1 THE ENTROPY LAW AND CONVERGENCE IN ECONOMIC SYSTEMS[1]

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Abstract

Drawing on the entropy law, this paper proposes a moving-target model to investigate the long-run convergence of countries' per capita income toward the average income of their reference group. Using evidence from the global economy and the European Union, we show that income convergence follows dynamics consistent with entropy-based physical systems. However, while convergence is observed across countries, regional and sub-regional disparities within countries often widen, indicating that convergence at the macro level may coexist with divergence at lower territorial levels.

Keywords: entropy law, economic development, real convergence, growth, economic forecast

JEL Classification: C0, C6, O10, O11, O52
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1. Introduction

Differences in economic performance across countries and regions remain a central concern for both policymakers and researchers. Explaining why some economies gradually reduce these gaps while others continue to lag behind is fundamental to understanding long-run economic growth, the evolution of income inequality, and improvements in living standards. Within this framework, the concept of economic convergence describes the process through which disparities in economic performance across countries or regions gradually diminish over time (Benabou, 1996; Johnson and Papageorgiou, 2020; Chancel and Piketty, 2021; Amendola, 2025).

This paper examines the long-run dynamics of economic convergence from an entropy-law perspective. Drawing on international and European evidence, we show that countries' relative income levels tend to converge toward the average income of their reference groups over time. However, this process is accompanied by an opposite pattern at finer spatial scales, where regional and sub-regional disparities frequently increase. The coexistence of cross-country

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convergence and within-country divergence suggests that economic convergence is inherently a multilevel process whose dynamics depend on the level of territorial aggregation.

The convergence hypothesis, often referred to as the catch-up effect (Lupu *et al*., 2014), has long occupied a central place in economic growth theory. Understanding whether less developed countries or regions gradually narrow the income gap with more advanced economies has long been a central issue in the literature on economic growth and development. Numerous theoretical frameworks have been proposed to explain the relationship between economic integration, growth performance, and income convergence. According to the early neoclassical growth models, greater economic integration promotes convergence by facilitating the mobility of production factors and accelerating the diffusion of knowledge and technology (Cieślik and Misiak, 2025; Amendola, 2025).

Since the seminal contributions of Solow and Swan (1956), a large body of literature has argued that poorer economies tend to grow faster than richer ones, leading to a gradual reduction in cross-country income disparities (Baumol, 1986; Lucas, 1990; Mankiw *et al*., 1992; Phillips and Sul, 2009; Romer, 2011; European Central Bank, 2017). This interpretation of unconditional convergence nevertheless fails to account for substantial differences among economies in terms of technological development, institutional effectiveness, and access to productive resources, factors that may generate distinct long-run growth trajectories (Barro and Sala-i-Martin, 1997; Popovici and Călin, 2016; Alemu *et al*., 2025).

More recent research has also shown that convergence is not a uniform process but one characterized by heterogeneous adjustment paths, distinct behavioural regimes and considerable differences across territorial and structural dimensions. Building on our previous studies of real convergence in the European Union and the global economy (Albu, 2016a, 2016b; Albu *et al*., 2020, 2023, 2025), we interpret these long-run dynamics from a broader systemic perspective. In particular, we argue that the persistent tendency toward convergence across economies resembles the adjustment processes observed in complex physical systems and can therefore be interpreted through the conceptual lens of the entropy law.

This paper extends that research agenda by combining an entropy-inspired interpretation with a dynamic moving-reference framework for analysing long-run convergence. Rather than assuming a fixed equilibrium, the model considers the average income of each reference group as an evolving benchmark toward which individual economies gradually adjust over time. The proposed optimisation framework generates theoretical adjustment trajectories that can be directly compared with observed empirical dynamics. Using data for 139 economies worldwide together with detailed regional evidence for the European Union, we show that convergence and divergence are not contradictory phenomena but complementary processes operating simultaneously across different spatial scales.

The remainder of the paper is organized as follows. Section 2 introduces the entropy-law framework and its implications for economic convergence. Section 3 examines convergence and divergence patterns in the global economy. Section 4 extends the analysis to convergence among European Union countries and country groups, while Section 5 investigates convergence and divergence within the EU country groups. Section 6 analyses regional convergence and divergence across the European Union using regional data. Finally, Section 7 proposes a typology of regional convergence based on the NUTS 2 and NUTS 3 classifications.

2. Entropy Law and Economic Convergence

The entropy law states that, in an isolated physical system, natural processes evolve toward thermodynamic equilibrium through irreversible transformations. Drawing on this principle as a

conceptual analogy, we argue that economic systems also exhibit long-run adjustment mechanisms that reduce disparities among comparable economic units. In this context, convergence refers to the gradual reduction of differences in income per capita among the components of a given economic system, which may include individuals, regions, countries, or groups of countries. From this perspective, economic development is expected to be accompanied by a progressive adjustment toward the average level of the relevant reference group, although the speed and pattern of convergence may differ across levels of spatial aggregation. This interpretation is consistent with the literature on economic convergence and complex systems, including our previous studies on nonlinear convergence dynamics in the European Union and the global economy, which provide empirical evidence of persistent long-run adjustment processes (Albu, 2016a, 2016b; Albu *et al.*, 2020, 2023, 2025).

At the country level, economic convergence implies that economies with income per capita below the average of their reference group—such as the global economy, the European Union or another comparable economic system—should, over the long run, experience growth rates higher than the average growth rate of that group. Conversely, economies whose income per capita exceeds the group average are expected to grow at a relatively slower pace, allowing income differentials to gradually narrow over time. In the following sections, we provide empirical evidence that such adjustment mechanisms operate both within the global economy and within the European Union. Although short-run fluctuations may temporarily obscure these dynamics, the convergence process becomes apparent over sufficiently long time horizons. The resulting adjustment resembles the well-known moving-target problem in ballistics, where the reference point continuously evolves while individual trajectories gradually adapt to its changing position.

In the case of the European Union, the moving target is represented by the average income per inhabitant of the EU, while the "projectile", which gradually approaches this target over time, is represented by the income per inhabitant of an individual Member State. Accordingly, two types of adjustment trajectories can be distinguished: (a) a descending trajectory toward 100 (%), characterising countries whose income per capita is above the EU average ($g\%y > 100$), and (b) an ascending trajectory toward 100 (%), characterising countries whose income per capita is below the EU average ($g\%y < 100$), where $g\%y = y/yM$ denotes the ratio between the income per capita of a country, y, and the average income per capita of the European Union, yM.

To analyse the convergence process within the global economy and the European Union, we use annual data from the World Bank (WB) covering the period 1990–2024. The global sample consists of 139 countries and territories (W139), for which consistent data are available throughout the entire period, representing approximately 96% of the world's population. Following the World Bank classification, countries are grouped into three income categories according to their average income per capita: High (H), Middle (M), and Low (L). For the European Union, we employ our own conventional classification, dividing the 27 Member States into three groups: EU10 (North-Western Europe), EU6 (Southern Europe), and EU11 (Eastern Europe). In addition, regional convergence is analysed both within individual Member States and within these country groups using NUTS2 and NUTS3 regional data expressed in Purchasing Power Standards (PPS). PPS is an artificial currency unit developed by Eurostat that adjusts for differences in national price levels through purchasing power parities (PPPs), allowing income levels and other economic aggregates to be compared consistently across countries and regions.

Applying the entropy-law perspective within a moving-target framework, we simulate the long-run convergence of countries' income per capita toward the average income of their respective reference groups. This adjustment process is examined both at the level of the global economy and within the European Union. The empirical evidence provides strong support for the existence of such long-run convergence dynamics, consistent with the adjustment mechanisms observed in complex physical systems. At the same time, however, increasing the spatial granularity of the

analysis reveals an opposite tendency: within individual countries, regional and sub-regional disparities frequently widen, giving rise to processes of internal divergence.

To analyse convergence and divergence, we primarily employ the well-known coefficient of variation (denoted by σ). In this study, the indicator is calculated from the deviations of individual income per capita (y) from the corresponding average income of the reference group (y_M), thereby providing a simple measure of the degree of dispersion within the economic system under consideration.

To estimate the optimal adjustment trajectories of income per capita, we propose a general dynamic optimisation model that applies uniformly to all components of the economic system, including countries, regions and sub-regions. The model describes both downward adjustment toward the group average for economies with income per capita above the reference level ($y > y_M$) and upward adjustment for those with income below the reference level ($y < y_M$). Its dynamics are governed by a single acceleration parameter, a, yielding the following general specification:

$$Ye_{i,t} = Ye_{i,t-1}\left[a\left(\frac{\left(P_{i,t-1}\right)^2}{\left(Ye_{i,t-1}\right)^2}\cdot\frac{\sum_{i=1}^{n} Y\,e_{i,t-1}}{\sum_{i=1}^{n} P_{i,t-1}}+1\right)\right]$$

where Ye denotes the estimated annual income (GDP), P the population, $i = 1, \dots, n$identifies the countries or other territorial units, and $t = 1, \dots, T$ denotes the years included in the analysis. The model is solved numerically using two optimisation criteria. The first imposes that, in the final year of the analysis (2024), the estimated average income per capita is equal to the observed average value, that is, $y_M = y_{Me}$. The second requires that, over the entire sample period, the estimated average income per capita is equal to the corresponding observed average, that is, $y_{MM} = y_{MeM}$.

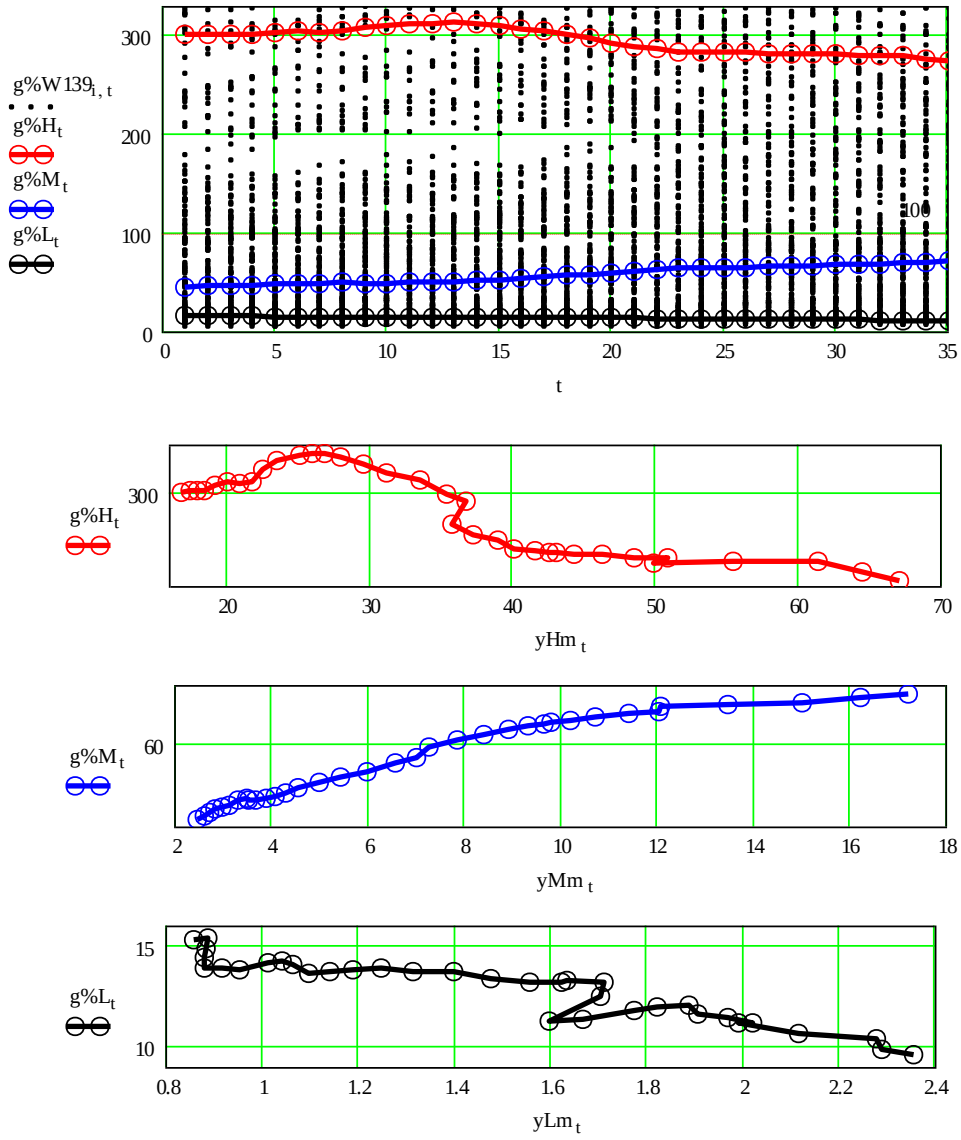
The degree to which the empirical trajectories of all territorial units (countries, regions or counties) follow the estimated convergence paths generated by the optimisation model is assessed by comparing the overall patterns of the observed and estimated trajectories. The closer the two sets of trajectories are, the better the proposed model captures the long-run convergence dynamics of the economic system under analysis.

3. Convergence and Divergence in the Global Economy

To analyse the convergence process in the global economy, we use World Bank data covering the period 1990–2024. The upper panel of Figure 1 presents the evolution of variable g%W139 for the 139 countries included in the sample. Each country is represented by a point, forming vertical distributions for each year of the analysed period (1990–2024, corresponding to $t = 1, \dots, 35$). For graphical clarity, the vertical axis is truncated at 330% for variable g%. The same panel also displays the trajectories of the average relative income for the three World Bank income groups: the High-income group (g%H, red line), the Middle-income group (g%M, blue line), and the Low-income group (g%L, black line).

In the remaining three panels of Figure 1, the horizontal axis no longer represents time but the average level of income per capita of each income group (yHm, yMm, and yLm), expressed in thousands of US dollars at Purchasing Power Parity (PPP). PPP-adjusted values account for differences in national price levels by expressing income in a common purchasing-power-equivalent currency, thereby allowing meaningful comparisons across countries with different price structures.

Figure 1. Convergence dynamics in the global economy, 1990–2024



Source: Authors' computation

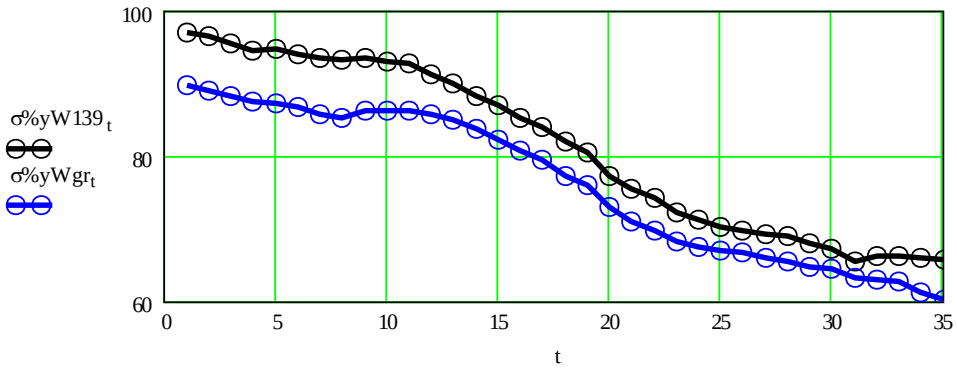
Figure 1 also reveals a clear divergence pattern for the Low-income group, whose trajectory moves progressively farther away from the 100 reference line (black line in the lower panel). By contrast, both the High-income group (red line) and the Middle-income group (blue line) exhibit convergence trajectories toward the world average. These three trajectories may therefore be

interpreted as distinct behavioural regimes characterising the long-run adjustment process within the three World Bank income groups.

An alternative way to evaluate convergence is through the variation coefficient, $\sigma\%,y$. An increasing value of this indicator reflects a divergence process, whereas a decreasing value indicates convergence. For the global economy, we estimate the σ indicator for the entire sample (W139), measuring the dispersion of income across all countries, as well as at the group level, capturing the evolution of disparities among the three World Bank income groups.

The estimation results are presented in Figure 2. The figure also reports the correlation coefficients between income per capita and the $\sigma\%, y$ indicator for the W139 sample and for the world economy represented by the three World Bank income groups (H, M, and L). In both cases, the correlations are significantly negative, indicating that as income per capita increases, the convergence process advances.

Figure 2. Convergence dynamics in the global economy measured by the variation coefficient



$\text{corr}(\sigma\%\text{yW139}, \text{yW139}) = -0.950$ $\text{corr}(\sigma\%\text{yWgr}, \text{yWm}) = -0.962$

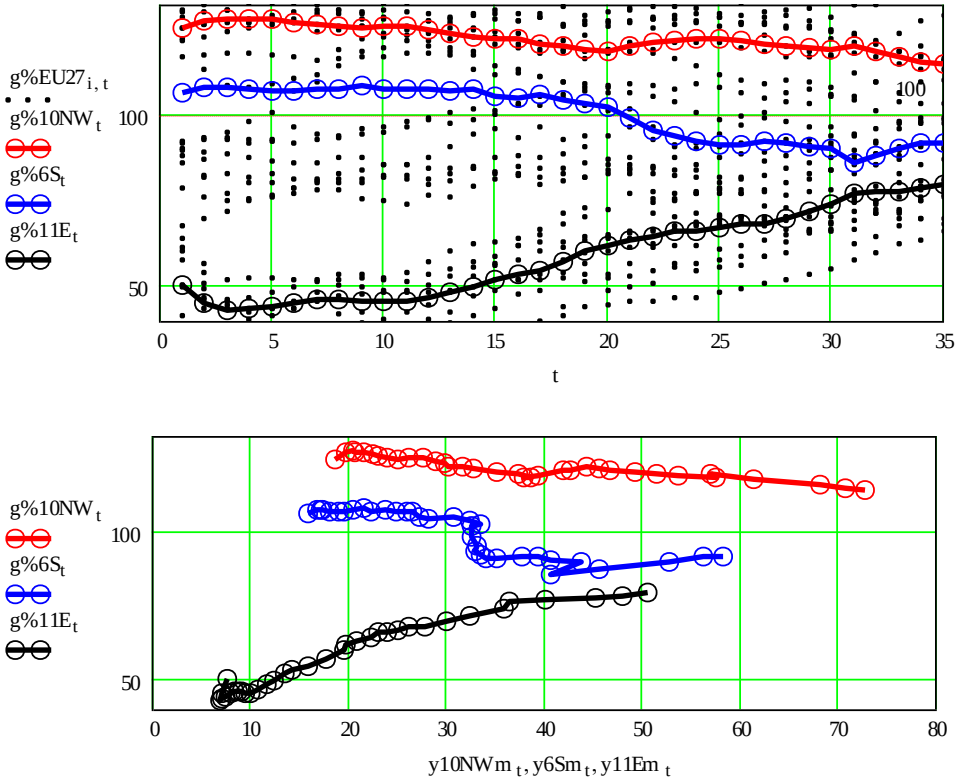
Source: Authors' computation

4. Convergence among Countries and Groups within the European Union

According to the literature, Gross Domestic Product (GDP) per capita expressed at Purchasing Power Parity (PPP), either in euro PPS or international dollars, is the standard indicator used to analyse real convergence at the macroeconomic level. Building on detailed analyses of economic structures and long-run macroeconomic behaviour, we classify the EU Member States into three conventional groups: North-Western (EU10NV: Austria, Belgium, Denmark, Finland, France, Germany, Ireland, Luxembourg, the Netherlands, and Sweden), Southern (EU6S: Cyprus, Greece, Italy, Malta, Portugal, and Spain), and Eastern (EU11E: Bulgaria, Czech Republic, Croatia, Estonia, Latvia, Lithuania, Poland, Romania, Slovakia, Slovenia, and Hungary).

To examine convergence within the European Union, we use World Bank data for the period 1990–2024, covering all 27 Member States. Figure 3 presents the dynamics of the convergence process both for the European Union as a whole and for the three conventional country groups defined above.

Figure 3. Convergence dynamics within the European Union.



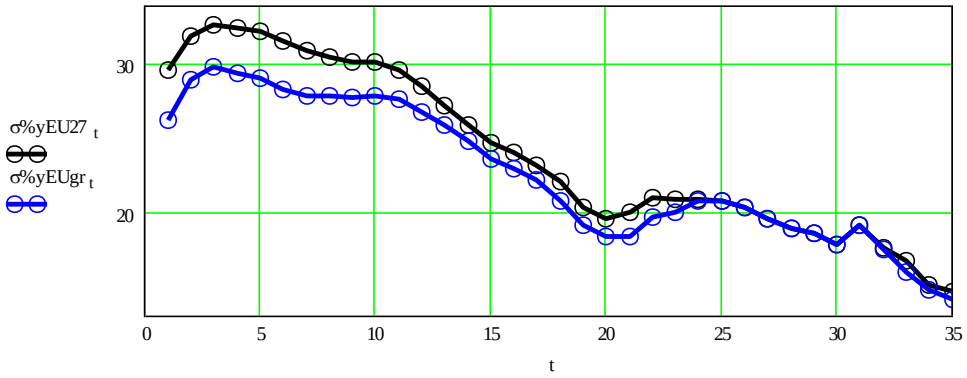
Source: Authors' computation

The upper panel of Figure 3 presents the evolution of variable g% for the 27 EU Member States. Each country is represented by a point, forming vertical distributions for each year of the analysed period (1990–2024, corresponding to $t = 1, \ldots, 35$). For graphical clarity, the vertical axis is truncated at 132% for variable g%. The lower panel displays the corresponding trajectories of the three conventional country groups: the North-Western group (g%10NW, red line), the Southern group (g%6S, blue line), and the Eastern group (g%11E, black line).

In the lower panel, the horizontal axis no longer represents time but the corresponding average income per capita of the three country groups ($y10NWm$, $y6Sm$, and $y11Em$), expressed in thousands of PPP-adjusted US dollars. The figure reveals three distinct convergence paths within the European Union. The North-Western group follows a downward trajectory toward the EU average (100%), whereas the Eastern group exhibits a clear upward convergence path. The Southern group occupies an intermediate position, with its trajectory gradually approaching the common benchmark. Toward the end of the sample period, the Eastern trajectory comes close to that of the Southern group, reflecting the substantial progress achieved by the Eastern Member States in closing the income gap.

As in the analysis of the global economy, we estimate the variation coefficient ($\sigma\%,y$) for the European Union in two cases: first, to measure the evolution of income disparities among the 27 Member States (EU27), and second, to assess the dispersion among the three conventional country groups. The corresponding estimation results are presented in Figure 4.

Figure 4. Convergence dynamics within the European Union measured by the variation coefficient.



$\text{corr}(\sigma\%\text{yEU27}, \text{yEU27}) = -0.933$ $\text{corr}(\sigma\%\text{yEUgr}, \text{yEUm}) = -0.930$

Source: Authors' computation

Figure 4 also reports the correlation coefficients between income per capita and the $\sigma\%,y$ indicator, calculated both for the sample of the 27 EU Member States and for the three conventional country groups (North-Western, Southern, and Eastern). In both cases, the estimated correlations are significantly negative, indicating that higher levels of income per capita are associated with lower income dispersion and, consequently, with a stronger convergence process.

5. Convergence and Divergence within EU Country Groups

Using our conventional classification of the 27 EU Member States into the three country groups (EU10, EU6, and EU11), we apply the same methodology based on the dynamics of the variation coefficient to analyse the convergence process within each group over the period 1990–2024. The analysis uses World Bank data on GDP per capita expressed in PPP-adjusted international dollars.

Figure 5 presents the estimated trajectories of the convergence indicator for the three country groups. The results reveal two pronounced convergence processes: one within the Eastern group (decreasing black trajectory) and another within the Southern group (decreasing blue trajectory). By contrast, the North-Western group exhibits a divergence pattern during the analysed period, as indicated by the increasing red trajectory. The corresponding correlation coefficients are reported below the figure and are interpreted as follows:

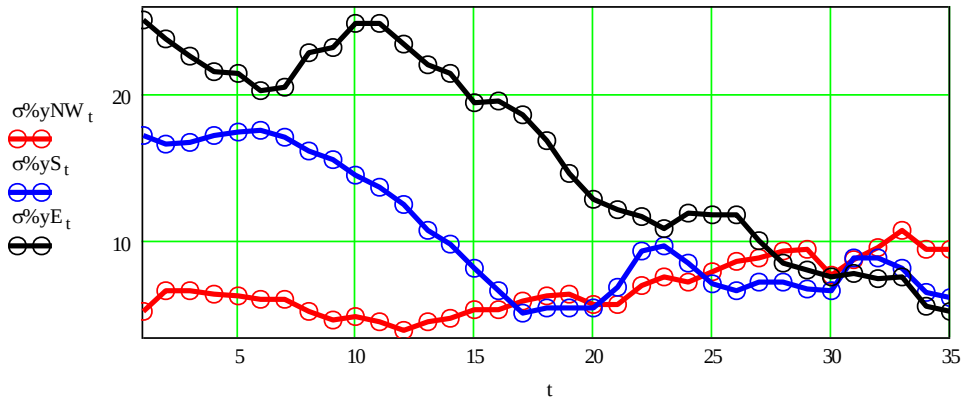
In the Eastern group, the convergence process among the member countries was accompanied by the convergence of the group as a whole toward the average income per capita of the European Union. This result is reflected in the negative value of the estimated correlation

coefficient and indicates that both internal convergence and external catch-up occurred simultaneously.

By contrast, the North-Western group experienced increasing divergence among its member countries while its relative income position with respect to the EU average gradually declined. The negative correlation coefficient therefore reflects the coexistence of growing internal disparities and a decreasing relative advantage over the EU average.

The Southern group presents a different pattern. Although the member countries exhibited a process of internal convergence, the group's relative income per capita declined with respect to the EU average. This combination is reflected in the positive value of the estimated correlation coefficient and suggests that internal convergence does not necessarily imply convergence toward the overall European average.

Figure 5. Convergence dynamics within the three European Union country groups measured by the variation coefficient



$\text{corr}(g\%mNW, \sigma\%yNW) := -0.642$ $\text{corr}(g\%mS, \sigma\%yS) := 0.629$ $\text{corr}(g\%mE, \sigma\%yE) := -0.973$

Source: Authors' computation

6. Convergence and Divergence across EU Regions

Regional convergence is analysed at two territorial scales using the Eurostat NUTS (Nomenclature of Territorial Units for Statistics) classification. The analysis is conducted at the NUTS 2 level, which comprises the basic regions used for the implementation of regional policies, and at the NUTS 3 level, which consists of smaller territorial units primarily employed for detailed regional analysis. The Eurostat dataset covers the period 2000–2024 (25 years) and uses GDP per capita, expressed in Purchasing Power Standards (PPS), as the measure of income per inhabitant.

The Eurostat dataset covers the period 2000–2024 (25 years) and uses GDP per capita, expressed in Purchasing Power Standards (PPS), as the measure of income per inhabitant.

After processing the data, the final sample comprises 244 NUTS 2 regions, grouped into 23 countries or country groups. Because some EU Member States are represented in the Eurostat NUTS 2 database by a single region, we combined Belgium with Luxembourg, Cyprus with Malta,

and the three Baltic countries (Estonia, Latvia, and Lithuania) into a single group referred to as the Baltics.

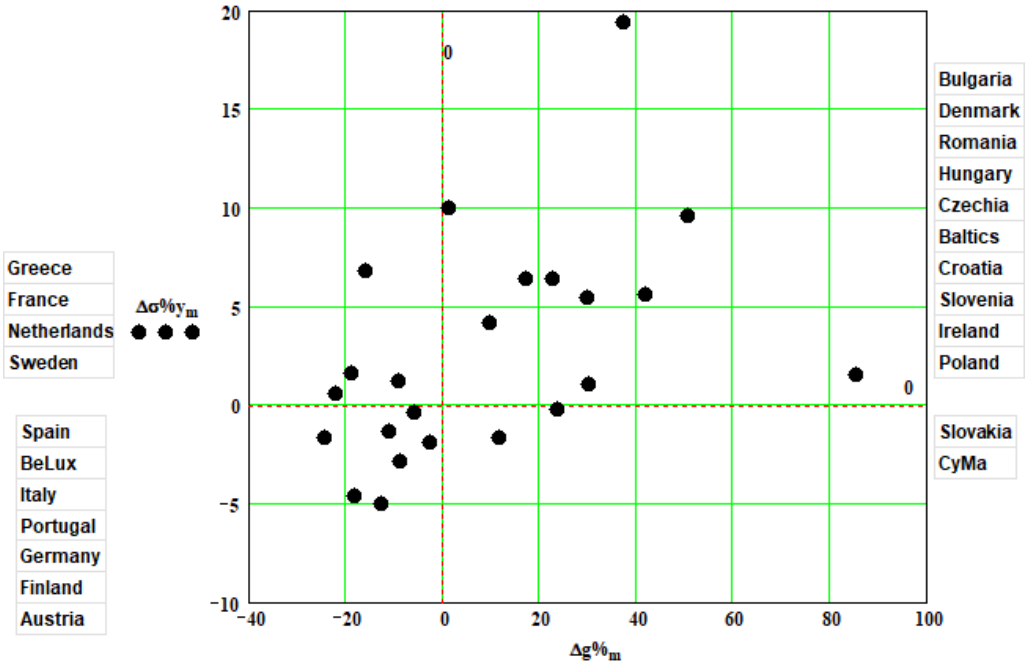
The regional analysis is based on two key indicators: the variation coefficient ($\sigma\%$), which measures income dispersion among the regions within each country or country group, and the relative income indicator ($g\%$), defined as the ratio between the GDP per capita of an individual region and the corresponding national average.

For the NUTS 3 analysis, the dataset includes 1,165 sub-regions grouped into the same 23 countries or country groups over the same period. The analysis employs the same two indicators, allowing a direct comparison between the NUTS 2 and NUTS 3 levels.

7. Typology of Regional Convergence in the European Union (NUTS 2 and NUTS 3)

Based on the statistical analysis of the NUTS 2 data for the period 2000–2024, we propose a typology of regional convergence, which is illustrated in Figure 6.

Figure 6. Typology of regional convergence in the European Union (NUTS 2)



Source: Authors' computation

Figure 6 plots the changes (expressed in percentage points) in the two key convergence indicators: $\Delta g\%$ on the horizontal axis and $\Delta\sigma\%$ on the vertical axis. These indicators measure, respectively, changes in the relative income position of a country with respect to the EU average

income per capita and changes in the degree of regional convergence within each country. The regional convergence indicator, $\sigma\%$, is the variation coefficient calculated across the regions of a country, while the relative income indicator, $g\%$, is defined as the ratio between a country's GDP per capita and the corresponding EU average value ($g\%_M$). Annex 1 presents the complete set of graphs for the 23 countries or country groups over the period 2000–2024, obtained by applying the proposed methodology to the NUTS 2 data.

Based on the proposed typology, four main categories of countries or country groups can be distinguished. Each category corresponds to one of the four quadrants of the coordinate system (numbered according to the trigonometric convention), reflecting the changes observed between 2000 and 2024, as follows:

Q1) Countries or country groups that improved their relative income position with respect to the EU average while simultaneously experiencing increasing regional divergence (Bulgaria, Denmark, Romania, Hungary, Czechia, the Baltics, Croatia, Slovenia, Ireland, and Poland).

$$\Delta g\% > 0 \text{ and } \Delta\sigma\% > 0$$

Q2) Countries or country groups whose relative income position declined with respect to the EU average while also experiencing increasing regional divergence (Greece, France, the Netherlands, and Sweden).

$$\Delta g\% < 0 \text{ and } \Delta\sigma\% > 0$$

Q3) Countries or country groups whose relative income position declined with respect to the EU average but experienced increasing regional convergence (Spain, Belgium and Luxembourg, Italy, Portugal, Germany, Finland, and Austria).

$$\Delta g\% < 0 \text{ and } \Delta\sigma\% < 0$$

Q4) Countries or country groups that improved their relative income position with respect to the EU average while simultaneously experiencing regional convergence (Slovakia and Cyprus and Malta).

$$\Delta g\% > 0 \text{ and } \Delta\sigma\% < 0$$

Applying the same methodology to the NUTS 3 data for the period 2000–2024 yields the typology presented in Figure 7. The results can be summarized as follows:

Q1) Countries or country groups that improved their relative income position with respect to the EU average while simultaneously experiencing increasing regional divergence (Ireland, Bulgaria, Romania, Denmark, Slovenia, Czechia, Hungary, Poland, the Baltics, Slovakia, Croatia, and Cyprus and Malta).

$$\Delta g\% > 0 \text{ and } \Delta\sigma\% > 0$$

Q2) Countries or country groups whose relative income position declined with respect to the EU average while also experiencing increasing regional divergence (Greece, France, the Netherlands, and Sweden).

$$\Delta g\% < 0 \text{ and } \Delta\sigma\% > 0$$

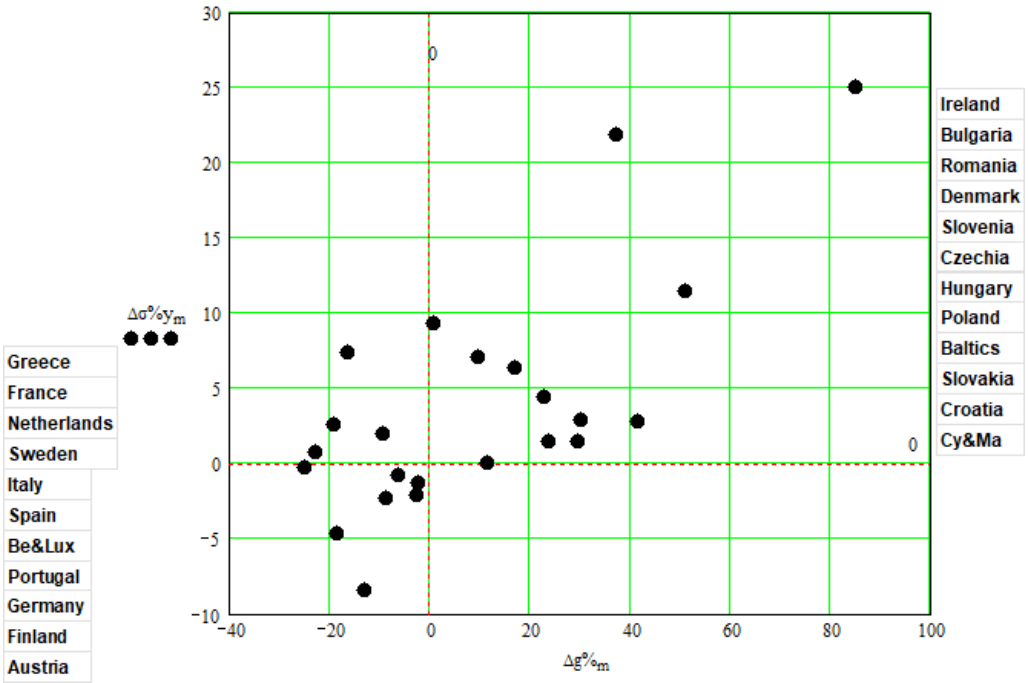
Q3) Countries or country groups whose relative income position declined with respect to the EU average but experienced increasing regional convergence (Austria, Finland, Germany, Portugal, Belgium and Luxembourg, Spain, and Italy).

$$\Delta g\% < 0 \text{ and } \Delta\sigma\% < 0$$

Q4) No country falls into this category; therefore, no country simultaneously improved its relative income position with respect to the EU average while also experiencing regional convergence.

$$\Delta g\% > 0 \text{ and } \Delta\sigma\% < 0$$

Figure 7. Typology of regional convergence in the European Union (NUTS 3)



Source: Authors' computation

Annex 2 presents the complete set of graphs for the 23 countries or country groups over the period 2000–2024, obtained by applying the proposed methodology to the NUTS 3 data.

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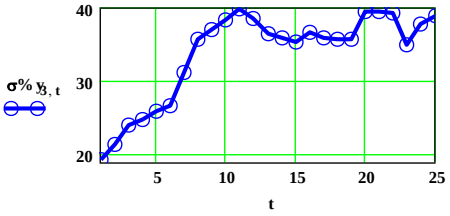
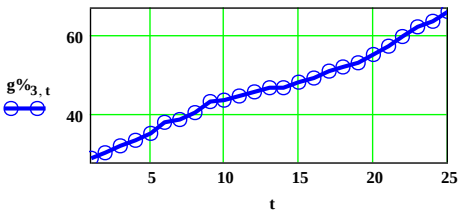
Appendix 1: Quadrants in NUTS 2

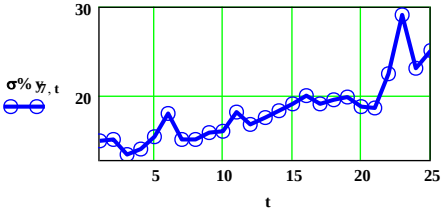
Quadrant I – 10 countries

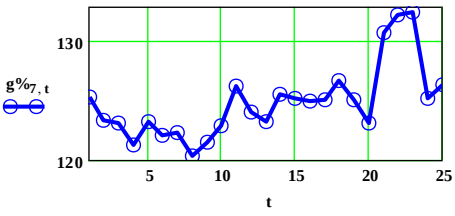
1) Bulgaria corr(g%,s%) = 0.792



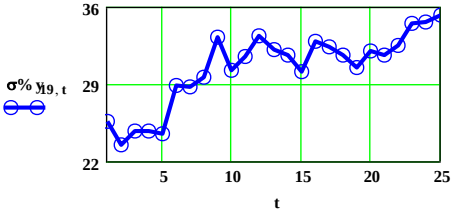


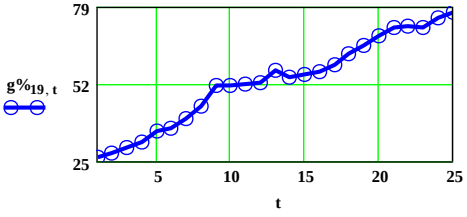
2) Denmark corr(g%,s%) = 0.733



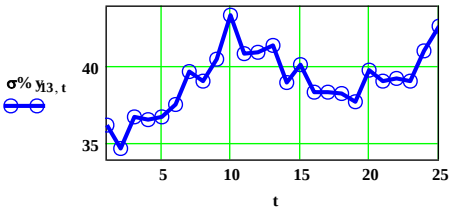


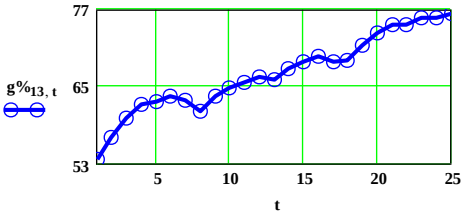
3) Romania corr(g%,s%) = 0.877



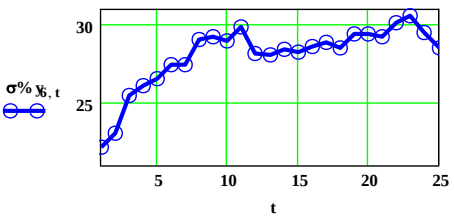


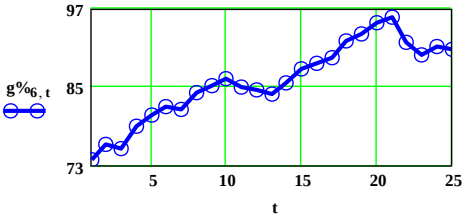
4) Hungary corr(g%,s%) = 0.499



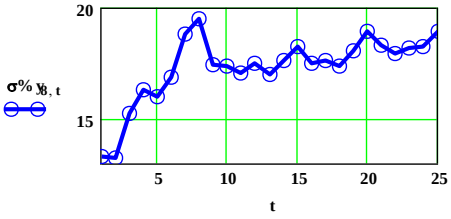


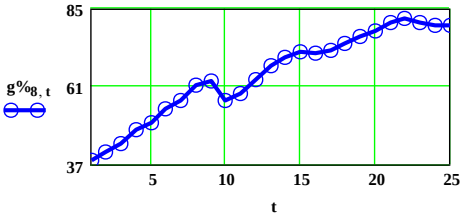
5) Czechia corr(g%,s%) = 0.829



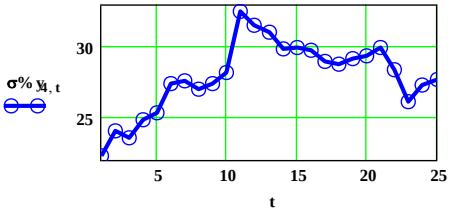


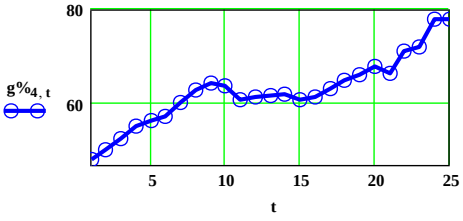
6) Baltics corr(g%,s%) = 0.782



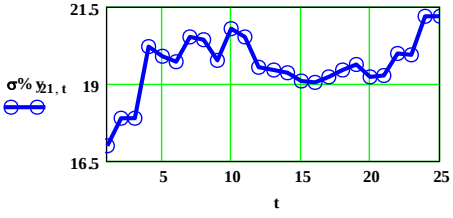


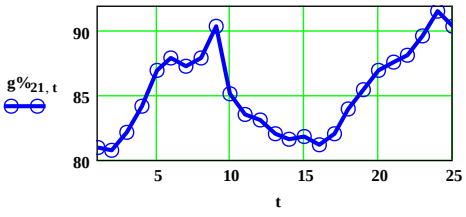
7) Croatia corr(g%,s%) = 0.430



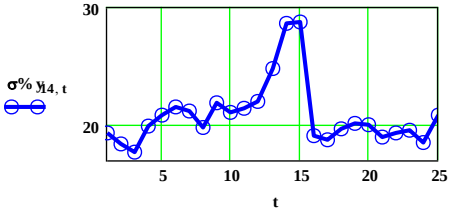


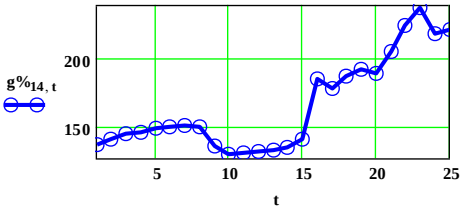
8) Slovenia corr(g%,s%) = 0.677



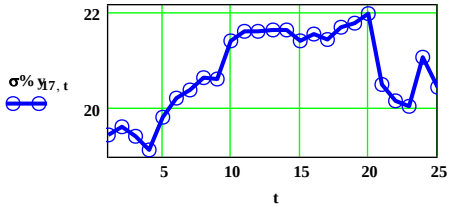


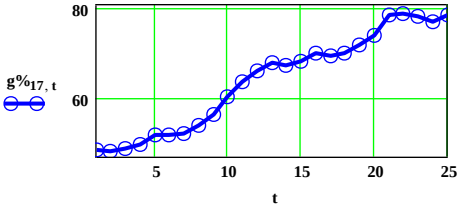
9) Ireland corr(g%,s%) = -0.423





10) Poland corr(g%,s%) = 0.548

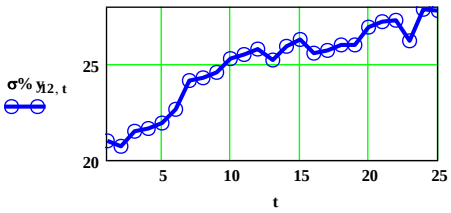


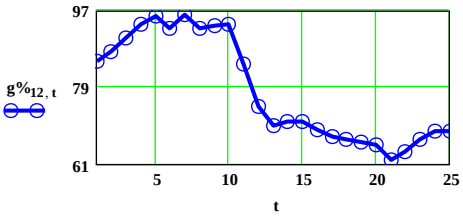


Source: Authors' computation

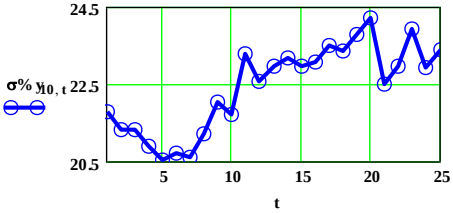
Quadrant II (the most unfavourable) – 4 countries

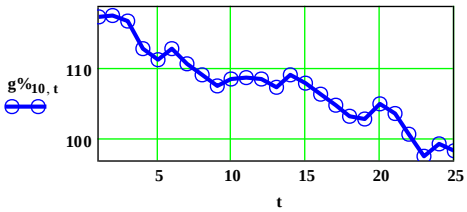
1) Greece corr(g%,s%) = -0.768



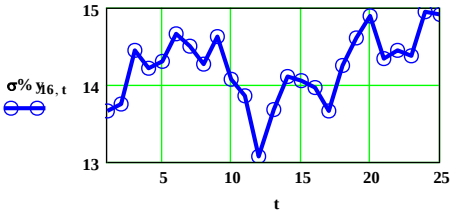


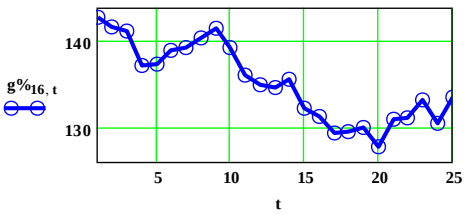
2) France corr(g%,s%) = -0.722



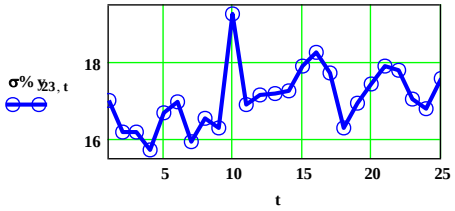


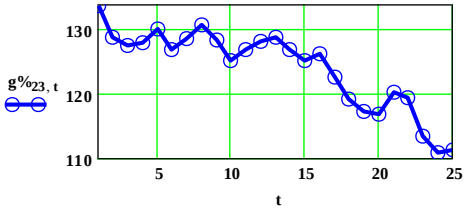
3) Netherlands corr(g%,s%) = -0.186





4) Sweden corr(g%,s%) = -0.237

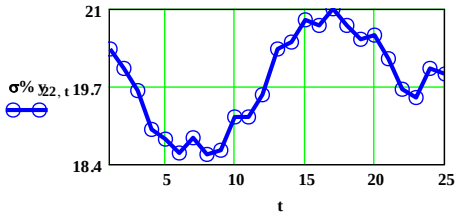


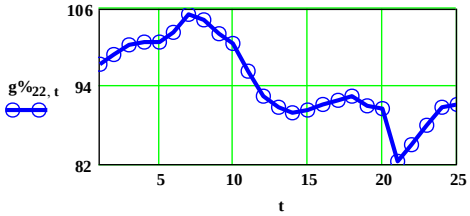


Source: Authors' computation

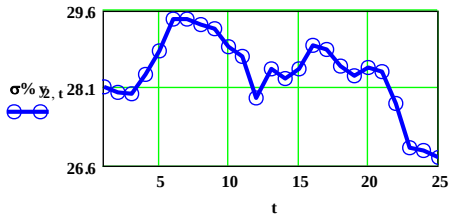
Quadrant III – 7 countries

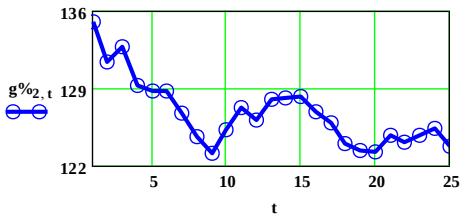
1) Spain corr(g%,s%) = -0.701



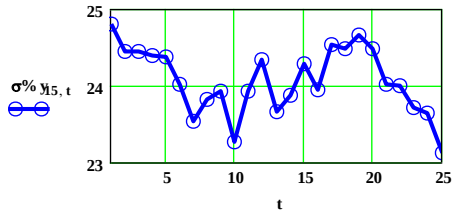


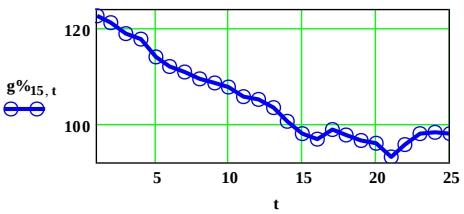
2) BeLux corr(g%,s%) = 0.029



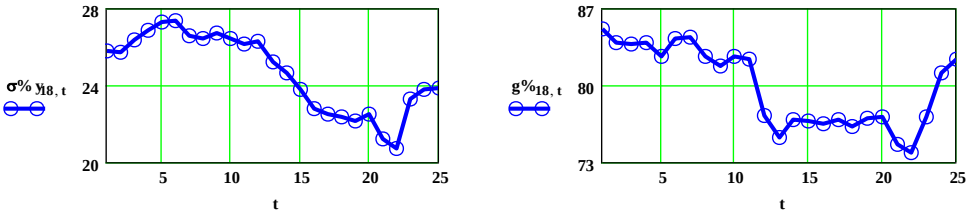


3) Italy corr(g%,s%) = 0.255

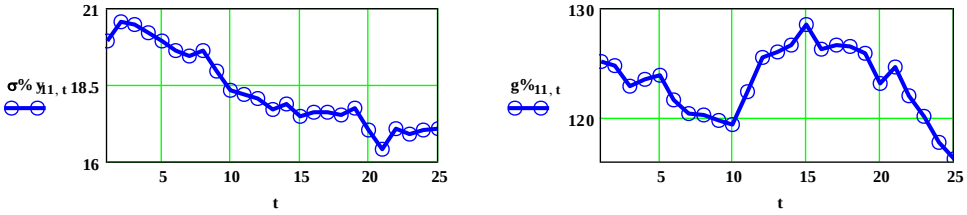




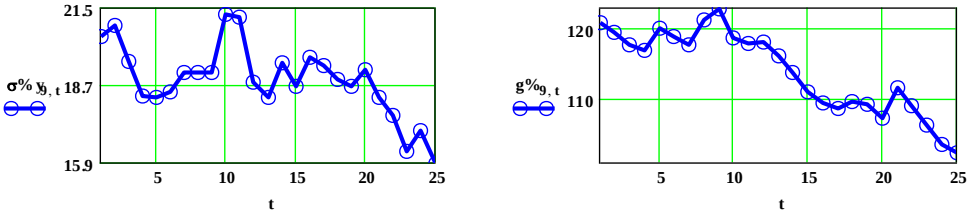
4) Portugal corr(g%,s%) = 0.801



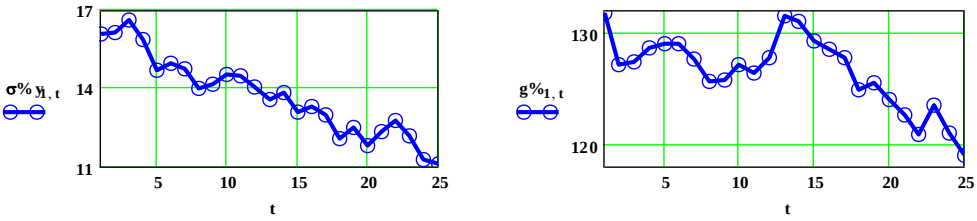
5) Germany corr(g%,s%) = -0.023



6) Finland corr(g%,s%) = 0.613



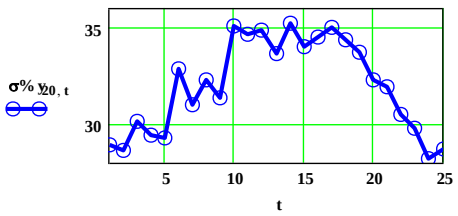
7) Austria corr(g%,s%) = 0.672

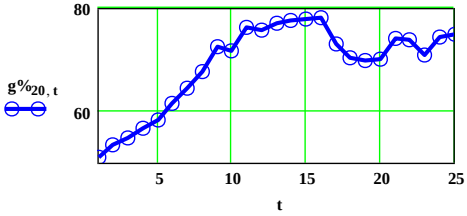


Source: Authors' computation

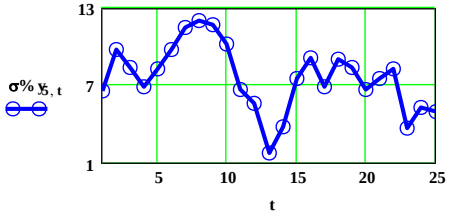
Quadrant IV (the most favourable) – 2 countries

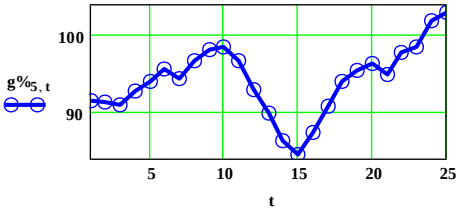
1) Slovakia corr(g%,s%) = 0.590





2) CypMal corr(g%,s%) = 0.102



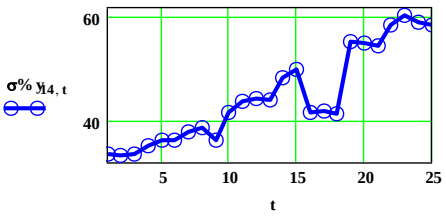


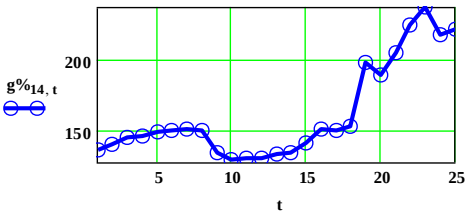
Source: Authors' computation

Appendix 2: Quadrants in NUTS 3

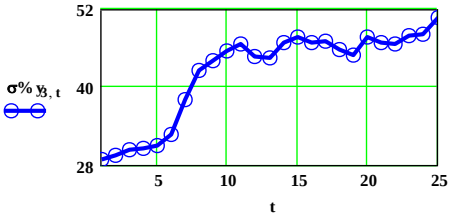
Quadrant I – 12 countries

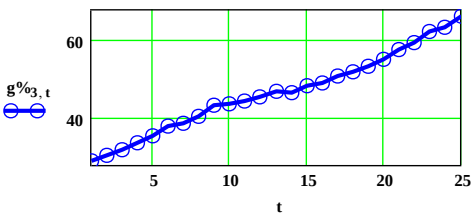
1) Ireland corr(g%,s%) = 0.828



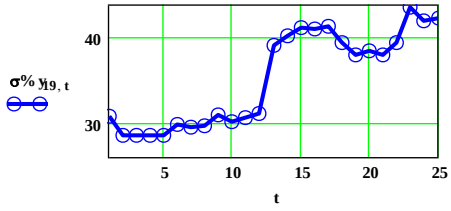


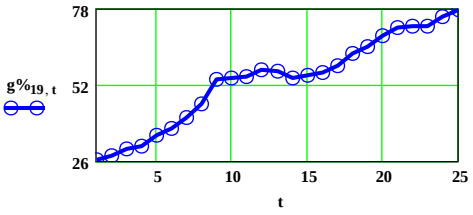
2) Bulgaria corr(g%,s%) = 0.869



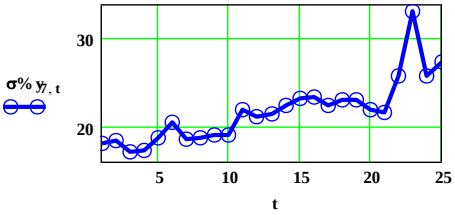


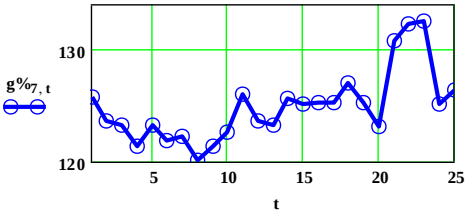
3) Romania corr(g%,s%) = 0.810



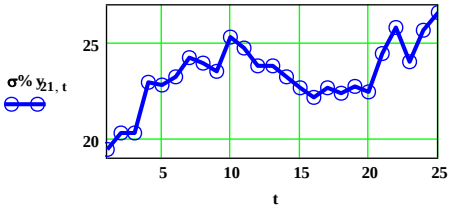


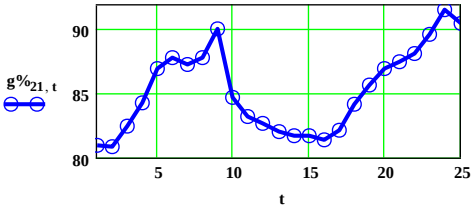
4) Denmark corr(g%,s%) = 0.743



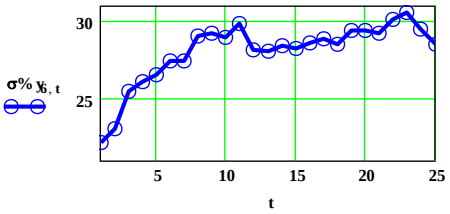


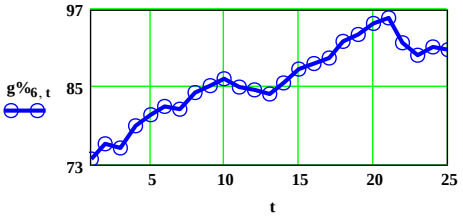
5) Slovenia corr(g%,s%) = 0.652



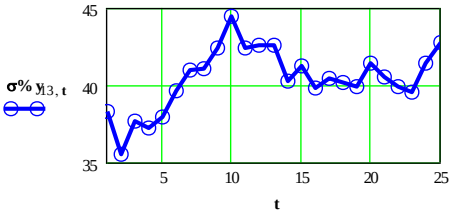


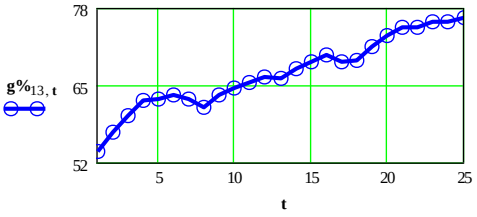
6) Czechia corr(g%,s%) = 0.822



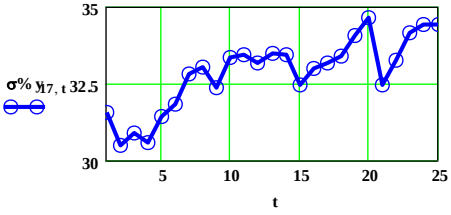


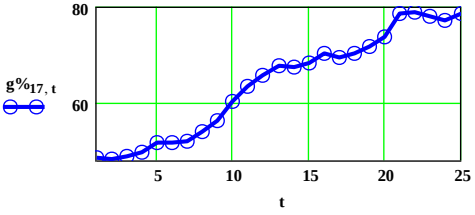
7) Hungary corr(g%,s%) = 0.404



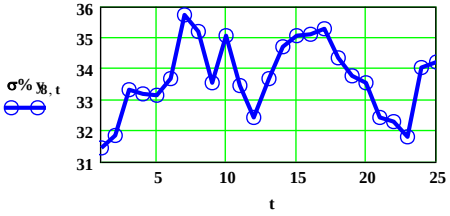


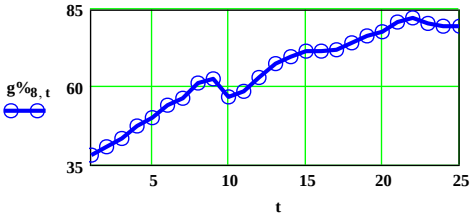
8) Poland corr(g%,s%) = 0.803



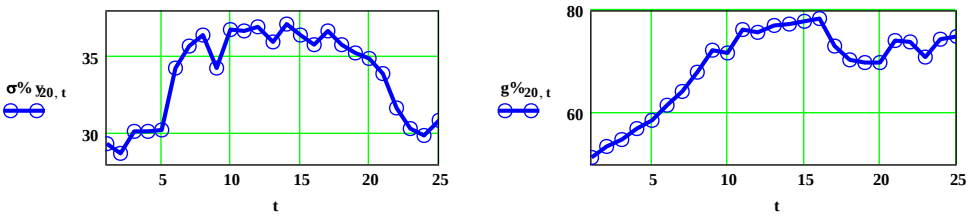


9) Baltics corr(g%,s%) = 0.204

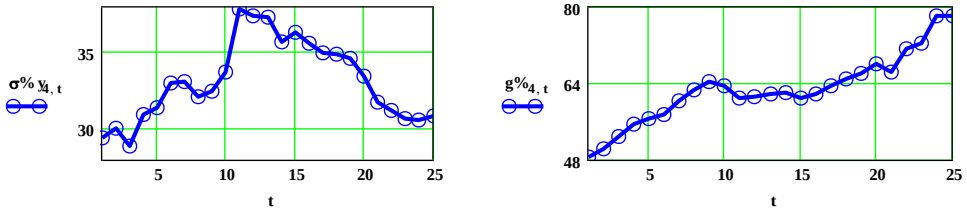




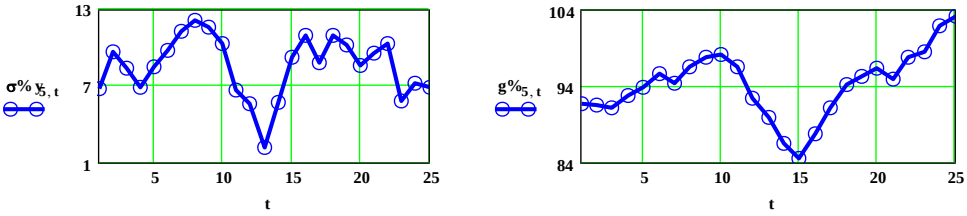
10) Slovakia corr(g%,s%) = 0.646



11) Croatia corr(g%,s%) = 0.058



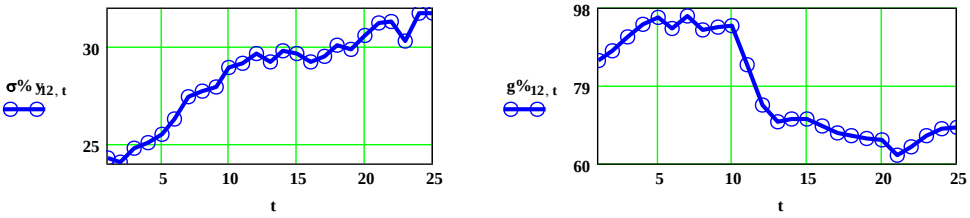
12) CypMal corr(g%,s%) = 0.133



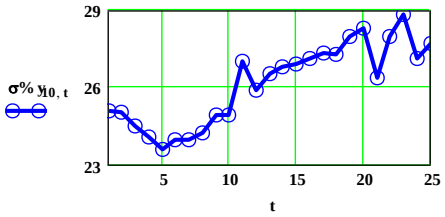
Source: Authors' computation

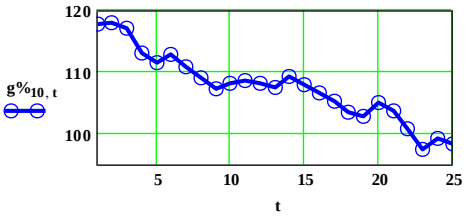
Quadrant II (the most unfavourable) – 4 countries

1) Greece corr(g%,s%) = -0.795

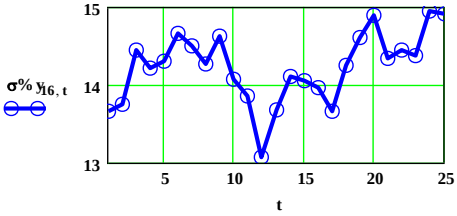


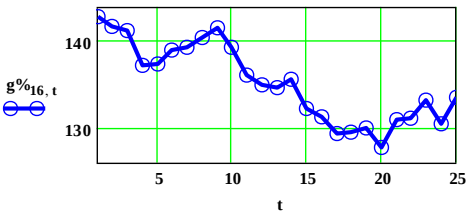
2) France corr(g%,s%) = -0.744



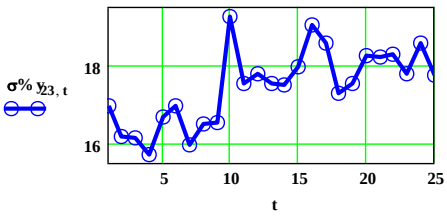


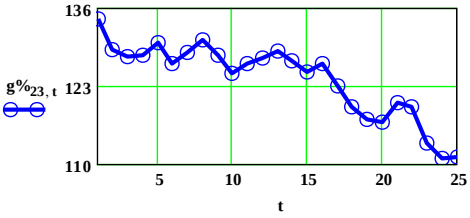
3) Netherlands corr(g%,s%) = -0.814





4) Sweden corr(g%,s%) = -0.504

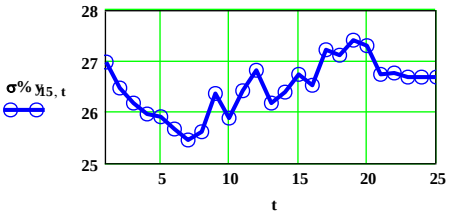


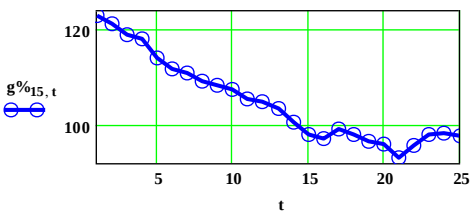


Source: Authors' computation

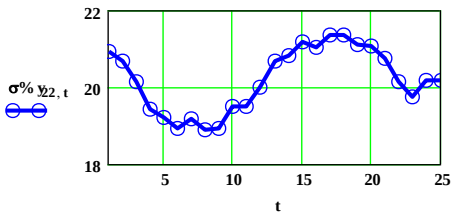
Quadrant III – 7 countries

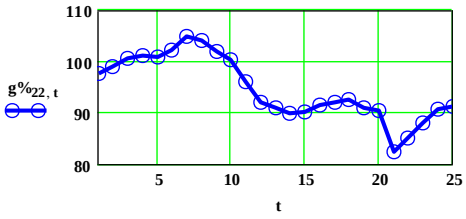
1) Italy corr(g%,s%) = -0.530



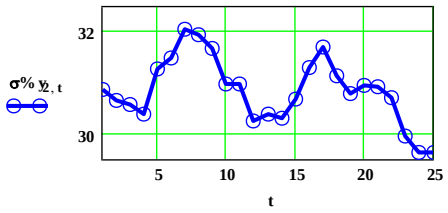


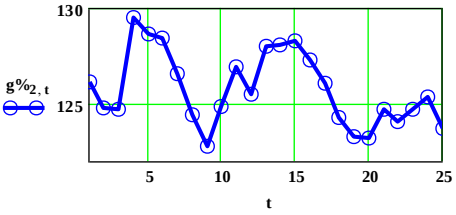
2) Spain corr(g%,s%) = -0.660



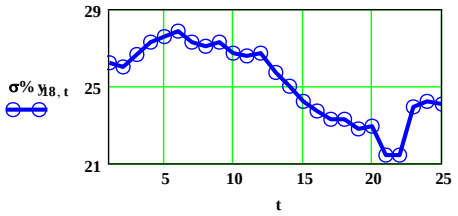


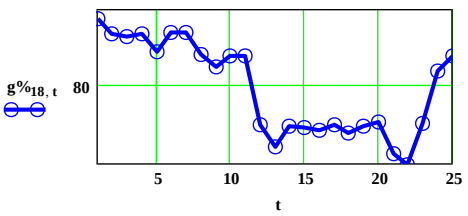
3) BeLux corr(g%,s%) = 0.022



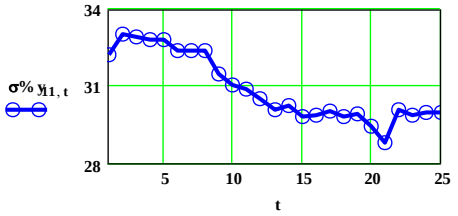


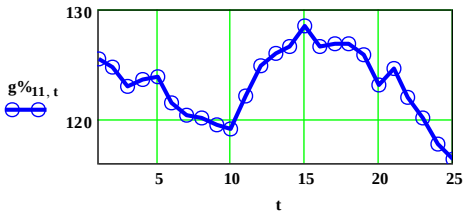
4) Portugal corr(g%,s%) = 0.778



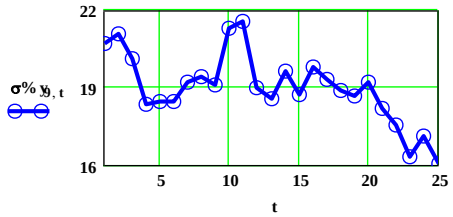


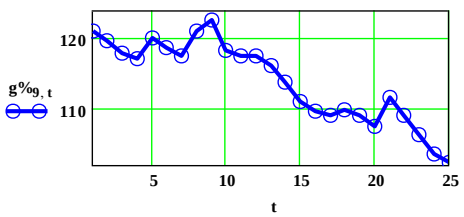
5) Germany corr(g%,s%) = -0.173



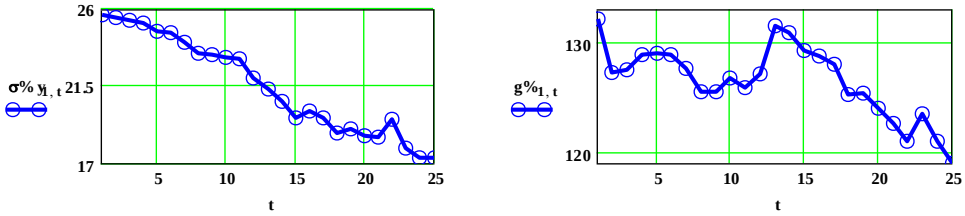


6) Finland corr(g%,s%) = 0.636





7) Austria corr(g%,s%) = 0.612



Quadrant IV (the most favourable) – 0 countries