannot prevent others from using it without permission.

Furthermore, Barro and Sala-i-Martin (1992; 1995; 1997) elucidate the *convergence* process towards a *steady state*, wherein output and capital grow at the same rate whilst technological progress remains stagnant (at a ‘resting point’). This scenario leads to no increase in growth per capita. Researchers have extensively debated the convergence hypothesis, which has garnered significant academic interest, although empirical findings remain inconclusive.

Illustration of The Limits to Growth



Source © "The Limits to Growth" (1972): *Time Magazine*, 24th January 1972

Theoretical frameworks are only as effective as the assumptions they rely on, and each framework has its own set of strengths and limitations in modelling empirical reality. Insights from behavioural economics and social sciences complement these modern theories, emphasising *incentives* and *motivations for innovation*, along with perspectives from economic history that highlight the necessity of change over time. Importantly, researchers have intricately interwoven the strengths and limitations of these theories within their inherent nature.

In a related exploration, "The Limits to Growth" (1972), a seminal study based on computer model simulations exploring the consequences of relationships between the Earth and human systems, investigated fundamental factors that decide and eventually constrain sustainable growth across countries. Their study suggests that our current understanding of growth may evolve significantly, particularly in relation to *sustainability*, in the decades and centuries ahead.

Finally, evidence-based studies and literature substantiate the adoption of Solow's framework focusing on input factors and factor accumulation, as well as the integration of human capital (*Endogenous Theory*), which we use in our paper to inform our modelling approach. The subsequent section will examine empirical evidence that builds upon and challenges these theoretical foundations.

2.2 Empirical Evidence

The theoretical and empirical framework proposed by Mankiw, Romer, and Weil (1992) has had a tremendous impact on cross-country growth empirics in the literature. Consequently, a wealth of evidence emerged from studies such as Islam (1995), Caselli, Esquivel, and Lefort (1996), Lee, Pesaran, and Smith (1997), and Bond, Hoeffler, and Temple (2001), which tested and challenged various aspects of Mankiw's findings.

Islam critiqued Mankiw's methodology on two primary grounds. Firstly, employing a single-cross section regression does not adequately account for unobservable country-specific effects within the aggregate production function, leading to *omitted variable bias*. Secondly, Ordinary Least Squares (OLS) estimation is inadequate in addressing potential *shocks* to the aggregate production function. If these shocks, which may arise from changes in production technology, endowments, or institutions, are correlated with the independent variables, the OLS estimators could become biased and inconsistent. To address these issues, Islam proposed a panel data approach as a more robust alternative.

Due to the inadequacies of the Solow Growth Model in explaining African growth, numerous studies have concentrated on the region. Easterly and Levine (1997) highlight the strong, positive impact of education levels on Sub-Saharan African growth whilst identifying *assassinations*, *political* and *foreign exchange instabilities*, and *inadequate infrastructure* as negatively affecting Africa's growth between 1960 and 1988.

Additionally, Hoeffler (2002) challenges the notion of the "African dummy", suggesting fundamental differences in Africa's growth compared to other regions. *Ethnic fractionalisation* emerges as a potential explanatory variable for these differences, although Hoeffler discredits the "African dummy" theory due to methodological flaws. Using the Sys-GMM[3] estimator, Hoeffler's model finds the "African dummy" insignificant, attributing African growth to *low investment levels* and *high population growth*.

Nkurunziza and Bates (2003) support Hoeffler's findings, refining her model to demonstrate the statistical significance of *political stability* and *regime type* in affecting economic growth and addressing remaining variance in Hoeffler's regression. These insights

[3] Generalised Method of Moments

underscore the limitations of Solow modelling, which fails to account for *political conflict* and *violence* associated with *low investment levels* in Africa. Tsangarides (2005) further supports these findings by highlighting the significance of *institutions* and *political power* in determining African growth.

Notably, the available empirical evidence *directly* informs the use of panel data analysis, human capital factors, and growth accounting techniques in this paper. Furthermore, our study aims to fill *a gap in the literature* by affirming the *usefulness* of the Solow Growth Model predictions through evidence-based approaches and analyses. Finally, Table 1 presents other representative studies, providing a chronological summary that offers insights into the evolution of empirical studies on the *determinants* of economic growth over time.

Table 1 Empirical Studies on the *Determinants* of Economic Growth

Study	Key Findings
Stern (1991)	Presents an argument on defining a knowledge-producing sector, suggesting Research and Development (R&D) as a challenging yet vital component.
Barro (1996)	Identifies evidence for conditional convergence and highlights factors like lower fertility, government expenditure, and inflation influencing growth rates.
Barro and Sala-i-Martin (2004)	Compiles a comprehensive compendium covering economic growth aspects, including accounting methodologies and cross-section estimations.
Arvanitidis, Petrakos, and Pavleas (2007)	Discusses economic performance, emphasising investment, innovation, R&D, trade openness, and Foreign Direct Investment as key factors varying across countries.
Ciccone and Jarocinski (2008)	Highlights sensitivity of Bayesian and Classical Linear Regression approaches to income differences across datasets, recommending adjustments for data quality.
Moral-Benito (2009; 2010)	Utilises Bayesian Model Averaging to identify drivers of growth, including prices of investment goods, geographical distances, and political rights.
Bhalla (2012)	Provides historical context and a list of economic growth determinants, including currency undervaluation, middle-class dynamics, and fortune considerations.
Mirestean and Tsangarides (2016)	Introduces a method addressing model dynamics, endogeneity, and uncertainty, supporting Neo-Classical Theory.
Khare and Mugenya (2021)	Reviews literature on growth determinants in developing versus developed countries, exploring convergences and divergences in economic growth factors.

3 Method

3.1 Data

Our sample[4] comprises a balanced panel with 912 observations spanning twenty-four years from 1996[5] to 2019 (T = 24). It consists of thirty-eight developed countries, specifically all current constituent OECD countries as of May 2024. The data is sourced from the Penn World Table database (PWT 10.01, the latest version), hereinafter referred to as PWT. This national-accounts dataset is valuable for measuring GDP growth of countries over time, having collected data since 1950, with the latest version extending up to 2019. Whilst several datasets were initially considered, the decision to utilise PWT over other datasets was deemed most appropriate as it facilitates comparisons of GDP per capita and productivity and provides data for a longer timeframe compared to other sources.

Moreover, we opted for PWT over other datasets to minimise inconsistencies arising from variations, particularly in *income per capita*, which can result from discrepancies in GDP and population figures, as noted in the literature (Bosworth and Collins, 2003; Ciccone and Jarocinski, 2008; Dalgaard and Hansen, 2015). These discrepancies extend to other variables, such as *average hours worked*, which would have added layers of uncertainty and complexity to interpreting the results consistently.

Whilst this decision helps contain sources of variation by limiting the analysis to a large, well-established dataset, it also reflects a weakness in being ambivalent to other potentially useful data sources. Recognising this limitation, we address the impact of different time horizons on our findings in Section *'Robustness Checks'*, specifically exploring shorter periods and outliers. We also discuss broader limitations related to dataset variation in Section *'Limitations'*.

3.2 Variables

Several models were tested, and this process will be discussed in Section *'Empirical Strategy'*. The Preferred Model consists of five variables, all expressed as *Average Annual Growth Rates (AAGR)* in natural logarithms (base e), i.e., *logarithmic growth rates*, as detailed[6] in Table 2. *GDP-per-Capita* is a continuous dependent variable and serves as the focal point of the analysis, being determined by a constant, four regressors, and a residual.

[4] By *sample* we refer to the OECD countries *relative* to all 195 UN-recognised countries. The sample comprises all thirty-eight OECD countries, representing a *population* of developed economies.

[5] The data starts in 1995; however, the first year is omitted in *growth rate* calculations since our variables represent *Annual Average Growth Rates (AAGR)*. When discussing *levels*, we typically reference data from 1995 in this paper.

[6] For instance, by *'GDP-per-Capita'*, we mean the logged AAGR of *GDP-per-Capita*.

Table 2 The Five Variables of the Preferred Model (Model I)

Variable name in PWT	Variable Definition	Variable renamed in the Preferred Model	Equivalent in the Cobb-Douglas Production Function
rdgpna	Real GDP at constant 2017 national prices, in million 2017 US$	*GDP-per-Capita*	$\frac{Y}{N}$, where Y = rdgpna N = pop
hc	Human capital index, based on years of schooling and returns to education	*Human-Capital*	h , where h = hc
avh	Average annual hours worked by persons engaged	*Labour-Population-ratio*	$\frac{L}{N}$, where L = avh *x* emp N = pop
emp	Number of persons engaged, in millions	*Labour-Population-ratio*	$\frac{L}{N}$, where L = avh *x* emp N = pop
pop	Population, in millions	*Labour-Population-ratio*	$\frac{L}{N}$, where L = avh *x* emp N = pop
rnna	Capital stock at constant 2017 national prices, in million 2017 US$	*Capital-GDP-ratio*	$\frac{K}{Y}$, where K = rnna Y = rgdpna
rtfpna	TFP at constant national prices, where US rtfpna in 2017 = 1	*TFP*	A, where A = TFP

Source: PWT, version 10.01. Data from 1995 to 2019. *Note:* The *Labour-Population-ratio* (or '*total hours worked-population ratio*') is a single variable in the Preferred Model and is derived from the *'avh'*, *'emp'*, and *'pop'* variables from the PWT dataset. All variables are expressed as logged AAGR.

3.3 Descriptive Statistics

Between 1996 and 2019, the OECD countries experienced an *aggregated* AAGR of *GDP-per-Capita* of 2.13 percent, as shown in Table 3. Ireland achieved the highest *GDP-per-Capita* with an AAGR at 21.90 percent in 2015, whilst Estonia witnessed the lowest at -15.29 percent in 2009, coinciding with the end of the Financial Crisis.

Additionally, 90 percent[7] of OECD countries have a logged AAGR of *GDP-per-Capita* lower than 5.32 percent, indicating that only 10 percent of the countries have growth rates above this. Similarly, 25 percent of observations have a logged AAGR of *GDP-per-Capita* lower than 0.83 percent, implying that the top 75 percent of OECD countries have growth rates above this value.

[7] We calculated percentiles (90th, 75th, and 25th, respectively), but they are not shown in Table 3 to keep the layout simple and clean.

Table 3 *Descriptive Statistics* of Model I

Stats	*GDP-per-Capita*	*Human-Capital*	*Labour-Population-ratio*	*Capital-GDP-ratio*	*TFP*
Mean	2.13	0.59	0.26	-0.01	0.42
Max.	21.90	1.71	8.98	16.86	15.87
Min.	-15.29	-0.48	-17.71	-16.83	-10.09
Std. Dev.	3.05	0.35	2.23	2.68	2.10
Obs.	912	912	912	912	912

Source: PWT 10.01. Period from 1996 to 2019. Author's calculations.
Note: All variables are expressed as logged AAGR in *percentages*.

Table 4 below presents the *maximum* and *minimum* values associated with the findings shown in Table 3 above. Upon close examination, several observations emerge:

- A negative *Labour-Population-ratio* (-17.71 percent) may have negatively impacted Estonia's *GDP-per-Capita* (-15.29 percent) during the Financial Crisis.
- Two factors, one positive (16.86 percent) and one negative (-10.09 percent), may have influenced Lithuania's *GDP-per-Capita* in 2009.
- New Zealand's *Human-Capital* (-0.48 percent) may have been sensitive to the Financial Crash in 2007.
- Lastly, a unique event may have affected Ireland's growth in 2015. Khder, Montornès, and Ragache (2020) confirm this observation, attributing the reason for this event to the recalculation of intangible assets within multinationals.

This illustrates that important findings can be derived from simple statistical analysis.

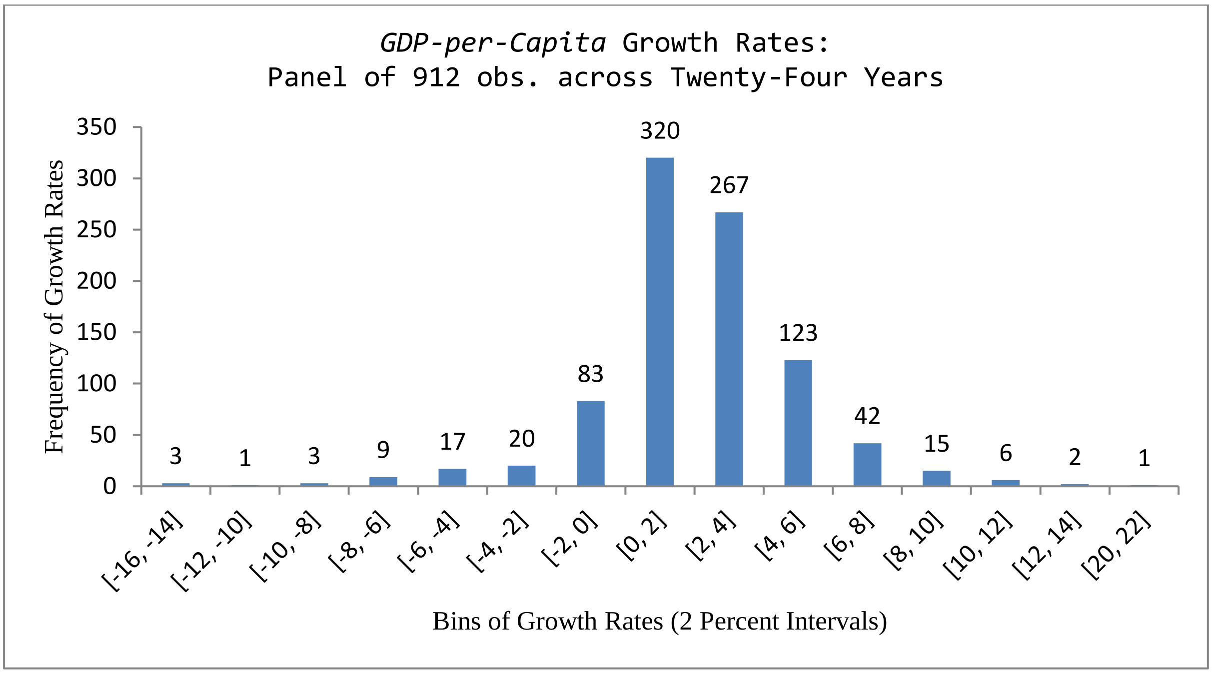
Table 4 Statistics of Model I, by Country

Stats	*GDP-per-Capita*	*Human-Capital*	*Labour-Population-ratio*	*Capital-GDP-ratio*	*TFP*
Max.	IRL (2015)	EST (1998)	EST (2011)	LTU (2009)	IRL (2015)
Min.	EST (2009)	NZL (2007)	EST (2009)	IRL (2015)	LTU (2009)

Source: PWT 10.01. Period from 1996 to 2019. Established by the author.

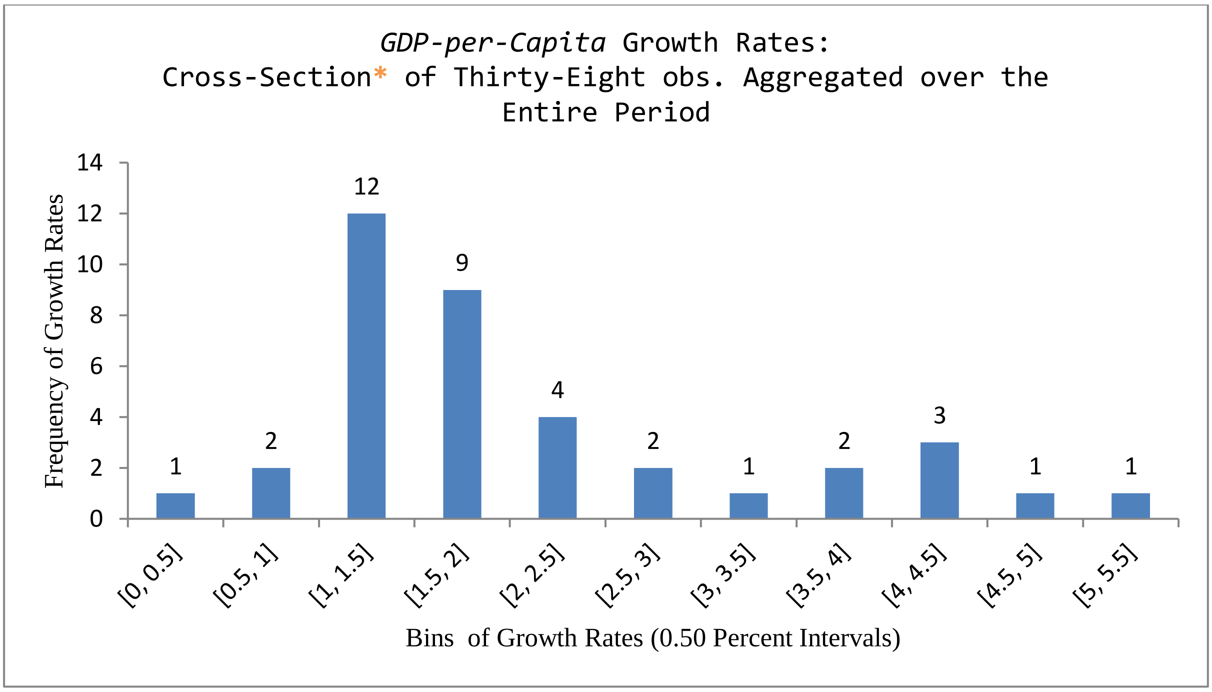
The histograms below illustrate the variation in *GDP-per-Capita* across the OECD. The first distribution reveals that most OECD countries experienced growth rates between 0 and 6 percent from 1996 to 2019. Approximately 9 percent (eighty-three observations) of countries experienced growth rates between -2 and 0 percent during this period. The second distribution considers each country as a single observation across the same period. It shows that most OECD countries grew at rates between 1 and 2 percent between 1996 and 2019.

Figure 2 Histogram of Growth Rates for Thirty-Eight OECD Countries between 1996 and 2019



Source: PWT 10.01. Author's calculations. *Note:* Interval Bounds are between [-16, -14] and [20, 22]. Intervals with *zero* occurrences are not shown.

Figure 3 Histogram of Growth Rates for Thirty-Eight OECD Countries between 1996 and 2019



Source: PWT 10.01. Author's calculations. *Note:* Interval Bounds are between [0, 0.5] and [5, 5.5].
*Single observation for each OECD country across the entire period.

3.4 Empirical Strategy

Initially, we explored a *cross-section* approach using *OLS*. This approach, combined with the AAGR method, resulted in one observation per country across the twenty-four-year period (Model II). However, Model II was considered weaker compared to the Preferred Model because it provides only a snapshot of growth over time. Conversely, we found a *panel* approach to be more robust due to the temporal dimension it captures. This is important because countries often experience bursts of accelerated growth at different periods, and their growth paths vary over time.

Subsequently, we considered a *panel* approach. Firstly, we examined *Pooled OLS*[8] and *Least Squares Dummy Variable (LSDV)* specifications (Models III and IV, respectively). Despite passing desirable model diagnostic tests, these models were less useful due to their reliance on the OLS estimator, which may introduce upward bias and potentially violate the *Best Linear Unbiased Estimator (BLUE)* condition, as suggested by Caselli, Esquivel, and Lefort (1996). If the BLUE condition does not hold, the OLS estimators become biased and inconsistent, affecting the validity of inference.

Secondly, to address these concerns, we explored 'proper' *panel* approaches such as *Fixed Effects (FE)* and *Random Effects (RE)* Models[9]. Theoretically, our panel has a shorter time span (fewer time periods, T) with a larger number of observations (N). In such cases, the distinction between FE and RE becomes trivial; however, FE models are typically preferred due to their simpler assumptions. Furthermore, the Hausman test rejected[10] the Null Hypothesis (H_0) that the *Generalised Least Square* estimators of RE are consistent, indicating that FE models are indeed appropriate. Therefore, both *theoretical* and *practical* econometrics support the *Fixed Effects Model (FEM)* as the Preferred Model (Model I) henceforth. [The *Random Effects Model (REM)* represented Model V in the analysis].

The chosen functional form is a *Log-Log* regression, denoted by Equation (1), which serves as the preferred estimation strategy for the Model I. The variables used in this regression are outlined in Table 2. In this context, α (alpha) represents the intercept parameter for the FEM, remaining constant across all entities (countries) and time periods, indicating *time*- and *entity-invariance*. The β's (betas) represent the slope parameters associated with the four control variables, indicating the elasticities of *GDP-per-Capita* with respect to these regressors, assuming the variables are greater than zero. As discussed in the *'Variables'* Section, all variables in the Preferred Model represent *logged growth rates*; however, for stylistic and simplification purposes, variable names have been kept straightforward.

[8] Also known as *Constant Coefficient Panel Data Model*.
[9] Multiple 'proper' *panel* models were evaluated, including some incorporating '*time*' and '*entity*' effects to ensure robustness and comprehensive analysis.
[10] At the 5 percent significance level (P-value of 0.0188).

$$\text{GDP-per-Capita}_{it} = \alpha + \beta_1 \text{ Human-Capital}_{it} + \beta_2 \text{ Labour-Population-ratio}_{it} + \beta_3 \text{ Capital-GDP-ratio}_{it} + \beta_4 \text{ TFP}_{it} + \mathcal{E}_{it} \quad (1)$$

where i = 1, 2, …, N, and t = 1, 2, …, T.

Additionally, we adopt a Cobb-Douglas production function of the following form:

$$Y = K^{\alpha} (EhL)^{1-\alpha} = AK^{\alpha} (hL)^{1-\alpha} \quad (2)$$

This choice was informed by relevant literature (Hall and Jones, 1999; Bosworth and Collins, 2003; Koopman and Wacker, 2023), which highlights the empirical success and theoretical foundations of the Cobb-Douglas specification in modelling production processes. Specifically, these studies emphasise the *flexibility* and *intuitive* nature of the Cobb-Douglas form in capturing key aspects of economic growth and production dynamics.

Table 5 Cobb-Douglas Production Function

Component	Meaning
Y	GDP (total output)
A	Productivity[11], i.e., $A \equiv E^{1-\alpha}$
E	Labour-augmenting technology[12]
h	Human Capital *per worker*
K	Physical Capital stock
L	Labour[13]
α	Constant[14], where $0 < \alpha < 1$

'*EhL*' represents the quality-adjusted labour. ['*N*' represents the population].

Using algebraic notation, GDP per capita ($\frac{Y}{N}$) is expressed as a function of productivity (A), physical capital-GDP ratio ($\frac{K}{Y}$), human capital (h), and labour-population ratio ($\frac{L}{N}$), as follows:

- Divide both sides of the production function given by Equation (2) by Y^{α} to get:

$$\frac{Y}{Y^{\alpha}} = Y^{1-\alpha} = A \left(\frac{K}{Y}\right)^{\alpha} (hL)^{1-\alpha} \quad (3)$$

11 Or residual TFP, representing the efficiency with which input factors are used.
12 Or the technology level.
13 Defined as the *'total hours worked'*.
14 The elasticity of GDP (output) with respect to capital.

- Raise both sides to the power of $\frac{1}{1-\alpha}$ to get:

$$Y = A^{\frac{1}{(1-\alpha)}} \left(\frac{K}{Y}\right)^{\frac{\alpha}{(1-\alpha)}} hL \quad (4)$$

- Divide both side by population, N, to get Equation (5):

$$\frac{Y}{N} = A^{\frac{1}{(1-\alpha)}} \left(\frac{K}{Y}\right)^{\frac{\alpha}{(1-\alpha)}} h\frac{L}{N} \quad (5)$$

The last equation requires careful consideration. The left-hand side does not represent the product between productivity (A) and *factors of productions*. Due to the physical capital-GDP ratio ($\frac{K}{Y}$) ratio, GDP (Y) cannot simultaneously represent *output* on the left-hand side and *input* on the right-hand side. GDP (output) is not a factor of production for GDP (output). In other words, $\left(\frac{K}{Y}\right)^{\frac{\alpha}{(1-\alpha)}} h\frac{L}{N}$ cannot be treated as factors of production. Equation (5) *implicitly*[15] reconfigures the Cobb-Douglas production function (Equation (2)) by weighing its component parts differently. This formulation allows us to derive the *unobservable* productivity from the observable variables, as demonstrated mathematically in Section *'Growth Accounting'*.

4 Empirical Results

4.1 Results of Model I

As discussed in the *'Method'* Section, Model I, which employs a Fixed Effects estimation, is designated as the Preferred Model. This section examines the proximate drivers of *GDP-per-Capita* growth using Model I, providing insights into its results.

Due to having positive sign coefficients, the *Constant* and all explanatory variables exhibit a positive impact, aligning with our expectations, the Solow Growth Model, and empirical studies (Knigth, Loayza, and Villanueva, 1993; Caselli, 2005). This initial finding of positive coefficients is as expected, making sense both *economically* and *statistically*. Additionally, the *Constant* and the four control variables are statistically significant at the 1 percent level. With individual T-statistics being significant and P-values approaching zero, the regressors are highly significant at the 1 percent level, minimising the likelihood of these results occurring by chance.

[15] Said differently, Equation (5) is an *implicit* function of Equation (2).

Table 6 Model I, *Fixed Effects* estimator, using 912 obs.

Dependent variable: *GDP-per-Capita*					
Regressor	Coeff.	Std. Error	T-ratio	P-value	Sig. Level
Constant	0.0067	0.0018	3.7320	0.0006	***
Human-Capital	1.0483	0.2021	5.1870	<0.0001	***
Labour-Population-ratio	0.8956	0.0852	10.520	<0.0001	***
Capital-GDP-ratio	0.4452	0.1611	2.7630	0.0089	***
TFP	1.4704	0.1699	8.6540	<0.0001	***
LSDV R-squared	0.9526				
Within R-squared	0.9439				
F Test Statistic: F(4, 37)	993.91			<0.0001	

Source: PWT 10.01. Period from 1996 to 2019. Author's calculations.
Note: All variables are expressed as logged AAGR. *** p<0.01; ** p<0.05; * p<0.1

The LSDV R-squared indicates that Model I explains 95.26 percent of the variability in *GDP-per-Capita*, whilst the Within R-squared is similar at 94.39 percent. This suggests that the best-fit line closely matches the sample data. More precisely, it indicates *i)* that the variation in the four regressors is a good predictor of variation in *GDP-per-Capita*, and *ii)* the proportion of total variation in *GDP-per-Capita* that is accounted for by variation in the regressors. Similar magnitudes for the R-squared were found by Abu-Qarn and Abu-Bader (2007). Their study, which examined twenty-three OECD countries using a panel approach, estimated an Adjusted R-squared between 91 to 98 percent, depending on the estimators used. This finding supports the robustness of our model, demonstrating strong predictive power, as evidenced by the close correlation between the variation in the regressors and GDP-per-Capita. Additionally, the similarity in the R-squared values between our findings and those of Abu-Qarn and Abu-Bader further reinforces the reliability of our model.

The magnitudes of coefficients reveal insightful findings. *Ceteris paribus*, the *TFP* (1.47) has the highest effect on *GDP-per-Capita*, which is 40 percent higher *relative* to the second most important contributor to growth, which is *Human-Capital* (1.05). When holding all other factors constant, *Labour-Population-ratio* (0.90) is 100 percent more impactful on *GDP-per-Capita* than *Capital-GDP-ratio* (0.45). Finally, *TFP* (1.47) is approximately 3.27 times more significant in determining *GDP-per-Capita* compared to *Capital-GDP-ratio* (0.45). Table 7 presents the interpretation associated with the coefficients of Model I.

Table 7 Interpretation of the Coefficients of Model I

β_i	Coeff.	Computed	Meaning & Impact
β_1	1.05	$\frac{\Delta ln(Y)}{\Delta X_1}$	A 1 percent increase in the logged growth rate of *Human-Capital* will lead to a 1.05 percent increase in the logged growth rate of *GDP-per-Capita*.
β_2	0.90	$\frac{\Delta ln(Y)}{\Delta X_2}$	A 1 percent increase in the logged growth rate of *Labour-Population-ratio* will lead to a 0.90 percent increase in the logged growth rate of *GDP-per-Capita*.
β_3	0.45	$\frac{\Delta ln(Y)}{\Delta X_3}$	A 1 percent increase in the logged growth rate of *Capital-GDP-ratio* will lead to a 0.45 percent increase in the logged growth rate of *GDP-per-Capita*.
β_4	1.47	$\frac{\Delta ln(Y)}{\Delta X_4}$	A 1 percent increase in the logged growth rate of *TFP* will lead to a 1.47 percent increase in the logged growth rate of *GDP-per-Capita*.

Source: PWT 10.01. Period from 1996 to 2019. Author's calculations.

Labour and *Capital* variables:

Both coefficients for the *labour* and *capital* ratios appear lower than initially expected. However, considering these are amongst the most developed economies in the world, their GDP is substantial. By contrast, the Cobb-Douglas production function satisfies a crucial Solow assumption: the concave function displays *diminishing Marginal Product of Capital (MPK)*[16]. The first derivative of the production function shows that as capital increases, GDP, and consequently *GDP-per-Capita,* increases. However, as capital rises, MPK will decrease due to higher values of capital, causing the second derivative to become negative. This effect arises from the interaction of factors in the multiplicative expression and the elasticity of capital (α) being smaller than 1 ($0 < \alpha < 1$). Therefore, growth will eventually taper off. Capital alone, or capital deepening, cannot be *solely* responsible for long-run growth.

Despite the *Labour-Population-ratio* (0.90) being twice as impactful on *GDP-per-Capita* as the *Capital-GDP-ratio* (0.45), historical data paints a less optimistic picture. As highlighted in Table 2, the *Labour-Population-ratio* is composed of three variables – *average hours worked (avh)* times *employment (emp)*, representing the numerator, and *population (pop)* for the denominator. Over the period from 1995 to 2019, employment and population *levels* have steadily increased in the OECD. However, average hours worked have declined by approximately 6.63 percent during this period.

Notably, there are four outliers with significantly higher average hours worked above the OECD average, all representing North American countries (Chile, Colombia, Costa Rica, and Mexico). Despite this, average hours worked have fallen by 17.23 percent in Chile and 11.97 percent in Costa Rica, whilst Colombia and Mexico have remained stable.

[16] MPK is defined as the derivative of GDP (output) with respect to capital.

As shown in Figure 4, these changes in average hours worked are critical because they contribute to the numerator of the *Labour-Population-ratio*, which is shrinking over time. This trend reduces the overall impact of the *Labour-Population-ratio* on *GDP-per-Capita*.

Figure 4

Declining Trends in Average Annual Hours Worked per Worker

Source: PWT 10.01

The vast literature documents the persistent negative trends in average hours worked, which extend well before 1995[17] and beyond 2019, adding further complexity to the matter. In the OECD, average hours worked decreased by approximately 0.5 percent per year between the 1870s and 2000s (Boppart and Krusell, 2016). In Europe, the *productivity slowdown* witnessed between 1973/74 and 1995 was largely driven by high unemployment, falling labour force participation rates, and declining working hours (Timmer and Ark, 2005).

This trend is supported by evidence that labour force growth has been sluggish since the 2000s, characterised by slower prime-age population growth, slower growth in educational attainment, and aging populations (Moss, Nunn, and Shambaugh, 2020). Post-COVID-19, structural shifts continue to extend the long-run trend predating the 2019 pandemic, driven by reduced average hours worked within certain worker groups like young adults, men, and men with young children, consistently observed across Europe (Astinova et al., 2024).

Human Capital and *TFP* variables:

Notably, our modelling underscores *TFP* as a primary driver of growth, aligning with empirical findings by Aiyar and Dalgaard (2005) and Klenow and Rodriguez-Clare (1997). Aiyar and Dalgaard affirm that cross-country differences in GDP per capita are largely

[17] According to *OECD data*, the average annual hours worked *per worker* have fallen by 12.91 percent, from 2,029 in 1970 to 1,767 in 2019, reflecting a negative trend observed across the entire OECD economy.

attributable to variations in TFP, whilst Klenow and Rodriguez-Clare demonstrate that differences in *TFP growth rates* explain a substantial portion of *GDP per worker growth* variations across countries.

Regarding *Human-Capital*, our Model I provides support for Endogenous Theory, positing that human capital accumulation drives long-run growth (Lucas, 1988; Mankiw, Romer, and Weil, 1992). However, our findings diverge from studies such as those by Islam (1995), Caselli, Esquivel, and Lefort (1996), and Pritchett (1996), which do not find significant relationships between growth and education. Eckstein, Sarid, and Tamir (2019) shed light on this discrepancy, revealing a positively correlated and statistically significant *level effect* of human capital on GDP per capita, alongside a lack of *growth effect*. This suggests that whilst human capital has a positive impact, its magnitude in terms of GDP per capita growth may be more modest. To address these inconsistencies further, future research could explore *quality-based measures* for aggregate human capital, as suggested by Hanushek and Woessmann (2012; 2015).

The estimations and specifications discussed above confirm the robustness of our regression model, with Model I accurately representing OECD economies. This was validated through a series of econometric tests, systematically ensuring analysis quality across all modelling stages, consistent with econometric theory (Greene, 8th Edition, 2017; Wooldridge, 7th Edition, 2019). Identified issues such as heteroscedasticity (highlighted by the *Breusch-Pagan* and *Wald* tests with P-value < 0.0001) and autocorrelation (noted by the *Durbin-Watson* and *Wooldridge* tests with P-value < 0.0001) are well-documented in panel data analysis due to *inherent data characteristics*. To address these challenges, we employed robust (clustered) standard errors and utilised the *Arellano* correction method for panel data.

4.2 Growth Accounting

To distinguish between Model I and the growth accounting exercise derived directly from the PWT data, this section utilises notation associated with the Cobb-Douglas production function as described in Tables 2 (last Column) and 5, and Equations (2) and (5). This approach does *not directly* stem from Model I but is instead derived through growth accounting methodology using the PWT dataset. Using Equation (5), we decomposed the *growth rate* of GDP per capita into different constituent parts, as shown below.

$$g_{\frac{Y}{N}} = \frac{1}{1-\alpha} g_A + \frac{\alpha}{1-\alpha} g_{\frac{K}{Y}} + g_h + g_{\frac{L}{N}} \tag{6}$$

Re-arranging yields the productivity growth rate.

$$g_A = (1-\alpha)\left[g_{\frac{Y}{N}} - \frac{\alpha}{1-\alpha} g_{\frac{K}{Y}} - g_h - g_{\frac{L}{N}}\right] \tag{7}$$

Equation (7) contains one unknown, the growth rate of productivity, which we calculated assuming a standard $\alpha = \frac{1}{3}$; all other variables are *observable* from the PWT data.

We desire formulations as shown in Equations (6) and (7) for two reasons. Firstly, by assuming productivity growth, we emphasise the significance of productivity, as a more productive economy *inherently* leads to increased GDP per capita and promotes physical capital accumulation, thereby enabling greater capital *per worker*. These formulations assign *different weights* to contributions to GDP per capita because productivity enhancements positively affect both physical capital and GDP per capita growth. Secondly, this approach opens avenues for future exploration, allowing us to test our methodology by *statistically* re-estimating Model I with productivity derived through growth accounting, rather than solely from the PWT dataset. This presents an intriguing direction for further research and analysis.

As depicted in Table 8, OECD economies grew at an average rate of 2.13 percent per year, largely driven by productivity growth. It is noteworthy that the selected sample presented here had a lower GDP per capita than the OECD average, indicating that certain countries experienced strong[18] growth. In *the bottom part* of Table 8, we illustrate how the four factors contributed to GDP per capita growth. Both numerically and visually, the last column representing *productivity growth* emerges as the primary driver behind the growth experienced by OECD countries. In this sample, United States' productivity growth contributed by a factor of 104.57 percent to GDP per capita growth. Across the OECD, the Czech Republic led in productivity growth (115.81 percent), followed by Iceland (109.95 percent), whilst Italy's productivity growth (-252.09 percent) stood as the most negative contributor, not only in terms of productivity but across all factors within the OECD economy.

Table **8** Growth Accounting Overview

Economy	Average Annual Growth Rates				
	GDP per Capita	Human Capital	Labour-Population ratio	Physical Capital-GDP ratio	Productivity
Australia	1.53	0.09	0.13	-0.13	0.92
Canada	1.34	0.38	0.22	0.53	0.31
France	1.09	0.53	0.01	0.15	0.32
Germany	1.25	0.21	0.17	0.14	0.53
Japan	0.84	0.41	-0.39	0.22	0.47
United Kingdom	1.42	0.50	0.27	-0.01	0.44
United States	1.54	0.26	-0.12	-0.43	1.07
OECD	2.13	0.59	0.26	-0.01	0.86

[18] Leaders in GDP per capita growth were the Baltic states: Lithuania (5.25 percent), Latvia (4.96 percent), and Estonia (4.42 percent), whilst laggards were Japan (0.84 percent), and Italy (0.35 percent), as shown in Appendix, Table 2A.

Economy	GDP per Capita	Human Capital	Labour-Population ratio	Physical Capital-GDP ratio	Productivity
	Percentage Contributions to GDP per Capita Growth				
Australia	-	5.84	8.58	-4.39	89.97
Canada	-	28.49	16.50	19.96	35.05
France	-	48.22	0.57	7.05	44.16
Germany	-	16.57	13.84	5.66	63.93
Japan	-	48.52	-46.29	13.40	84.37
United Kingdom	-	34.93	19.09	-0.35	46.33
United States	-	16.92	-7.67	-13.82	104.57
OECD	-	36.17	12.86	6.21	44.75

Source: PWT 10.01. Period from 1996 to 2019. Author's calculations. *Note:* All figures are expressed in *percentages*.

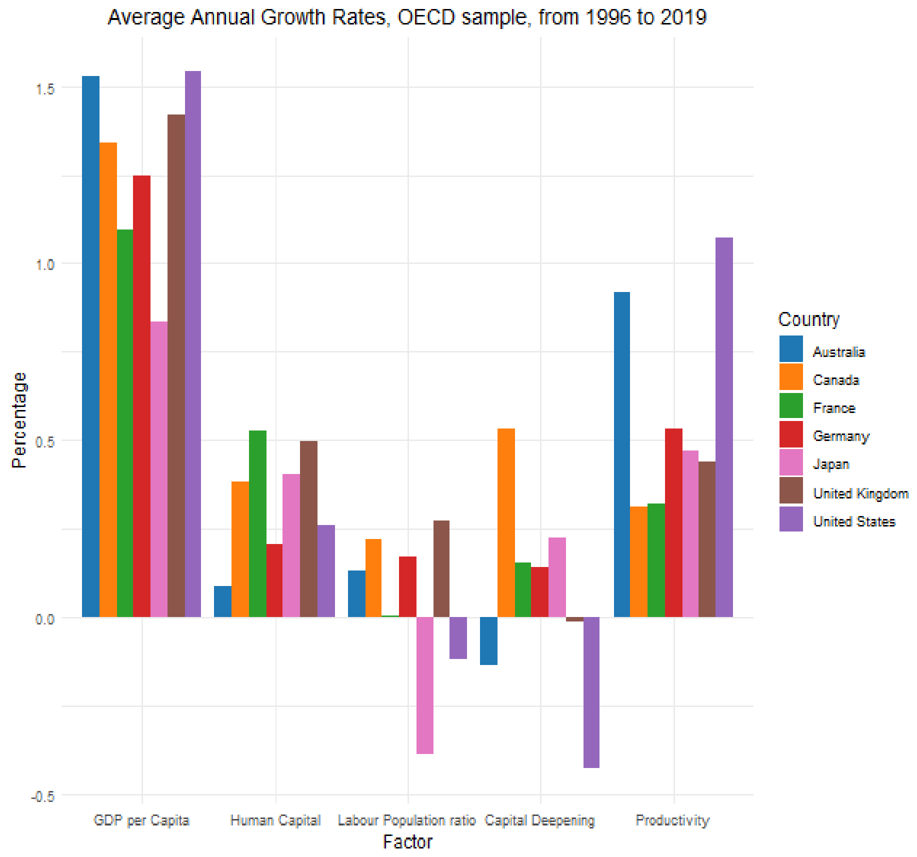
Whilst Table 8 summarises representative growth accounting results, we have expressed these findings in several ways to enhance intuition, as shown graphically below. Like Table 8, Figure 5 displays single observation growth rates across the entire period by country, whilst Figure 6 offers an alternative visualisation of the same outcome. These visualisations correspond to the *top part* of Table 8. Our findings highlight that Japan has experienced *negative labour-population ratio growth rates* averaging -0.39 percent per year, corroborating results from existing literature and studies (OECD, 2016).

Additionally, Figures 7, 8, and 9 correspond to the *bottom part* of Table 8. Figure 7 elucidates how the contributions of factors were computed: each factor was divided by GDP per capita and multiplied by its associated weight, if applicable. Consequently, each bar in the chart (corresponding to a country) sums up to one hundred percent across the four factors. Visually, the variability of factors can be observed, with very few factors in the sample exhibiting negative contributions to GDP per capita growth. Productivity (indicated in 'purple') emerges as the predominant driver, followed by human capital (in 'salmon/coral'), aligning with the findings of Model I. Figures[19] 8 and 9 are analogous to Figures 5 and 6, providing an alternative perspective on the *bottom part* of Table 8 and complementing Figure 7.

[19] However, instead of illustrating *growth rates*, they represent *percentage contributions*.

Figure 5

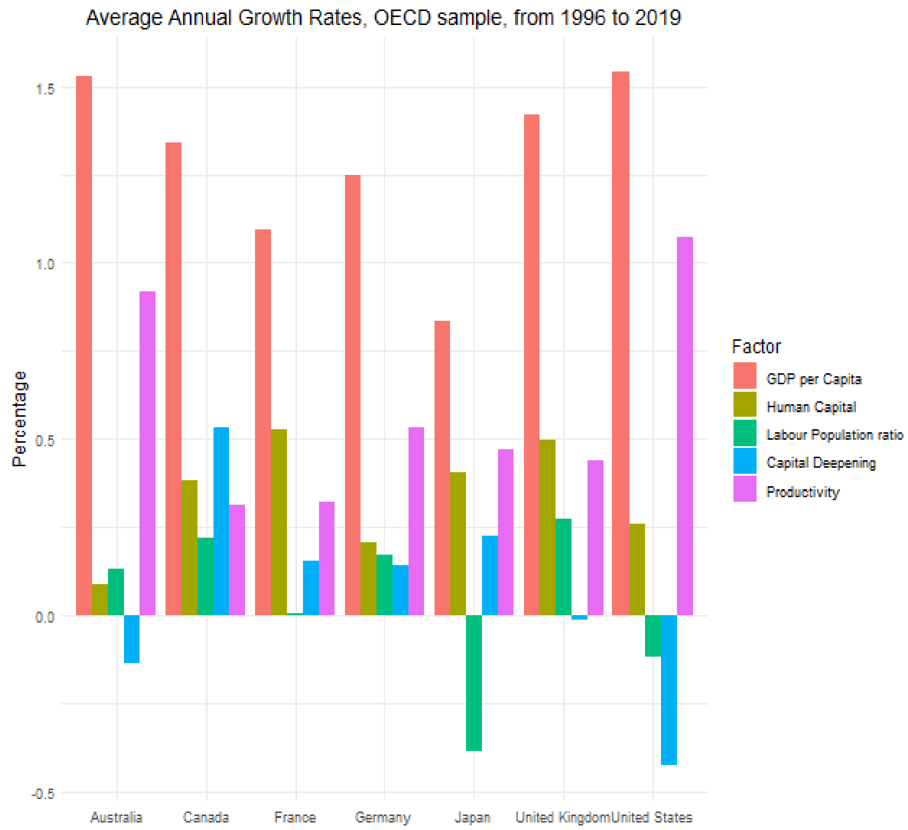
Growth Rates in OECD Economies



Source: PWT 10.01. Author's calculations.

Figure 6

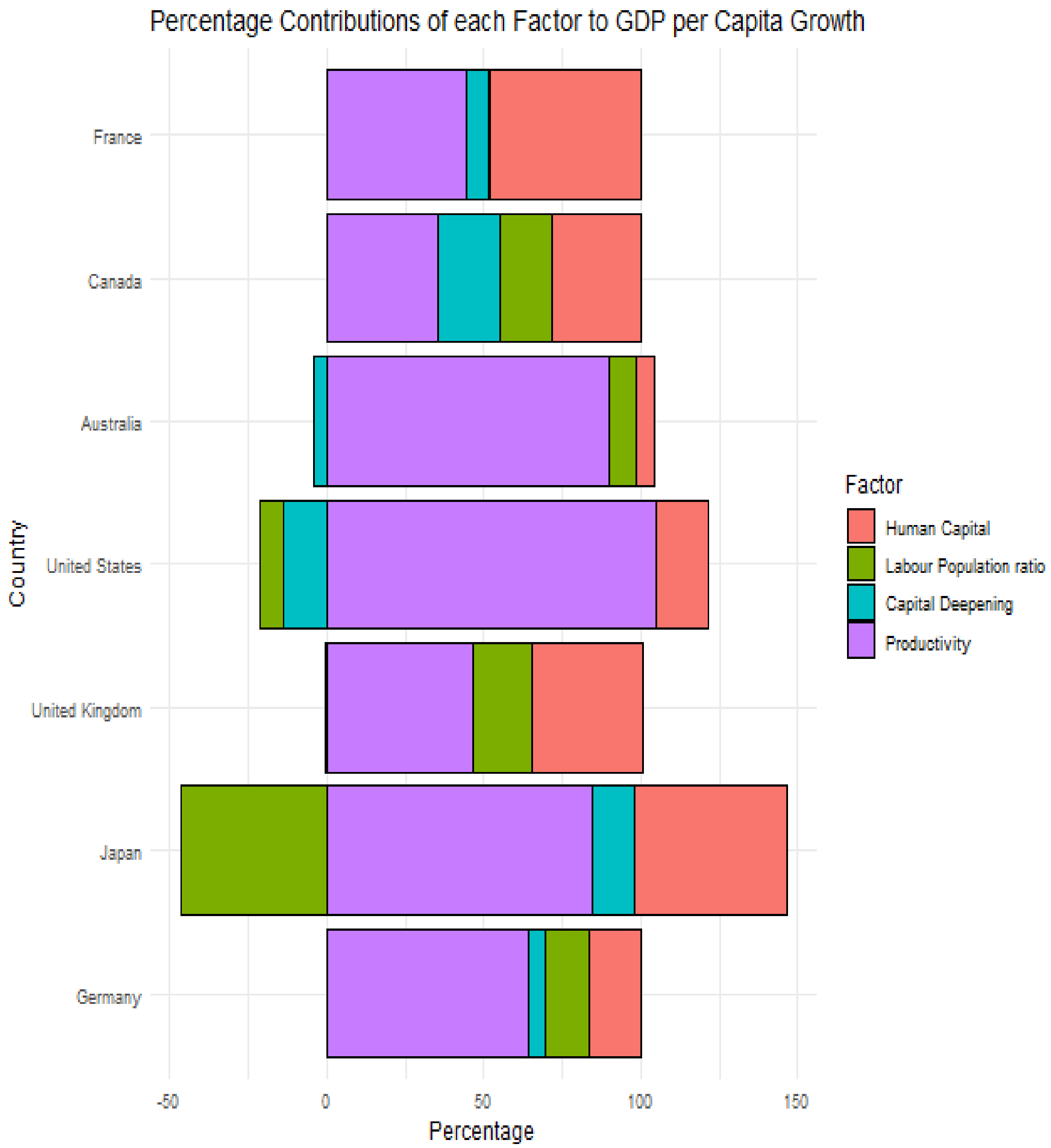
Growth Rates in OECD Economies



Source: PWT 10.01. Author's calculations.

Figure 7

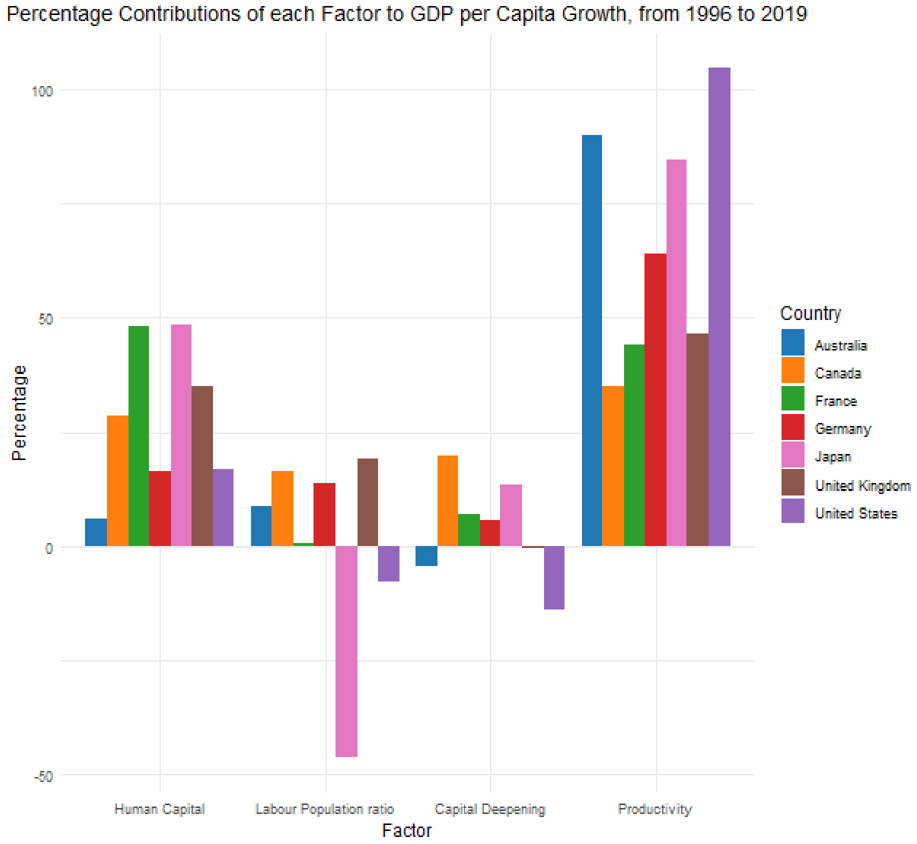
Percentage Contributions in OECD Economies



Source: PWT 10.01. Period from 1996 to 2019. Author's calculations.
Note: The four percentage factors within each economy add up to one hundred percent. 'Green' (0.57 percent) in France or 'turquoise' (-0.35 percent) in the UK cannot be observed due to low values (< than ± 1 percent); however, the values are confirmed in Table 8.

Figure 8

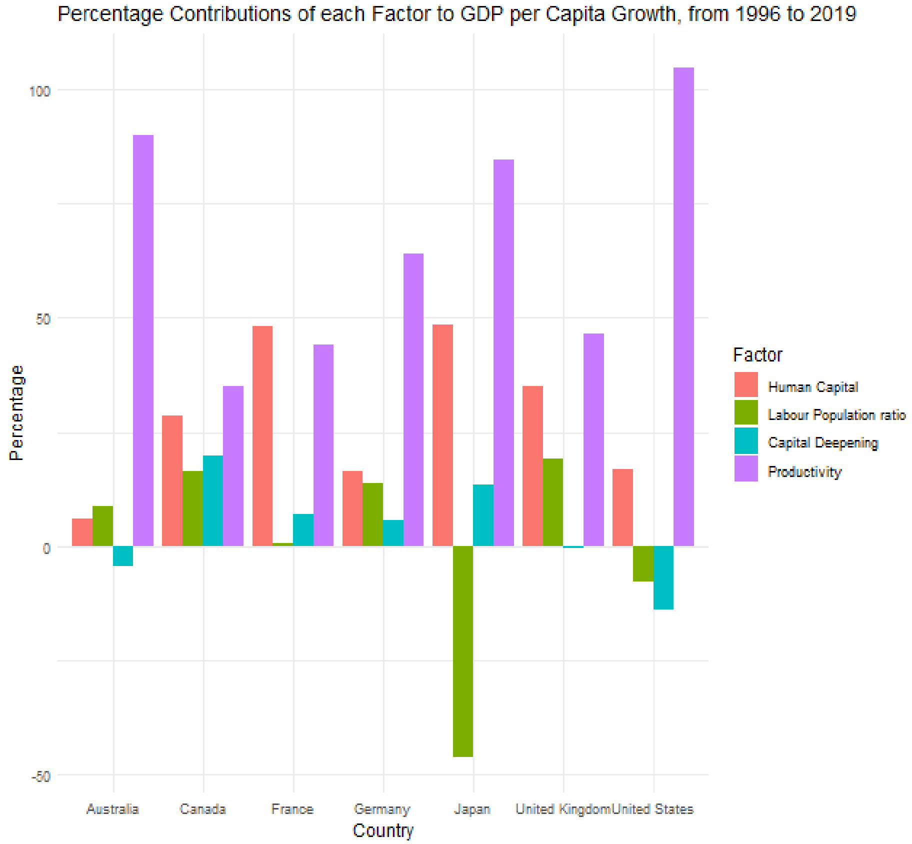
Percentage Contributions in OECD Economies



Source: PWT 10.01. Author's calculations.

Figure 9

Percentage Contributions in OECD Economies



Source: PWT 10.01. Author's calculations.

Moreover, we conducted an OLS regression as follows:

$$\frac{ln(GDP\ per\ Capita_{i,\ 2019}) - ln(GDP\ per\ Capita_{i,\ 1995})}{24} = \alpha + \beta\ \ln(\text{GDP per Capita}_{i,\ 1995}) + \mathcal{E}_{i,} \quad (8)$$

where *'GDP per capita, i, t'* represents the GDP per capita for country *i* in year *t*, and *ln* denotes the natural logarithm (base e). The dependent variable is the AAGR (in natural logs) for each country *i* from 1995[20] to 2019, whilst the independent variable is the natural logarithm of GDP per capita (not the AAGR) for each country *i* in 1995. The results are presented in Table 9.

Table 9 Model VI, *OLS* estimator, using 38 obs.

Dependent variable: *GDP per Capita*					
Regressor	Coeff.	Std. Error	T-ratio	P-value	Sig. Level
Constant	0.1711	0.0271	6.3220	<0.0001	***
GDP per Capita in 1995	-0.0148	0.0027	-5.5435	<0.0001	***
R-squared	0.4605				
Adjusted R-squared	0.4455				
F Test Statistic: F(1, 36)	30.730			<0.0001	

Source: PWT 10.01. Period from 1995 to 2019. Author's calculations. *Note:* Both variables are expressed as natural logarithms; however, only the dependent variable represents an AAGR. *** p<0.01; ** p<0.05; * p<0.1

The regression produces a *negative* estimate for β (-0.0148), which is statistically significant at the 1 percent level. This finding indicates that as GDP per capita increases, the growth rate of GDP per capita decreases, as evidenced by $\beta < 0$. Firstly, this suggests *β-convergence*, wherein lower GDP per capita countries exhibit faster growth rates compared to higher GDP per capita countries within the OECD. Conversely, higher-income countries experience lower growth rates than their lower-income counterparts. Secondly, this convergence signifies *absolute* rather than *conditional* convergence, as we do not account for all factors that may affect growth rates. Since we do not condition[21] on country-specific factors or other determinants of economic growth and instead use data from across all OECD economies, this indicates *absolute β-convergence*, where lower-income countries are closing the gap with higher-income countries within the OECD. Notably, our findings confirm evidence from Kremer, Willis, and You (2021) on convergence but differ from findings by

[20] Unlike in Model I, which employs *panel* estimation requiring the exclusion of the first year, this *OLS* estimation approach analyses *single observation growth rates* for each country across the entire study period, allowing the inclusion of data from the starting year.

[21] Said differently, we have no control variables that could explain the growth rate differences.

Benhabib and Spiegel (1994), who observed that countries catch up in TFP but not in GDP per capita.

Finally, consider Figure 10. In 1995, Australia (£36,156), Canada (£36,335), and Ireland (£35,872) had similar GDP per capita *levels*. However, by 2019, Ireland's income per capita had risen substantially to £96,812 (4.14 percent AAGR per year), compared to Australia's £52,205 (1.53 percent AAGR per year) or Canada's £50,097 (1.34 percent AAGR per year). This means that Australia's GDP per capita in 2019 was 46 percent lower than Ireland's, whilst Canada's GDP per capita in 2019 was 48 percent lower than Ireland's, as shown in Table 10. This finding underscores a significant outcome of our analysis: even minor differences in *growth rates* can lead to substantial disparities in *income levels* across OECD economies in the long run.

Table **10** Small Difference in Growth Rates, Large Difference Across Income Levels

Country	GDP per Capita in 1995 (Level)	AAGR between 1996 and 2019 (Percentage)	GDP per Capita in 2019 (Level)
Australia	£36,156	1.53	£52,205
Canada	£36,335	1.34	£50,097
Ireland	£35,872	4.14	£96,812

Source: PWT 10.01. Data starts in 1995. Period from 1995/96 to 2019. Author's calculations.

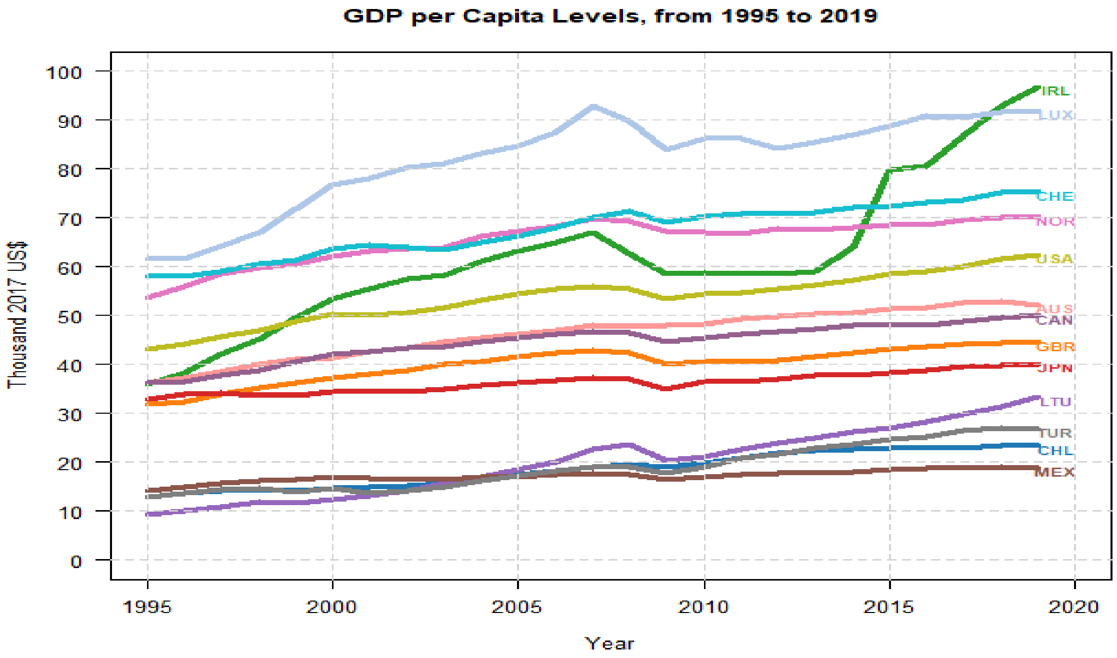


Figure 10 Small Difference in Growth Rates, Large Difference Across Income Levels

Source: PWT 10.01. Author's calculations.

5 Robustness Checks

We rigorously *validated* our results using multiple methods to ensure the *quality* and *integrity* of our analysis and minimise measurement errors, uncertainties, and biases in our assumptions and modelling approach. Here, we highlight two key validation methods.

5.1 Shorter period

In this approach, we focused on a 10-year observation period[22] (from 2010 to 2019) to examine the effects of this compressed timeline and isolate the impact of excluding the Financial Crisis from our data. The corresponding results are detailed in Table 11.

[22] For Model I, our analysis begins in 1995, and we observe the first growth rate in 1996. In contrast, Model VII initiates data collection in 2009, with the first growth rate observed in 2010.

Table 11 Model VII, *Random Effects* estimator, using 380 obs.

Dependent variable: *GDP-per-Capita*					
Regressor	Coeff.	Std. Error	T-ratio	P-value	Sig. Level
Constant	0.0015	0.0007	2.1150	0.0344	**
Human-Capital	1.2079	0.1235	9.7820	<0.0001	***
Labour-Population-ratio	1.1230	0.1385	8.1060	<0.0001	***
Capital-GDP-ratio	0.9204	0.2192	4.1990	<0.0001	***
TFP	1.8631	0.1739	10.720	<0.0001	***

Source: PWT 10.01. Period from 2010 to 2019. Author's calculations.
Note: All variables are expressed as logged AAGR. *** p<0.01; ** p<0.05; * p<0.1

A notable observation is that the Fixed Effects model is no longer suitable due to the Hausman test (P-value 0.5717), indicating that Random Effects are necessary. This finding challenges our initial assumption used in Model I that OECD economies do not constitute a purely random sample but rather a group of well-developed economies, supporting Fixed Effects as a suitable estimator. Despite this change, the significance levels of the variables remain consistent, with all variables remaining significant at the 1 percent level. However, the intercept becomes significant at the 5 percent level. Notably, the coefficients' magnitudes have changed significantly relative to Model I (Table 6): *Human-Capital's* magnitude has increased by 15.22 percent, *Labour-Population-ratio* by 25.39 percent, *Capital-GDP-ratio* by 106.73 percent, and *TFP* by 26.70 percent compared to the baseline model. These results suggest that with a shorter time horizon, the impact of these variables on *GDP-per-Capita* is more pronounced, highlighting a promising avenue for further analysis.

5.2 Outliers

The second validation approach builds on the first by revisiting the growth accounting method to identify data irregularities. With a compressed 10-year timeline for the OECD case, the *percentage contributions* of factors to GDP per capita growth differ significantly compared to the twenty-four-year approach, primarily due to Italy's outlier status. By excluding Italy, which exhibits an unusual pattern of percentage contributions, we focus on the *'OECD excluding Italy'* case, as shown in Table 12.

The most substantial *relative* change in percentage contributions is observed in the labour-population ratio, accounting for 19.88 percent of GDP per capita growth in the 10-year period, compared to 12.72 percent over twenty-four years. In contrast, the physical capital-GDP ratio exhibits significant *absolute* changes, contributing -2.62 over the 10-year period for *OECD excluding Italy* case, versus 2.87 over twenty-four years in the same context.

It is noteworthy that the growth rates of GDP per capita decreased from 2.18 percent over the twenty-four-year period to 1.90 percent over the compressed 10-year period, whilst productivity declined from 0.90 percent to 0.72 percent. This finding suggests that long-term growth rates may exhibit greater stability, potentially reflecting reduced sensitivity to short-run fluctuations or medium-term variations in business cycles. Exploring this aspect further could present valuable opportunities for future research within this analysis.

Table 12

Impact of Time Horizon on Growth Rates and Percentage Contributions *(OECD excl. Italy)*

Period from 1996 to 2019					
Economy	GDP per Capita	Human Capital	Labour-Population ratio	Physical Capital-GDP ratio	Productivity
Average Annual Growth Rates					
OECD	2.13	0.59	0.26	-0.01	0.86
OECD excl. Italy	2.18	0.58	0.26	-0.03	0.90
Percentage Contributions to GDP per Capita Growth					
OECD	-	36.17	12.86	6.21	44.75
OECD excl. Italy	-	31.63	12.72	2.87	52.77

Period from 2010 to 2019					
Economy	GDP per Capita	Human Capital	Labour-Population ratio	Physical Capital-GDP ratio	Productivity
Average Annual Growth Rates					
OECD	1.85	0.56	0.33	-0.18	0.69
OECD excl. Italy	1.90	0.56	0.35	-0.19	0.72
Percentage Contributions to GDP per Capita Growth					
OECD	-	196.86	-64.70	43.54	-75.70
OECD excl. Italy	-	33.16	19.88	-2.62	49.58

Source: PWT 10.01. Author's calculations. *Note:* All values are expressed in *percentages*.

6 Discussion

This paper employed two primary empirical methods: *growth regression* and *growth accounting*. The growth regression approach indicates that a 1 percent increase in *TFP* growth corresponds to a 1.47 percent increase in *GDP-per-Capita* growth. In contrast, the growth accounting technique reveals that within the OECD, 44.75 percent of variation in the income growth rate is the result of variation in TFP productivity, rising to 52.75 percent when excluding Italy – an outlier with the lowest GDP per capita in the analysis. Both methods underscore the significance of productivity growth in driving income growth. Our findings highlight the value of these frameworks in economic growth analysis under well-defined assumptions, aligning with the conclusions of Bosworth and Collins (2003). However, the magnitude of cross-country productivity differences amongst OECD economies varies significantly based on *modelling assumptions*, as demonstrated by Calderón (2001), fuelling debates about the merits of the Solow Growth Model.

6.1 Limitations

> *"[…] all models are approximations. Essentially, all models are wrong, but some are useful. However, the approximate nature of the model must always be borne in mind […]." (George E. P. Box, 1987, p. 424)*

Our analysis has limitations. Seven limitations are summarised in Table 13. A key observation is that researchers' discourse arises from their *expectations* and *modelling assumptions*. Particularly, the *tension* is evident in the degree to which researchers aim to *adhere to* or *deviate from* the Solow Model, as shown by Bosworth and Collins (2003).

Crucially, the Solow Model predicts that in the long run the growth rate of income per capita is *zero*. Economies reach a steady state, at which point they no longer grow. This prompts the question of *'How 'long' is the long run?'* Whilst countries have experienced exponential growth in recent periods, the assumption of infinite growth, considering *sustainability* and *fundamental causes* of growth, is not realistic. Countries cannot amass infinite wealth. Therefore, *at some point* in the very long run, the Solow Model may no longer replicate empirical realism.

Table 13

Overview of Study Limitations

Limitation	Explanation	Recommendation
α	Using a fixed (constant) α value ($\frac{1}{3}$) in the Cobb-Douglas model may introduce bias across countries.	Test with different α values, such as those demonstrated by Bosworth and Collins (2003) (α = 0.35) and Abu-Qarn and Abu-Bader (2007) (α = 0.50), to assess and mitigate bias.
Data Sources	Dependency on a single data source has both strengths and weaknesses.	Explore alternative growth accounting sources, such as the *OECD database*, *Our World in Data*, and *World Development Indicators*, supported by empirical evidence and existing literature.
Endogeneity	Our Model I functional form, informed by literature and empirical evidence (see Section *'Empirical Strategy'*), assumes no omitted variable bias.	Replicate model results using *Instrumental Variables* and *Two-Stage Least Squares* models and compare for differences.
Estimators	We employed panel method as per extensive empirical evidence (see Section *'Literature Review'*).	Consider using *GMM* models instead of *FEM* or *REM* based on evidence from Bond, Hoeffler, and Temple (2001).
Growth Accounting	Growth Accounting represents a 'gold standard' in growth modelling.	Investigate alternative measures like *Development Accounting*, focusing on GDP *per worker* (Aiyar and Dalgaard, 2005; Jones, 2015).
Human Capital	We utilised an Index of Human Capital based on years of schooling and returns to education from the *Barro-Lee Educational Attainment Dataset*.	Consider using the *Human Development Index* instead, from the *United Nations Development Programme*.
Variables	We assumed no omitted variables, as indicated by the functional form assumed (Equation (1)).	- Include the *depreciation rate* to adjust the capital stock contribution to capital and GDP growth. - Consider incorporating the *growth rate of populations* to better predict income growth. - Explore the impact of *investment* and *savings* variables to add complexity to the regression.

7 Conclusions

In this paper, we aimed to achieve three primary objectives. Our findings indicate *absolute β-convergence* amongst OECD countries, with poorer countries catching up by growing at a faster rate, addressing the *'why'* question. Additionally, we identified productivity and other factors as statistically significant at the 1 percent level, underscoring productivity as a key driver of economic growth. Through the growth accounting method, we analysed the percentage contributions of various factors to GDP per capita growth, providing insights into the determinants of countries' growth dynamics. Collectively, these analyses address *'what'* determines growth and *'how'* countries grow over time.

This research has both economic and policy implications. Government spending decisions involve opportunity costs; by strategically allocating resources to specific growth components or factor shares, countries can maximise returns whilst minimising trade-offs. Additionally, a society with a well-informed workforce and a reliance on productive input factors is more likely to foster sustainable economic growth, thereby improving living standards, health outcomes, and life expectancy.

We aimed to minimise bias, and although our results appear consistent and robust, we exercise caution against overstating them, generalising their applicability, or inferring direct policy recommendations. Our analysis represents only one perspective on economic growth. Future research could explore deeper, *fundamental determinants* of growth – the root causes – as outlined by Acemoglu (2009).

In conclusion, we have demonstrated the economic, statistical, and mathematical utility of the Solow Growth Model, particularly within OECD economies. It is essential that the social sciences – including fields like epistemology and ethics – along with considerations of inclusive growth, complement these findings, providing interdisciplinary insights that further refine economic and policy decision-making. Finally, as George E. P. Box reminds us, *"(...) all models are wrong; the practical question is how wrong they have to be to not be useful"* (1987, p. 74). This perspective underscores the importance of robust, evidence-based analysis in optimising[23] government spending to achieve sustainable growth.

[23] *Optimisation* here refers to the strategic allocation of resources to maximise desired outcomes, considering the trade-offs involved and the concept of *opportunity cost*.

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9 Appendix

Table 1A

Section *'Data'*

List of OECD Countries in the Study	
AUS	Australia
AUT	Austria
BEL	Belgium
CAN	Canada
CHE	Switzerland
CHL	Chile
COL	Colombia
CRI	Costa Rica
CZE	Czech Republic
DEU	Germany
DNK	Denmark
ESP	Spain
EST	Estonia
FIN	Finland
FRA	France
GBR	United Kingdom
GRC	Greece
HUN	Hungary
IRL	Ireland
ISL	Iceland
ISR	Israel
ITA	Italy
JPN	Japan
KOR	Republic of Korea
LTU	Lithuania
LUX	Luxembourg
LVA	Latvia
MEX	Mexico
NLD	Netherlands
NOR	Norway
NZL	New Zealand
POL	Poland
PRT	Portugal
SVK	Slovakia
SVN	Slovenia
SWE	Sweden
TUR	Turkey
USA	United States

Figure **1A**

Scatter Plots with Different Scales

Section *'Results of Model I'*

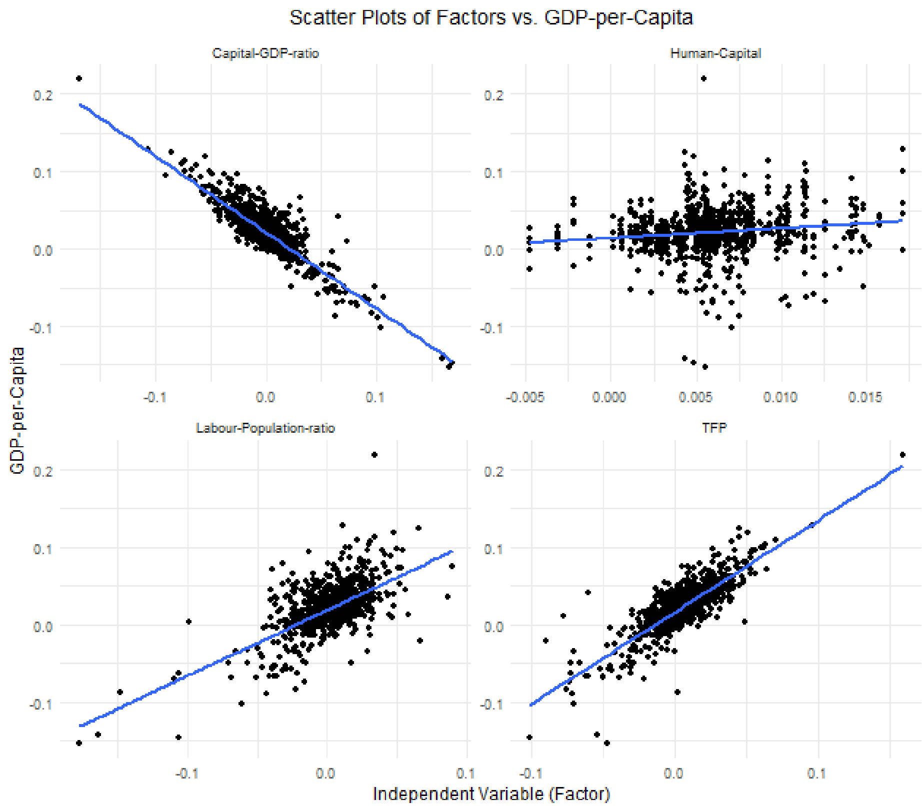

Table 2A

Section *'Growth Accounting'*

	Average Annual Growth Rates, from 1996 to 2019				
	GDP per Capita	Human Capital	Labour-Population ratio	Physical Capital-GDP ratio	Productivity
AUS	1.53	0.09	0.13	-0.13	0.92
AUT	1.34	0.44	0.12	0.21	0.45
BEL	1.31	0.36	0.49	0.53	0.13
CAN	1.34	0.38	0.22	0.53	0.31
CHE	1.10	0.24	-0.14	0.12	0.63
CHL	2.50	0.62	0.14	1.65	0.61
COL	1.83	1.01	0.65	0.10	0.07
CRI	2.44	0.56	0.40	1.49	0.49
CZE	2.43	0.35	-0.02	-1.44	1.87
DEU	1.25	0.21	0.17	0.14	0.53
DNK	1.25	0.49	0.01	0.17	0.44
ESP	1.46	0.66	0.75	0.36	-0.08
EST	4.42	0.78	0.18	-0.95	2.62
FIN	1.82	0.59	0.40	-0.09	0.59
FRA	1.09	0.53	0.01	0.15	0.32
GBR	1.42	0.50	0.27	-0.01	0.44
GRC	0.90	0.73	-0.06	0.38	0.03
HUN	2.85	0.71	0.50	-0.17	1.15
IRL	4.14	0.55	0.53	0.12	2.00
ISL	2.44	0.77	-0.25	-1.53	1.79
ISR	1.65	0.78	0.36	0.10	0.31
ITA	0.35	0.71	0.06	0.91	-0.59
JPN	0.84	0.41	-0.39	0.22	0.47
KOR	3.63	0.93	-0.63	0.94	1.91
LTU	5.25	0.76	1.20	-1.86	2.81
LUX	1.67	1.07	1.22	0.13	-0.46
LVA	4.96	0.62	0.71	-2.77	3.34
MEX	1.19	0.79	0.83	-0.02	-0.29
NLD	1.56	0.42	0.56	-0.11	0.43
NOR	1.12	0.46	0.06	0.77	0.14
NZL	1.79	0.17	0.38	0.24	0.74
POL	4.07	0.73	0.50	0.50	1.72
PRT	1.34	0.80	0.20	0.65	0.01
SVK	3.66	0.74	0.19	-1.30	2.26
SVN	2.50	0.47	-0.07	-0.65	1.61
SWE	1.88	0.35	0.18	-0.92	1.21
TUR	3.04	1.27	-0.04	1.75	0.62
USA	1.54	0.26	-0.12	-0.43	1.07
OECD Average	2.13	0.59	0.26	-0.01	0.86

Table 3A

Section *'Growth Accounting'*

		Percentage Contributions to GDP per Capita Growth, from 1996 to 2019			
		Human Capital	Labour-Population ratio	Physical Capital-GDP ratio	Productivity
	AUS	5.84	8.58	-4.39	89.97
	AUT	33.09	8.73	7.87	50.31
	BEL	27.33	37.10	20.18	15.39
	CAN	28.49	16.50	19.96	35.05
	CHE	21.89	-13.04	5.33	85.82
	CHL	24.82	5.56	32.92	36.70
	COL	55.46	35.87	2.84	5.82
	CRI	23.03	16.56	30.48	29.93
	CZE	14.54	-0.74	-29.61	115.81
	DEU	16.57	13.84	5.66	63.93
	DNK	38.99	1.19	6.78	53.03
	ESP	45.16	51.22	12.28	-8.67
	EST	17.75	3.99	-10.75	89.01
	FIN	32.16	22.00	-2.58	48.41
	FRA	48.22	0.57	7.05	44.16
	GBR	34.93	19.09	-0.35	46.33
	GRC	81.23	-7.08	21.24	4.60
	HUN	24.94	17.69	-3.05	60.42
	IRL	13.28	12.74	1.39	72.58
	ISL	31.63	-10.28	-31.29	109.95
	ISR	47.20	21.48	3.08	28.24
	ITA	204.17	18.22	129.69	-252.09
	JPN	48.52	-46.29	13.40	84.37
	KOR	25.52	-17.30	12.90	78.89
	LTU	14.54	22.81	-17.76	80.41
	LUX	63.92	73.19	3.85	-40.97
	LVA	12.48	14.32	-27.88	101.09
	MEX	66.78	70.11	-0.65	-36.24
	NLD	26.98	35.69	-3.65	40.99
	NOR	41.23	5.53	34.28	18.95
	NZL	9.73	21.26	6.62	62.38
	POL	18.06	12.34	6.12	63.48
	PRT	59.55	14.83	24.18	1.43
	SVK	20.15	5.09	-17.75	92.51
	SVN	19.02	-3.00	-13.02	97.00
	SWE	18.62	9.44	-24.43	96.37
	TUR	41.76	-1.29	28.88	30.65
	USA	16.92	-7.67	-13.82	104.57
	OECD Average	36.17	12.86	6.21	44.75

Table 4A

Section *'Outliers'*

		Average Annual Growth Rates, *excluding Italy*, from 2010 to 2019				
		GDP per Capita	Human Capital	Labour-Population ratio	Physical Capital-GDP ratio	Productivity
	AUS	0.85	0.31	0.05	0.22	0.25
	AUT	0.86	0.35	0.10	-0.01	0.29
	BEL	0.96	0.20	0.46	0.55	0.02
	CAN	1.16	0.22	0.13	0.52	0.37
	CHE	0.91	0.21	-0.30	-0.11	0.70
	CHL	2.10	0.61	-0.13	1.61	0.54
	COL	2.47	0.95	-0.19	0.44	0.99
	CRI	2.46	0.65	-0.58	1.05	1.24
	CZE	2.19	0.12	0.50	-1.55	1.57
	DEU	1.59	0.08	0.57	-0.62	0.83
	DNK	1.49	0.50	-0.30	-0.59	1.05
	ESP	1.00	0.69	-0.12	0.07	0.26
	EST	3.74	0.58	1.19	-1.04	1.66
	FIN	0.87	0.56	0.02	0.51	0.02
	FRA	0.95	0.61	0.02	0.09	0.18
	GBR	1.08	0.24	0.65	-0.17	0.18
	GRC	-1.75	0.71	-1.01	1.60	-1.50
	HUN	3.03	0.53	1.85	-0.95	0.75
	IRL	5.05	0.55	0.44	-1.03	3.05
	ISL	1.99	0.80	0.50	-1.99	1.13
	ISR	2.00	1.05	0.55	-0.05	0.28
	JPN	1.40	0.32	0.32	-0.84	0.79
	KOR	2.88	0.91	-0.05	0.43	1.21
	LTU	4.88	0.50	1.95	-1.47	2.11
	LUX	0.90	1.40	0.49	0.23	-0.74
	LVA	3.65	0.45	0.63	-1.90	2.35
	MEX	1.37	0.72	1.45	-0.33	-0.42
	NLD	1.13	0.42	0.48	-0.13	0.20
	NOR	0.42	0.31	0.01	1.12	-0.30
	NZL	1.84	0.57	0.62	-0.02	0.43
	POL	3.69	0.75	0.23	0.47	1.65
	PRT	1.16	0.74	0.17	-0.34	0.28
	SVK	2.84	0.70	0.45	-0.79	1.39
	SVN	1.65	0.58	-0.13	-1.35	1.25
	SWE	1.68	0.31	0.33	-0.82	0.96
	TUR	4.09	1.37	0.95	1.06	0.82
	USA	1.56	0.17	0.64	-0.95	0.82
	OECD Average	1.90	0.56	0.35	-0.19	0.72

Table 5A

Section *'Outliers'*

	Percentage Contributions to GDP per Capita Growth, *excluding Italy*, from 2010 to 2019			
	Human Capital	Labour-Population ratio	Physical Capital-GDP ratio	Productivity
AUS	36.85	5.48	13.01	44.67
AUT	40.07	11.20	-0.75	49.48
BEL	20.42	47.98	28.61	2.99
CAN	19.07	10.95	22.55	47.43
CHE	23.67	-33.17	-6.19	115.69
CHL	29.09	-6.07	38.30	38.68
COL	38.61	-7.67	8.98	60.08
CRI	26.36	-23.41	21.26	75.78
CZE	5.26	22.64	-35.30	107.40
DEU	5.31	36.04	-19.58	78.23
DNK	33.40	-20.04	-19.77	106.40
ESP	69.51	-12.30	3.43	39.35
EST	15.49	31.78	-13.92	66.65
FIN	64.30	2.01	29.43	4.26
FRA	64.01	2.32	4.62	29.05
GBR	22.47	59.88	-7.83	25.48
GRC	-40.74	57.71	-45.78	128.81
HUN	17.39	61.16	-15.72	37.17
IRL	10.98	8.68	-10.17	90.51
ISL	40.18	24.96	-50.12	84.98
ISR	52.34	27.50	-1.18	21.33
JPN	22.58	22.59	-29.92	84.74
KOR	31.45	-1.89	7.40	63.05
LTU	10.34	39.89	-15.01	64.78
LUX	155.71	54.39	13.06	-123.17
LVA	12.45	17.18	-26.04	96.41
MEX	52.32	105.78	-12.08	-46.02
NLD	36.97	42.14	-5.61	26.51
NOR	73.29	1.44	132.77	-107.50
NZL	31.01	33.98	-0.53	35.53
POL	20.34	6.28	6.42	66.96
PRT	63.42	14.55	-14.55	36.58
SVK	24.62	15.74	-13.91	73.54
SVN	35.45	-8.03	-40.99	113.57
SWE	18.68	19.82	-24.41	85.91
TUR	33.56	23.29	12.93	30.22
USA	10.80	40.80	-30.45	78.85
OECD Average	33.16	19.88	-2.62	49.58