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Unveiling the shadows: tracing the informal economy in the Balkans from 1996 to 2021

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ABSTRACT

Using the MIMIC model, we analyse the informal economy (IE) in Balkan countries from 1996 to 2021. Results show a decline in the IE, which started at approximately 35% in 1996 but remained relatively high at over 29% of GDP by 2021. This was driven by regulatory burden, financial freedom, urbanisation, macroeconomic factors, and government size. The COVID-19 pandemic caused a rise in informal activity in 2020, increasing by 1–3% points compared to 2019. This study highlights the role of policy-driven and macroeconomic factors in shaping the IE, addressing gaps in understanding post-reform socio-economic developments in the region.

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1. Introduction

The informal economy (IE) has attracted growing interest among economists and policymakers in recent decades, mainly due to its significant impact on society, national economies, tax revenues, and labour market dynamics. While the rapid expansion of many economies has led to a relative decline in unreported economic activity compared to traditional economies (Medina & Schneider, 2021), the informal sector remains substantial in developing or underdeveloped countries, posing considerable challenges to policymakers (Schneider, 2023; Dell'anno, 2022, 2023).

The IE is broadly described as a sector that does not adhere to national government regulations, conventions, or laws (Hart, 2008; Ihrig & Moe, 2004). It may involve both illegal and legal behaviour in monetary and non-monetary transactions. Illegal activities range from the sale of stolen goods to the sale and production of drugs, prostitution and trafficking, and drug smuggling, cultivation, and manufacturing (Mirus & Smith, 1997). Legal but informal activities can be classified as tax evasion or tax avoidance from both a monetary and non-monetary aspect (Dell'anno, 2023). For this study, we employ a narrower definition of the IE, focusing primarily on unreported economic activities that result in tax evasion and avoidance.[1]

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This study focuses on the Balkan Peninsula,[2] a region that offers a unique and compelling case for examining the IE due to its distinctive cultural, religious, political, and social structures. Over the last century, the Balkan countries have undergone significant transformations due to wars, conflicts, and ongoing social and political instability (Bartlett, 2009; Micevska, 2004; Penev, 2012). The effects of prolonged periods of destabilised governments have led to citizens' mistrust, resulting in increased informality (Micevska, 2004). Furthermore, since the 1990s, the Balkan countries, including Türkiye,[3] have undergone dramatic social and economic transformations, transitioning from command to market economies, which produced remarkable changes in their social, political, and economic infrastructure (Micevska, 2004).

The Balkan region's history of political upheaval and economic transition makes it particularly susceptible to informal economic activities. Many countries in the area face higher levels of corruption, organised crime, tax evasion, and black-market activity, all of which contribute to the scale of the region's informal sector (Berdiev et al., 2018; Gërxhani & van de Werfhorst, 2013; Williams & Horodnic, 2015). Additionally, the region's heavy reliance on remittances and the IE's role as a social safety net adds complexity to the issue (Meyer & Shera, 2017; Petreski et al., 2017).

While the MIMIC approach has been widely applied across various global contexts, this paper provides a timely, regionally focused contribution by applying the method to the Balkans over a 25-year period, including the COVID-19 crisis. Importantly, our study introduces refinements to the modelling specification, such as updated cause and indicator variables reflecting governance and institutional quality and captures the dynamic impact of global shocks on the informal sector.

Notably, the region has experienced a significant transformation from centrally planned, command economies during the post-communist era to liberalised, market-oriented systems. This transition was not smooth in most cases (Estrin & Mickiewicz, 2011; Raiser et al., 2002). Wars, ethnic conflicts, and political instability deeply disrupted institutional development and trust in public authorities (Efendic et al., 2011). As a result, examining the evolution and dynamics of the IE across this period provides critical insights into how informal sectors emerge, persist, or decline during prolonged economic and political restructuring.

In this article, we present the estimates of the IE in 10 Balkan Peninsula nations from 1996 to 2021 using the MIMIC (Multiple Indicators Multiple Causes) approach. This method allows us to integrate observable and latent data, providing a comprehensive analysis of the IE's size and trends. Our study makes several key contributions to the existing literature. Firstly, we provide a comprehensive, long-term analysis of the IE in the Balkans, spanning 25 years across countries. This extended timeframe allows us to capture long-term trends and the impacts of significant regional economic and political changes. Secondly, we apply the MIMIC method to this region, offering insights into its effectiveness in capturing the dynamics of the IE in transition economies.

Furthermore, while previous studies have used MIMIC in emerging economies, few have offered a harmonised, multi-country application for the Balkans that incorporates both pre- and post-COVID-19 dynamics, enabling us to uncover structural differences in informal economic behaviour across nations in a post-pandemic recovery setting. Furthermore, while previous global estimates, such as those in the World Bank's Informal Economy Database (Elgin et al., 2021), provide broad insights, they often rely

on heterogeneous data sources and lack the regional focus and model harmonisation we apply. Building on Breusch's (2005) critique of the MIMIC model's 'one-size-fits-all' application, it becomes imperative to adopt a region-specific approach when estimating the size of the informal economy, as applying uniform causes and indicators across highly diverse countries risks overlooking important contextual differences that shape informality. Thus, our estimates are produced using a consistent, tailored model across Balkan countries, incorporating region-specific structural factors and updated data through 2021. This enables more accurate, context-sensitive comparisons over time and across the region, especially during the post-communist and post-COVID transition periods. This application contributes to the methodological discourse on measuring informal economic activity.

Our estimating framework incorporates a wide range of variables, including monetary variables, non-monetary indicators, and contextual factors, providing a more nuanced understanding of the drivers of informality. This multifaceted approach allows for a more robust analysis of the complex factors influencing the IE (Dell'anno, 2023). We capture the impact of significant events, such as the 2008 financial crisis and the COVID-19 pandemic, on the IE in the region. This analysis provides valuable insights into how external shocks affect informal economic activity. Lastly, our study offers policy recommendations based on empirical findings, contributing to the ongoing dialogue on addressing the challenges the IE poses in developing regions.

The relevance of this research extends beyond academic interest. Understanding the size, trends, and drivers of the IE is crucial for policymakers in the Balkan region and beyond. It can inform strategies for economic development, tax policy, labour market regulations, and social welfare programs. Moreover, as some Balkan countries aspire to join the European Union, addressing the IE becomes a critical aspect of their accession process.

Our analysis not only provides estimates of the size of the IE but also examines its trends, drivers, and policy implications. We investigate how factors such as tax burden, regulatory quality, institutional effectiveness, and macroeconomic conditions influence the size of the informal sector. Additionally, we explore how the IE interacts with formal economic structures and how it responds to policy interventions and external shocks. By adopting an updated model structure, cross-country harmonisation, and an extended period that includes COVID-19, this study provides fresh insights not previously captured in the literature. By providing this in-depth analysis of the IE in the Balkan Peninsula, we aim to contribute to a better understanding of this complex economic phenomenon and to inform policy discussions on how to address the challenges and opportunities it presents.

Our findings also speak to broader policy agendas, particularly in relation to the Sustainable Development Goals (e.g. SDG 8 on decent work and SDG 10 on inequality) and the EU's formalisation strategies. Many countries in our sample are EU member states or accession candidates, and understanding the structure and drivers of informality is key to designing targeted interventions that encourage formalisation without displacing vulnerable informal workers.

The rest of the paper is structured as follows: Section two provides a comprehensive literature review, discussing the key theories and findings concerning the size and causes of the IE. We pay particular attention to previous studies on the Balkan region and other

transitioning economies. Section three presents our data sources and methodology, providing a detailed explanation of the MIMIC approach and our model specifications. Section four presents our analysis and discussion of results, including country-specific findings, we discuss their implications for policy, and acknowledge the limitations of our study. In Section five and six, we provide some analysis on the impact of COVID-19 and comparisons with existing estimates and regional trends. Finally, we conclude with suggestions for future research directions in this field.

2. Literature review

The first issue when someone delves into the relevant literature is deciding which terminology and definitions to use. Informality is often referred to as the hidden economy, the informal economy, the shadow economy, the grey economy, the black economy, or the cash economy. For consistency, we will employ the 'informal economy' throughout this study. We use Medina and Schneider's (2021) and United Nations (2025) definitions of the IE, which captures all economic activity concealed from official authorities for monetary, regulatory, and institutional reasons. This definition includes motives such as tax evasion, avoidance of social security contributions, corruption, insufficient political institutions, and a lack of rule of law. It is vital to stress that the activities included in this definition are productive and would contribute to the country's GDP if counted. However, it does not apply to certain domestic and illegal activities.

The literature on estimating the size of the IE is divided into two categories: direct and indirect approaches. Direct approaches rely on surveys, whereas indirect methods use indicators to determine the extent of the IE. We apply the multiple indicator-multiple cause (MIMIC) method, addressed in more depth in section three.

Using a MIMIC model, Schneider et al. (2010) estimated the IE of 162 countries globally from 1999 to 2007. Their estimates also include the Balkan Peninsula, indicating that the IE in that region accounts for an average of almost 30% of GDP. According to this study, Albania had a 35.7% IE in 1999, which decreased to about 32.9% in 2007; Bulgaria's IE amounted to 37.3% of GDP in 1999, which then declined to 32.7% in 2007; Greece's IE was estimated to be less than 30%, with 28.5% and 26.5% in 1999 and 2007, respectively; and Bosnia and Herzegovina's IE was estimated to be less than 30%. This report does not include data on Serbia's informal sector.

Other studies also measure the IE using a worldwide dataset that includes countries on the Balkan Peninsula. Such studies are Schneider and Buehn (2007)[4]; Schneider (2009)[5]; Buehn and Schneider (2012)[6]; Schneider et al. (2013)[7]; Alm and Embaye (2013)[8]; Hassan and Schneider (2016)[9]; Bitzenis et al. (2016)[10]; Elgin et al. (2021)[11] and Medina and Schneider (2021).[12] However, different studies, depending on the use of methodology or model for measuring the size of the IE, can provide different results (Schneider, 2023). This is particularly the case for transition economies, where data quality can be an issue (Andrei et al., 2010).

While these studies have significantly contributed to our understanding of informal economies, particularly in the Balkan region, several gaps remain. First, most existing research focuses on shorter periods, failing to capture long-term trends and the full impact of economic transitions in the Balkans. Second, studies often examine a limited number of countries or use varying methodologies, making regional comparisons

difficult. Third, there is a lack of comprehensive analysis that incorporates the effects of major economic events (such as the 2008 financial crisis) and recent shocks (such as the COVID-19 pandemic) on the IE in this region. Finally, while many studies identify the drivers of informality, few provide actionable policy recommendations tailored to the unique context of the Balkan countries. Our study aims to address these gaps by providing a comprehensive, long-term analysis of Balkan countries using a consistent methodology, incorporating recent economic shocks, and offering policy implications based on our findings.

2.1. Main causes of informality and key indicators

Understanding the variables contributing to the IE and the indicators used to measure its size is crucial for developing a robust model of the informal sector. This knowledge is essential for academic purposes and policymakers, as the IE has significant implications for the general economy, tax revenues, and labour market dynamics. Based on a comprehensive analysis of current research, we have identified four major factors as the underlying causes of the IE: (i.) Tax and regulations burden,[13] (ii.) Quality of institutions and government,[14] (iii.) Economic conditions,[15] (iv.) Structural characteristics of the economy.[16] These factors are discussed in detail below, with particular attention to their relevance in the Balkan context and their evolution over the 1996–2021 period.

2.1.1. Tax and regulations burden

One of the most prominent reasons for informal activity is the tax burden. The cost of direct and indirect taxation creates a significant incentive for individuals and businesses to conceal their income or engage in the IE. The cost of social security contributions is also an important consideration at this level. Most research employs the tax rate as a key indicator (Giles et al., 2002; Schneider & Buehn, 2007; Dell'anno, 2007 Schneider, 2022). Other studies use government revenues, spending, and the Fiscal Freedom Index (Buehn & Schneider, 2012). Due to data availability constraints, our study will use three variables as proxies for the social security and taxation burden: Government Revenues as a percentage of GDP, Government Spending Index, and Fiscal Freedom Index. Tax morality – people's attitudes towards the state – reflects individuals' tendency to quit official employment for the informal sector. When tax morality deteriorates, it expands the informal sector (Schneider & Enste, 2000). To capture this aspect, we will use the Government Spending Index and the Government Effectiveness Index to analyse economic informality.

Similarly, the regulatory burden incentivises entry into the IE, particularly in countries with stringent legal and administrative restrictions. The more stringent the rules, such as those requiring business registration, permits, labour market constraints, and trade barriers, the greater the incentive to enter the IE. The main channel is the increased costs businesses face due to the high regulatory burden. Following existing literature, we will obtain this data from the Heritage Foundation's Business Freedom Index (Schneider and Buehn, 2007; Dell'anno, 2007; Vo & Ly, 2014).

In the Balkan context, the tax and regulatory burden has evolved significantly over the 1996–2021 period. Many countries in the region have undergone substantial reforms as part of their transition from command to market economies and, in some cases, as part of

their EU accession process. For instance, Bulgaria and Romania have made efforts to simplify their tax systems and reduce regulatory burdens as they prepare for EU membership. However, other countries, such as Bosnia and Herzegovina, struggle with complex regulatory systems that may encourage informal activity.

2.1.2. Quality of institutions and government

The quality of institutions, public services, and a government's capacity to combat corruption while still protecting people in the formal sector are key causes of informality (Buehn & Schneider, 2012; Medina & Schneider, 2021). We use the World Bank's World Governance Indicators' Government Effectiveness Index to capture the effectiveness of institutions and government. Most countries in our sample have a high level of corruption (Micevska, 2004). Corruption is evident in the judicial system, ambiguous legislation, and heavy bureaucracy. This is measured using the Government Effectiveness Index, Government Integrity Index, Rule of Law Index, Corruption Control Index, and Regulatory Quality factors (Buehn & Schneider, 2012; Schneider & Enste, 2000; Zhanabekov, 2022). The quality of institutions and government has been a particularly significant factor in the Balkan region. Countries like Slovenia and Croatia have made substantial progress in improving institutional quality, likely contributing to a reduction in their informal sectors. In contrast, countries like Albania and North Macedonia continue to struggle with corruption and weak institutions, which may be sustaining larger informal economies.

The political environment is another crucial component of the IE. The Balkan region has experienced significant political upheavals in recent decades. Most of these changes have been brought about by internal conflicts, revolutions, civil wars, or wars. As a result, uncertainty and unstable political institutions can impact a country's economic growth and the scope and development of informal economic activity (Teobaldelli & Schneider, 2013).[17] The Rule of Law Index and the Government Integrity Index will be used in the study as proxies for this informality driver.

2.1.3. Economic conditions

Several authors have identified inflation as a significant factor in informality (Alm & Embaye, 2013; Elshamy, 2015; Giles, 1999; Vuletin, 2008; Zhanabekov, 2022). Inflation distorts income distribution, which may lead to disregard for tax laws because it tends to be uneven across sectors. According to the theory, the IE should expand when inflation rises. This will be measured using the inflation variable (GDP Deflator) and the Heritage Foundation's Monetary Freedom Index.

Multiple studies demonstrate that during a recession, people engage in informal economic activities to compensate for income losses in the formal sector (Bajada & Schneider, 2005; Dell'anno, 2007; Hassan & Schneider, 2016; Vuletin, 2008). As a result, unemployment may be seen as a fundamental factor of economic informality; the higher the unemployment rate in a country, the greater the incentive for individuals to engage in or enter the informal sector (Buehn & Schneider, 2012; Feld & Schneider, 2010; Hassan & Schneider, 2016).

The International Labour Organisation's unemployment rate is used in this study to represent this. We also use the World Bank's employment-to-population ratio for the inverse effect. While the link between the unemployment rate and the level of the IE is

likely to be positive, the relationship between the employment-to-population ratio and the level of the IE is expected to be negative. People who appear in official statistics as employed and pay taxes may also be involved in the informal sector (Schneider & Enste, 2000). The need for robustness justifies the use of one or both variables.

Economic conditions have played a crucial role in shaping the IE in the Balkans over the study period. The region has experienced significant economic volatility, including the effects of the global financial crisis in 2008 and the COVID-19 pandemic in 2020–2021. These events have led to spikes in unemployment and economic uncertainty, potentially driving more activity into the informal sector. For instance, Greece experienced a severe crisis in 2009 that lasted many years, likely contributing to its IE's expansion during this period.

2.1.4. Structural characteristics of the economy

The economy's structural characteristics may have a substantial impact on the formation of opportunities to engage in informal economic activity. We identify two possible causes for this. The first is the size of an economy's agriculture sector. The theory is that the more dominant the agriculture sector is, the greater the IE will be, all else being equal. This is reinforced by empirical research demonstrating that informal labour is sectoral and ubiquitous in the primary sector (Elshamy, 2015; Hassan & Schneider, 2016; Vuletin, 2008). The World Bank Development Indicators' (WBDI) agriculture value added (% of GDP) will be used to estimate the size of the agriculture sector.

Second, we anticipate that a country's level of informality would be influenced by its degree of urbanisation. The government's inadequate enforcement powers in rural areas are a primary cause of the concerns above (Alm & Embaye, 2013; Elshamy, 2015). To capture this, the model will utilise the urban population fraction from WBDI as a proxy for the total population. Interchangeably, we will use the Degree of Urbanisation from WBDI as a proxy for agriculture value added (% of GDP).

In the Balkan context, the economy's structural characteristics have undergone significant changes over the study period. Many countries in the region have seen a decline in the relative importance of their agricultural sectors and an increase in urbanisation. However, these changes have not been uniform across the region. Countries like Albania and North Macedonia still have relatively large agricultural sectors, which may contribute to their higher levels of informality.

The relative importance of these causes varies across the Balkan countries and has evolved over the 1996–2021 period. In the early years of our study, the transition from command to market economies was a dominant factor, leading to significant restructuring of tax systems, regulatory environments, and economic structures. High levels of informality characterised this period across much of the region. As the transition progressed, institutional quality became an increasingly important factor. Countries that made more progress in improving their institutions, often as part of EU accession processes, generally saw declines in their informal sectors. However, these factors remained significant drivers of informality for countries that continued to struggle with weak institutions and corruption.

The economy's structural characteristics have generally become less important as drivers of informality over time, as most countries in the region have seen declines in

their agricultural sectors and increases in urbanisation. However, these factors remain significant in some countries.

2.2. Main indicators of informality

Changes in the size and development of the IE within a country can be reflected in the following four indicators:

- **Currency in circulation**: If the informal sector expands, there will be greater demand for cash transactions. As a result, monetary indicator trends must be considered (Schneider & Buehn, 2007; Dell'anno, 2007; Schneider et al., 2010; Buehn & Schneider, 2012). This is often reflected by the variable Money and quasi-money (M2) as a proportion of GDP, the M1 to M2 ratio, or Cash in circulation.
- **Labour-market activity**: Changes in the employment rate might be useful indicators (Buehn & Schneider, 2012; Dell'anno, 2007; Schneider & Buehn, 2007; Schneider et al., 2010). Increased engagement in the informal sector may lead to decreased participation in the formal economy. Similarly, more informal-sector activity may be expected to result in reduced working hours in the official economy. The labour force participation ratio has traditionally captured this.
- **Production market developments**: These are seen as a significant signal (Buehn & Schneider, 2012; Dell'anno, 2007; Schneider & Buehn, 2007; Schneider et al., 2010). An increase in the size of the informal sector means that inputs (such as labour) shift out of the official economy, potentially lowering the official growth rate. The GDP growth rate or GDP per capita will capture this.
- **Electric power consumption** is the single best physical indication of total (official plus unofficial) economic activity (Kaufmann & Kaliberda, 1996). This approach generally examines the link between electricity consumption and GDP, since they share a similar elasticity, and the difference in their growth rates is attributed to the IE (Alderslade et al., 2006; Schneider & Buehn, 2007). Kaufmann and Kaliberda (1996) create a proxy for the whole economy and then subtract the official GDP from it, yielding the unofficial GDP, a measure of the IE. This makes it a straightforward method for estimating the size of the informal sector. It is also a separate measurement of the IE that many scholars have widely used (Alderslade et al., 2006; Lackó, 2000; Schneider & Buehn, 2007). It is an important indicator of the IE, especially in transition and developing countries. Arby et al. (2012) previously used this as an indicator in the MIMIC model approach. We will use World Bank Development Indicators data on electric power consumption (kWh per capita) to measure this.

This study relies on datasets compiled from a variety of sources, including World Bank Development Indicators, World Bank Governance Indicators, Balkan Central Banks, the Heritage Foundation, and advanced datasets offered by the International Monetary Fund (IMF), European Bank for Reconstruction and Development (EBRD), European Central Bank (ECB), and more. Using multiple data sources allows us to cross-verify information and ensure the robustness of our analysis.

In conclusion, the causes and indicators of informality in the Balkan Peninsula are complex and interrelated. While we have identified four main categories of causes and

four key indicators, it is clear that these factors interact in ways that can reinforce or mitigate each other's effects. Our study aims to capture these complexities by incorporating multiple indicators and causes into our MIMIC model. By examining these factors over 25 years across Balkan countries, we hope to provide insights into the region's current state of informal economies and how they have evolved in response to significant economic, political, and social changes. This long-term perspective is crucial for understanding the persistence of informal economies and fordeveloping effective policies to address them.

3. Methodology

Our methodology employs the MIMIC model to measure the IE in the nations of the Balkan Peninsula. The MIMIC model consists of two components: the measurement model, which relates the unobserved variable to the observed indicators, and the structural equation model, which specifies the causal relationships between the observed variables and the unobserved variable (in this case, the size of the IE). A set of factors influences the magnitude of this unobserved variable, and the interaction over time between the causes (x_{it}), the size of the IE at time t (η_t), and the indicators (y_{it}) may be mathematically expressed and empirically measured.

Importantly, we apply a harmonised MIMIC model specification across 10 Balkan countries using a consistent framework and country-specific data over 25 years (1996–2021). Unlike many global databases that combine methodologies and periods, our unified approach enables more robust regional comparisons and dynamic analysis. We also introduce regionally relevant causes and indicators that reflect institutional quality, market and regulatory freedom, serving as a proxy for the transition from centrally planned to market economies.

3.1. Econometric model

After identifying and discussing the primary causes and indications, we can now incorporate them into a model, as per below. The Structural Equation Model (SEM) provides the essential empirical equation of a latent variable and investigates its interaction with other variables using covariance structures. The structural equation model is divided into the Structural Equation Model and the Measurement Model. Jöreskog and Goldberger (1975) gave the initial specification for the SEM model.[18] This specification considers a latent variable y^* that is linearly determined and is subject to a disturbance ε, by a set of observable exogenous causes $x_1, \ldots, x_k$:

$$y^* = \alpha_1 x_1 + \ldots + \alpha_k x_k + \varepsilon \tag{1}$$

According to the SEM classification, the equation with the relationships between the latent variable η (informal economy) and the X_q (causes) is:

$$\eta = \alpha + \gamma_1 x_1 + \gamma_2 x_2 + \gamma_3 x_3 + \gamma_4 x_4 + \gamma_5 x_5 + \gamma_6 x_6 + \ldots + \xi \tag{2}$$

The equations system that links the indicators and the unobservable variable (η) is the Measurement Model (Dell'anno, 2007):

$$Y_1 = \delta_1 + \lambda_1 \eta + \varepsilon \tag{3}$$

$$Y_2 = \delta_2 + \lambda_2 \eta + \varepsilon \tag{4}$$

where we have, Y_1 and Y_2 representing the possible observable indicators of the IE and η corresponds to the latent variable (in our case, the IE). Finally, ε is a random error term, and λ denotes the structural parameters of the measurement model. We can generalise the above equations as follows:

$$\eta = \alpha + \sum \gamma_q x_q + \xi \tag{5}$$

$$Y_q = \delta_q + \lambda_q \eta + \varepsilon \tag{6}$$

The structural part of the equation, as indicated in Equation (5), and the measurement part of the equation presented in Equation (6) above, can also be expressed in the following way:

Part 1: The Structural Equation Model

$$\text{Informal Economy} = \left[\gamma_1, \gamma_2, \gamma_3, \gamma_4, \gamma_5, \gamma_6 \ldots \gamma_q\right] \begin{bmatrix} \text{Business Freedom Index} \\ \text{Government Effectiveness} \\ \text{Dominance of the Agriculture sector} \\ \text{Unemployment Rate} \\ \text{Rule of Law} \\ \text{Degree of Urbanisation} \\ \text{Government Spending} \\ \text{Control of Corruption} \\ \text{Monetary Freedom Index} \\ \text{Tax revenue} \\ - \\ - \\ - \\ - \\ - \\ \text{etc.} \end{bmatrix} + \xi \tag{7}$$

Part 2: The Measurement Equation model

$$\begin{bmatrix} \textit{GDPperCapita} \\ \textit{LabourForceParticipationRatio} \\ \textit{ElectricPowerConsumption} \\ - \\ - \\ - \\ - \\ \textit{etc} \end{bmatrix} = \begin{bmatrix} 1 \\ \lambda_2 \\ \lambda_3 \\ \lambda_4 \\ - \\ - \\ \lambda_q \end{bmatrix} \textit{Informal Economy} + \varepsilon \tag{8}$$

To strengthen the business cycle analysis, we additionally explore fluctuations in the estimated size of the IE over time and relate them to key recessionary periods, notably the 2008 financial crisis and the COVID-19 pandemic. This approach allows us to comment on

the counter-cyclicality of informality, in line with recent literature (see for example Elgin et al., 2021).

To ensure harmonisation across the 10 Balkan countries, we apply identical model specifications to each country using the same set of causal and indicator variables. Unlike global databases that may use different methods or variables for different countries, our approach maintains consistency by: (1) using the same time period (1996–2021) for all countries; (2) applying identical variable definitions sourced from consistent international databases; and (3) using the same benchmarking procedure across all countries.

We rely on several key indices to assess the fit of our MIMIC models. The Root Mean Square Error of Approximation (RMSEA) and the Standardised Root Mean Square Residual (SRMR) assess absolute fit; values below 0.08 indicate good fit. For incremental fit, we use the Comparative Fit Index (CFI) and Tucker Lewis Index (TLI), where values above 0.90 suggest a good fit. Although sensitive to sample size, we also consider the chi-square statistic and the coefficient of determination (CD) to assess the model's explanatory power. These diverse criteria allow us to comprehensively evaluate our model's performance across different dimensions of fit.

While the MIMIC model is well-suited for studying informal economies, essential to acknowledge its limitations in the Balkan context. The model assumes a stable relationship between indicators and causes over time, which may not hold in rapidly transitioning economies. Additionally, the MIMIC approach relies on proxy variables for unobservable factors, which may not fully capture the complexity of informal economic activities. In the diverse Balkan region, country-specific informal practices may not be adequately represented by our general model. Nonetheless, our tailored model specifications, which predominantly focus on market economy (market freedom, regulatory burden and institutional quality proxies), offer a more context-sensitive framework for this region. Despite these limitations, the MIMIC model remains the most comprehensive tool for estimating the size of informal economies across multiple countries and periods (Dell'anno, 2023; Dell'anno & Schneider, 2006).

Our methodological approach builds upon and extends recent studies on informal economies in transition regions. Like Medina and Schneider (2021), we employ the MIMIC model but expand the timeframe to capture long-term trends specific to the Balkan region. Our approach is similar to that of Bitzenis et al. (2016), focusing on a specific European region. Still, we cover a broader set of countries over a more extended period. Unlike some studies that rely solely on macroeconomic indicators, we incorporate institutional quality measures, reflecting the importance of governance in transitioning economies. Moreover, our paper explicitly responds to recent academic and policy concerns by aligning with the EU's formalisation goals, mapping IE dynamics across critical shocks such as COVID-19, and generating policy-relevant estimates for countries both inside and aspiring to join the EU. This comprehensive and tailored approach allows us to contribute to the existing literature by providing a nuanced, long-term analysis of informality in the Balkan context.

3.2. The benchmarking procedure

There is no clear consensus in the literature over which benchmarking process, also known as a calibration or scaling method, should be used to derive the absolute values

of the IE from the MIMIC results (Buehn & Schneider, 2012; Schneider, 2023). However, the most widely used approach is the benchmarking procedure presented by Buehn and Schneider (2012) in response to Schneider et al. (2010). Later, Hassan and Schneider (2016) corroborate that the benchmarking model presented in Equation (9) is the most extensively utilised in the literature as it addresses Breusch's (2005) critique of allocating the monetary unit of measure from the reference indicator to the latent variable.

The benchmarking procedure is applied to calibrate ordinal estimates into cardinal values and to convert this index into percentage units. This proceduretherefore requires a prior estimate of a country's IE. The formula is as follows:

$$\eta_t = \frac{\tilde{\eta}_t}{\tilde{\eta}_{\text{the base year}}} \eta^*_{\text{the base year}} \tag{9}$$

To[19] ensure comparability with global datasets such as the World Bank Informal Economy Database, we align our base year with published estimates, while maintaining full control over the model structure, variable inclusion, and calibration. This enables us to retain methodological rigour while producing region-specific, policy-relevant estimates.

3.3. The problem of endogeneity

Including GDP or related variables as causes or indicators in the MIMIC model raises endogeneity concerns. Surprisingly, most existing empirical works that use GDP, GDP per capita, or GDP growth in their model do not address the endogeneity problem. One exception is the research by Medina and Schneider (2021), which employs the Night Lights intensity technique proposed by Henderson et al. (2012). Instead of GDP-related factors, this technique uses data on light intensity from space as a proxy for economic development. However, similar data for the Balkan Peninsula nations do not exist for the timeframe of this research.

Furthermore, this strategy overlooks the fact that some economic activity takes place without additional lighting, particularly in rural areas. Compared to other European nations, countries in the Balkan Peninsula are more reliant on rural economic activities such as agriculture. As a result, this method may underestimate the size of the country's informal sector.

Medina and Schneider (2021) recommend the Predictive Mean Matching approach. This technique treats the IE as missing. Thenit computes the missing values for the remaining sample using existing IE estimatesfrom surveys in select countries. The immediate issue is a lack of survey data for the countries in question during our sample period, as well as the possibility that institutional, political, economic, and social differences in these countries may result in under- or overestimation of missing values for the IE.

One might further evaluate the robustness of the model results by removing all GDP-related variables as causes and indicators from the MIMIC model. However, it should be emphasised that the features of the selected nations play a significant role in addressing the endogeneity problem. The Balkan Peninsula's countries face a strong IE. Previous studies indicate that the IE accounts for more than 30% of the GDP of the nations studied. The scale of the IE directly influences GDP, rather than GDP having an impact on the size of the IE. Exogenous causative variables such as the rule of law, the load of government

regulations, the level of agriculture, and people's attitudes their institutions and government are far more important than GDP growth rates. GDP growth or similar variables may play a small role in producing the IE, but they reflect a larger IE.

4. Results and analysis

Table 1 illustrates the MIMIC specifications chosen for the benchmarking technique. All MIMIC estimations were calculated using Equations (5) and (6). The benchmarking technique converts the MIMIC model indices into absolute values for the size of the IE in the Balkan countries. We chose six MIMIC specifications for the benchmarking procedure as they have the best model fit statistics.

All MIMIC specifications share common indicators and causal variables in the model analysis. GDP per capita and electric power consumption are the indicators considered in all specifications. GDP per capita is the reference indicator variable, limited to −1. The Business Freedom Index, Monetary Freedom Index, Degree of Urbanisation, and Government Effectiveness Index are four of the causal variables included in the models. Alternative specifications, as given in Table 1, introduce three more causal variables. MIMIC specifications 1 and 2 use a 6–1-2 model with six causal variables, one latent variable, and two indicators. The Business Freedom Index, Monetary Freedom Index, Degree of Urbanisation, Government Effectiveness Index, Financial Freedom Index, and Government Spending are the six causes. The employment-to-population ratio replaces the Financial Freedom Index in MIMIC specification 2.

The model analysis in MIMIC specification 3 includes seven causal variables and two indicators. In addition to the Financial Freedom Index, this model incorporates the ratio. Models 1 and 2 are robust and perform well despite including seven causal variables. Model 4 employs six causes, one latent variable, and two indicators, as do models 1 and 2. Instead of incorporating the government spending index, it uses a ratio to capture labour market characteristics in these countries. We also evaluated specifications with fewer causal variables to examine the model's robustness. Model specification 5 employs a 5–1-

Table 1. Selected MIMIC specifications for the benchmarking procedure.

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Causal Variables	6–1-2 model	6–1-2 model	7–1-2 model	6–1-2 model	5–1-2 model	4–1-2 model
Business Freedom Index	●	●	●	●	●	●
Monetary Freedom Index	●	●	●	●	●	●
Degree of Urbanisation	●	●	●	●	●	●
Government Effectiveness Index	●	●	●	●	●	●
Financial Freedom Index	●		●	●	●	
Government Spending	●	●	●			
Employment to Population ratio		●	●	●		
Indicator variables						
GDP per capita, PPP (constrained)	●	●	●	●	●	●
Electric Power Consumption	●	●	●	●	●	●

Note: A dot (●) indicates that the variable is included in the specified MIMIC model. Model structures refer to the number of cause-indicator variables (e.g. 6–1-2). Indicator variables refer to observable effects influenced by the IE.

2 model, omitting the Government Spending Index and the ratio. Similarly, model specification 6 is a 4–1-2 model that does not include the Financial Freedom Index.

All MIMIC regressions were conducted using robust SEM settings. The option was employed to improve the chi-square statistic when non-normal and non-stationary variables were present and to relax the assumption of multivariate normality (Satorra & Bentler, 1994). Furthermore, the regressions account for heteroscedasticity to ensure robustness of the analysis. The MIMIC specification analysis produced path coefficients that illustrate the influence of each cause and indicator on the latent variable, along with their directions. This tailored model structure reflects the region's unique historical and institutional features, including the transition to a market economy and EU alignment. The use of these variables in the MIMIC model analysis, as stated above, is supported by the literature (Abdih & Medina, 2013; Bitzenis et al., 2016; Dell'anno, 2007; Hassan & Schneider, 2016; Medina & Schneider, 2021; Schneider & Buehn, 2007; Schneider et al., 2010; Vuletin, 2008). The statistics produced by these variables, along with the chi-square and model fit statistics, justify their inclusionin the MIMIC model analysis.

Our MIMIC model specifications reveal significant variations in the size and trends of informal economies across the Balkan region. The average size of the IE across all countries decreased from approximately 35% of GDP in 1996 to around 29% in 2021, indicating a general trend towards formalisation. This finding supports the hypothesis that, over time, institutional strengthening and deeper European integration are associated with lower levels of informality. However, this trend is not uniform across all countries. Countries like Slovenia, Romania, and Bulgaria have shown the most significant reductions in their informal sectors, likely due to their EU accession processes and subsequent institutional reforms. In contrast, countries like Bosnia and Herzegovina and North Macedonia continue to have larger informal economies, suggesting persistent structural and institutional challenges. Compared to other studies, our results align with the general trend of declining informality in transition economies noted by Medina and Schneider (2021). However, our findings indicate that the Balkan region's informal sector remains more significant than the EU average, highlighting the ongoing challenges these countries face. Compared with global MIMIC-based estimates, such as those in the World Bank's Informal Economy Database, our results provide more regionally harmonised, context-specific insights for a consistent group of countries over a longer timeframe, including the COVID-19 period.

Table 2 summarises the variable coefficients utilised in the MIMIC model across all specifications. Almost all these variables are statistically significant at the 1% or the 5% confidence level. The latent variable has a significant negative relationship with the Business Freedom Index, Monetary Freedom Index, Degree of Urbanisation, Government Effectiveness Index, and employment-to-population ratio. The Government Spending Index and the Financial Freedom Index, on the other hand, indicate a positive association.

The usage of electricity is frequently regarded as a measure of the IE's effect (Alderslade et al., 2006; Arby et al., 2012; Kaufmann & Kaliberda, 1996; Schneider & Enste, 2000). According to the underlying theory, a larger informal sector increases per capita energy use. Under the assumption of unitary elasticity, a rise in power consumption corresponds to an increase in real GDP (Arby et al., 2012; Schneider & Enste, 2000). However, contrary to Arby et al. (2012) 's theory and conclusions, the data show

Table 2. MIMIC results for each model specification.

		MIMIC Model 1	MIMIC Model 2	MIMIC Model 3	MIMIC Model 4	MIMIC Model 5	MIMIC Model 6
	Model specification	6–1-2 model	6–1-2 model	7–1-2 model	6–1-2 model	5–1-2 model	4–1-2 model
Causal variables	Business Freedom Index	−1.37	−0.78	−0.95	−0.65	−0.91	−0.83
		(−5.12)	(−2.69)	(−3.51)	(−2.09)	(−3.27)	(−2.90)
	Monetary Freedom Index	−0.63	−0.87	−0.89	−0.90	−0.76	−0.71
		(−4.77)	(−5.47)	(−5.82)	(−5.77)	(−6.06)	(−4.81)
	Degree of Urbanisation	−1.20	−1.73	−1.69	−1.10	−0.93	−0.83
		(−4.18)	(−4.96)	(−5.19)	(−3.38)	(−3.02)	(−2.61)
	Financial Freedom Index	0.86		0.66	0.85	0.92	
		(4.97)		(3.97)	(4.88)	(5.37)	
	Government Spending	0.68	1.05	0.94			
		(6.33)	(8.79)	(7.78)			
	Government Effectiveness Index	−105.38	−88.81	−93.23	−112.89	−116.37	−113.52
		(−22.39)	(−16.52)	(−17.60)	(−23.29)	(−24.39)	(−22.34)
	Employment to Population ratio		−2.40	−1.92	−0.84		
			(−5.89)	(−4.92)	(−2.03)		
Indicator variables	GDP per capita, PPP (constrained)	−1.00	−1.00	−1.00	−1.00	−1.00	−1.00
		-	-	-	-	-	-
	Electric Power Consumption	−13.72	−13.70	−13.72	−13.35	−13.41	−13.29
		(−14.99)	(−14.91)	(−15.32)	(−14.85)	(−14.74)	(−13.94)

Note: The table reports estimated coefficients and t-values (in parentheses) for each causal and indicator variable across different MIMIC model specifications. The model structure notation (e.g. 6–1-2) refers to the number of cause variables and the indicator variables, respectively. A constrained coefficient of −1.00 is applied to the indicator (GDP per capita, PPP) for identification purposes. Balkan countries, 260 observations. MIMIC specifications 1, 2, 3, and 5 regression results are statistically significant at the 1% level. For MIMIC specification 4, the Business Freedom Index and the Employment-to-Population ratio are significant at the 5% level, while theother variables are significant at the 1% level. For MIMIC specification 6, regression analysis reveals that all variables are significant at the 1% level except the Degree of Urbanisation, which is significant at the 5% level.

a negative relationship between electricity use and the growth of the IE in Balkan Peninsula nations. One probable explanation is that people engaged in informal economic activities frequently undertake low-skilled, low-tech activities that require little or no energy. Individuals and businesses that depend on a reliable power supply for their operations prefer to follow laws and regulations to maintain a low profile. This may suggest that informal activity in the region is concentrated in low-skilled and low-tech occupations with minimal energy requirements, particularly in rural or agricultural sectors.

Individuals and businesses in the IE avoid excessive energy use because doing so may attract the attention of authorities, given their tendency to operate in secret. The negative relationship between the Degree of Urbanisation and the size of the IE confirms this finding. The Degree of Urbanisation is used in the literature as a proxy for the importance of the agriculture sector. Higher levels of urbanisation suggest a reduction in the importance of agriculture in GDP. As a result, a positive relationship between the size of the agriculture sector and the IE is anticipated. Although the model fit statistics are insignificant, other tested model specifications also show this association with statistical significance. Agricultural activities often demand less electricity than other businesses, as they rely on alternative energy sources such as petrol and natural gas.

Furthermore, the statistically significant relationship between the Degree of Urbanisation and the size of the IE implies that individuals living in cities engage in more formal economic activities than those living in rural areas. As a result, the variables

Table 3. Key model fit statistics for all MIMIC specifications with acceptable values.

Index type	Index name	MIMIC Spec 1 value22F[21]	MIMIC Spec 2 value	MIMIC Spec 3 value	MIMIC Spec 4 value	MIMIC Spec 5 value	MIMIC Spec 6 value	Acceptable Value
Incremental	CFI[22]	1.00	1.00	1.00	1.00	1.00	1.00	≥0.90
Fit Indices	TLI[23]	0.99	0.99	0.99	1.01	1.01	1.01	≥0.90
Absolute Fit	RMSEA[24]	0.05**	0.05**	0.04**	0.00***	0.00***	0.00***	≤0.08
Indices	SRMR	0.02**	0.02**	0.02**	0.01***	0.01***	0.01***	≤0.08
R-squared	CD	0.94	0.94	0.95	0.90	0.90	0.87	≥0.90

Note: This table reports model fit statistics for six MIMIC model specifications. CFI (Comparative Fit Index) and TLI (Tucker–Lewis Index) are incremental fit indices; values ≥0.90 indicate acceptable fit. RMSEA (Root Mean Square Error of Approximation) and SRMR (Standardised Root Mean Square Residual) are absolute fit indices, where values ≤0.08 suggest good.

of Agriculture Sector Dominance and Degree of Urbanisation can be used as proxies for one another. Last, GDP per capita has a negative relationship with the IE. Following the approach of Dell'anno (2007) and Hassan and Schneider (2016), this variable serves as the reference indicator variable and has been set to −1 for this regression.

The model fit statistics for all MIMIC specifications (Table 3) are highly significant and within the acceptable values. Based on these statistics, the rationale for selecting the six MIMIC specifications for the benchmarking procedure to convert the MIMIC model indexes into absolute values for the IE has been established. The model fit statistics for all the MIMIC specifications are statistically significant at the 1%, 5%, and 10% levels.

Our results demonstrate strong statistical significance across most variables and model specifications. The consistently high R-squared values, ranging from 0.87 to 0.95, indicate that our models explain a large proportion of the variance in informal economic activity. The robustness of our findings is supported by the consistency of results across different MIMIC specifications, providing confidence in the reliability of our estimates. However, it is important to acknowledge certain limitations of our study. Data quality and consistency across different Balkan countries and over the 25 years may vary, potentially affecting the precision of our estimates. Despite our comprehensive model, there may be unobserved country-specific factors influencing informal economic activity that our model does not capture. Our model also assumes a degree of stability in the relationship between causes and indicators of informality, which may not hold over the entire study period, given the region's significant economic and political changes.

Table 4 presents the full model fit statistics for all our MIMIC specifications. The RMSEA value for MIMIC Specifications 1 and 2 is 0.05, while MIMIC Specification 3 is slightly lower at 0.04. Notably, the RMSEA values for MIMIC Specifications 4, 5, and 6 are reduced to 0.00. RMSEA values indicate a robust model fit across all MIMIC specifications, well within acceptable ranges, and statistically significant at the 1% or 5% levels (MacCallum et al., 1996). Similarly, an SRMR value below 0.08 indicates a good fit (Hu & Bentler, 1999). The p-close measure is used to assess the accuracy of RMSEA, which is widely reported in the literature (Kenny, 2015).[20] The p-close values for all six MIMIC Specifications confirm the accuracy of the models' RMSEA and overall model fit. Only MIMIC Specifications 1 and 2 have a p-close value of 0.4, which is still close to 0.5. The R-squared or the CD value is another parameter in the MIMIC specifications that indicates a good model fit, demonstrating that the model explains more than 90% of the data around its mean.

Table 4. Full model fit statistics for all MIMIC specifications.

Model specifications (Balkan countries, 260 observations)		MIMIC Specification 1	MIMIC Specification 2	MIMIC Specification 3	MIMIC Specification 4	MIMIC Specification 5	MIMIC Specification 6
		6–1-2 model	6–1-2 model	7–1-2 model	6–1-2 model	5–1-2 model	4–1-2 model
Model Fit Statistics	Chi2	7.69, Prob > chi2 = 0.17	7.65, Prob > chi2 = 0.18	7.69, Prob > chi2 = 0.26	2.66, Prob > chi2 = 0.75	1.70, Prob > chi2 = 0.79	0.93, Prob > chi2 = 0.82
	SB Chi2	8.30, Prob > chi2 = 0.14	8.28, Prob > chi2 = 0.14	8.38, Prob > chi2 = 0.21	2.77, Prob > chi2 = 0.74	1.71, Prob > chi2 = 0.79	0.87, Prob > chi2 = 0.83
	RMSEA	0.05**	0.05**	0.04**	0.00***	0.00***	0.00***
	p-close	0.40	0.40	0.53	0.89	0.90	0.90
	SB RMSEA	0.06*	0.06*	0.05**	0.00***	0.00***	0.00***
	CFI	1.00	1.00	1.00	1.00	1.00	1.00
	SB CFI	0.99	0.99	1.00	1.00	1.00	1.00
	TLI	0.99	0.99	0.99	1.01	1.01	1.01
	SB TLI	0.98	0.99	0.99	1.01	1.01	1.01
	SRMR	0.02**	0.02**	0.02**	0.01***	0.01***	0.01***
	R^2	0.94	0.94	0.95	0.90	0.90	0.87
	CD	0.94	0.94	0.95	0.90	0.90	0.87
Number of observations		260	260	260	260	260	260

Note: This table presents model fit statistics for six MIMIC model specifications estimating the size of the IE in Balkan countries (260 observations). Model structures (e.g. 6–1-2) refer to the number of cause variables and indicator variables. ^ Models specifications to be used for calibration procedure since their model fit statistics are most significant, such as the RMSEA, SRMR, CFI, TLI and Chi-squared. Values presented in parentheses are the absolute z values. Values without any types of brackets are the coefficients. *** significant at 1% level, ** significant at 5% level, * significant at 10% level. SB = Satorra-Bentler.

The regression analysis and calibration procedure results show a declining trend in the size of the IE across the Balkan countries between 1996 and 2021. Figure 1 depicts the evolution of the IE in the Balkan countries over the same period for all six selected MIMIC specifications. Crucially, the observed patterns underscore the EU's policy objective of formalising (rather than eliminating) informal activities. Our findings suggest that EU integration and regulatory alignment play a key role in reducing informality, consistent with EU objectives under the European Pillar of Social Rights and SDG Target 8.3 (promote productive employment and decent work for all).

Except for Bosnia and Herzegovina, the figures above demonstrate a decreasing trend in the size of the informal sector in most Balkan Peninsula countries over time. These countries have undergone significant political, social, legal, and economic changes due to the influence of the EU, the European Commission, and the IMF. Albania, North Macedonia, Serbia, and Bosnia and Herzegovina are all candidates for EU membership (European Commission, 2023). The average IE in the Balkan countries accounts for just under 30% of GDP, across all MIMIC specifications. Figure 2 depicts the average size of each country's IE using each of the MIMIC specifications.

According to MIMIC estimates, informal economic activity is lower in the Balkan Peninsula in Slovenia, Greece, Romania, Bulgaria, and Türkiye. While the estimates of the IE's average vary slightly depending on the MIMIC specification used, they show a consistent downward trend across nearly all nations. On the other hand, Bosnia & Herzegovina and North Macedonia have the largest informal sectors in the region, with estimates ranging from 31.22% to 47% of GDP in Bosnia and Herzegovina and from

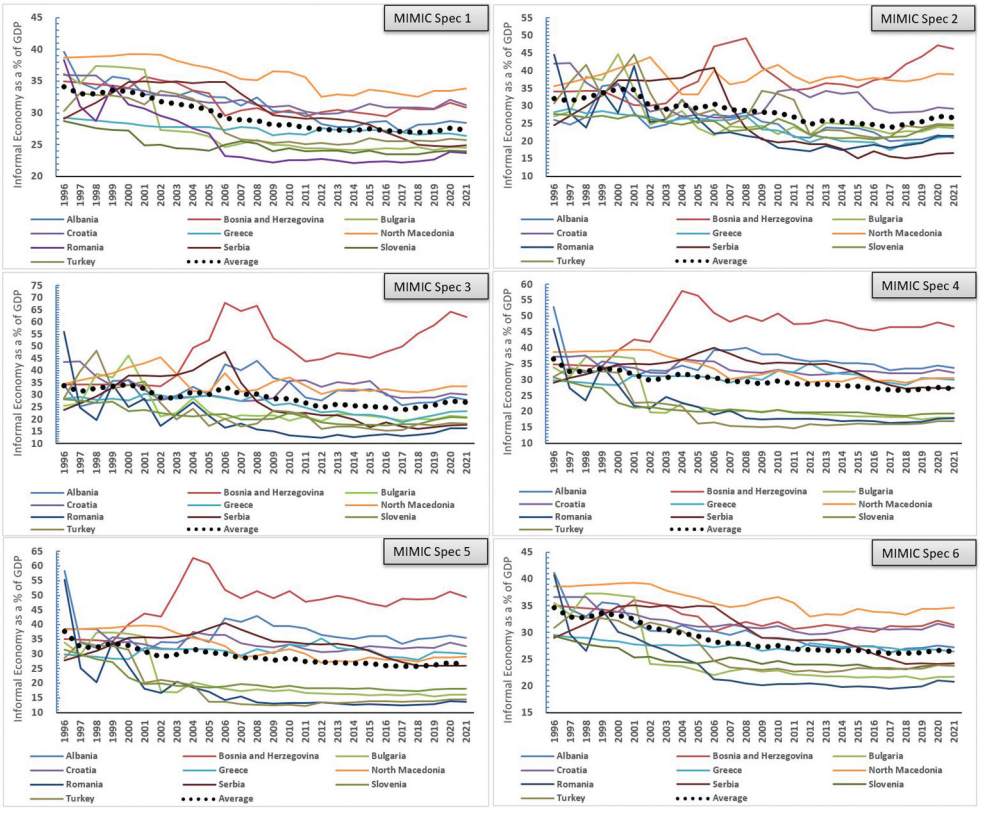

Figure 1. Estimates of the IE using each MIMIC specification. **Note:** These charts display the estimated size of the IE (as a percentage of GDP) for Balkan countries from 1996 to 2021, under six alternative MIMIC model specifications. Each panel corresponds to a different model specification (Spec 1-6), which varies in the causal variables, indicators, and the scaling (anchor) variable. The dashed line represents the cross-country average for each year. While overall trends are consistent across specifications, showing a general decline in informality over time, differences in levels reflect the sensitivity of MIMIC estimates to model specification. Estimates are derived from the enhanced MIMIC approach developed by the authors to improve robustness and comparability across time and countries.

32.44% to 38% of GDP in North Macedonia. Albania and Croatia have informal economies that account for more than 30% of their GDP.

All these MIMIC specifications produce comparable average results to other existing studies that estimate the size of the informal sector in Balkan nations as part of a larger sample of countries. Independent of the estimating methods, sample sizes, and time frame used, all estimates of the size of the IE in Balkan countries indicate that it accounts for a significant portion of the country's official GDP. Within the EU, the Balkan Peninsula countries that are EU members have some of the highest levels of informal economies (Almenar et al., 2020; Davidescu & Schneider, 2022; Hassan & Schneider, 2016; Schneider, 2022).

Table 5 provides the average values from the six MIMIC specifications' estimations. In Slovenia and Romania, the informal sector accounts for around 22 to 23% of GDP; in

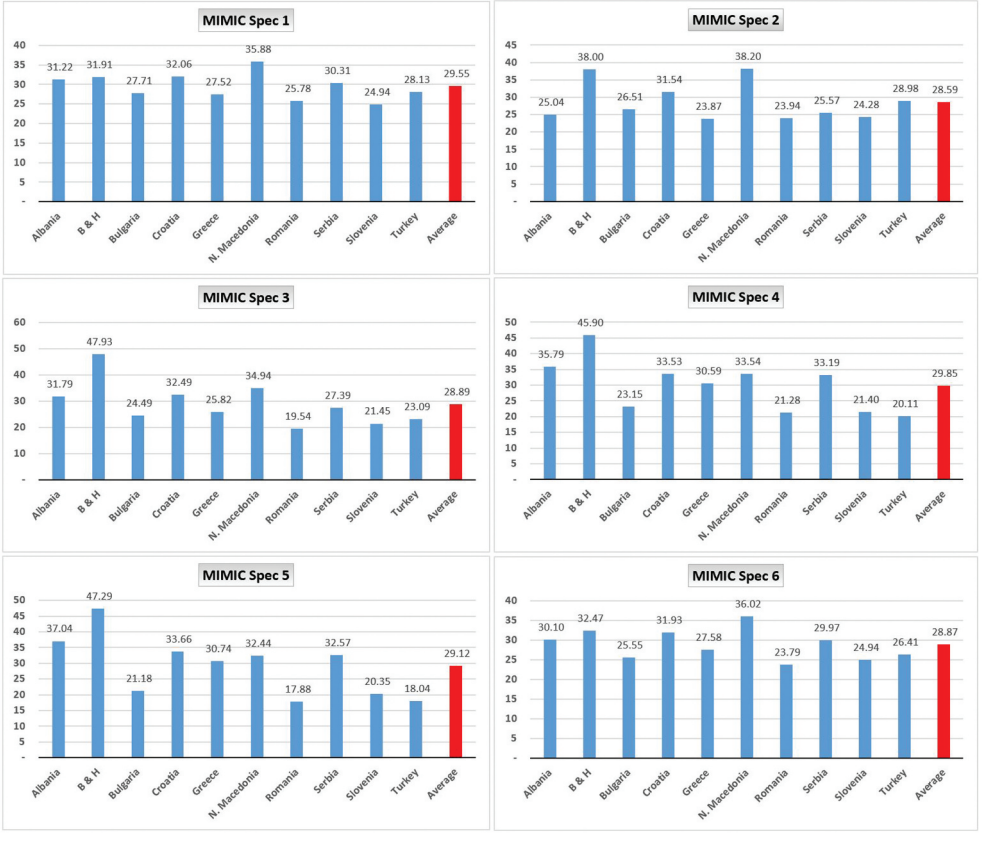

Figure 2. Average estimates for each country using each MIMIC specification. **Note:** These bar charts present the average size of the IE (% of GDP) from 1996 to 2021 for Balkan countries under six different MIMIC model specifications. Each panel corresponds to a distinct model, reflecting variations in the set of causal variables and indicators used. The red bar represents the cross-country average for each specification. While rankings remain broadly consistent, variations in estimated levels highlight the sensitivity of results to model structure.

Türkiye and Bulgaria, it accounts for just over 24% of GDP; in Greece, the informal sector is estimated to account for around 27 to 28%, while in Albania, and Croatia it is just under 30 to 32%. All six MIMIC yearly average estimates show that Bosnia and Herzegovina and North Macedonia have the largest informal economies in the Balkan Peninsula, with average estimates of over 40% and over 35% of GDP, respectively. The annual size and development of the IE in each country between 1996 and 2021 for each of the MIMIC specifications are provided in six tables in Figure 1 of this study. The all-country average has fallen from almost 35% in 1996 to just under 26% in 2021.

These findings have several important policy implications for the Balkan region. The strong negative relationship between government effectiveness and the size of the IE suggests that improving institutional quality should be a priority for policymakers aiming to reduce informality. Similarly, the significant impact of the Business Freedom Index indicates that simplifying regulations and reducing administrative burdens could help

Table 5. Average from all six MIMIC specifications (MIMIC average).

Year	Albania	Bosnia and Herzegovina	Bulgaria	Croatia	Greece	North Macedonia	Romania	Serbia	Slovenia	Türkiye	Avg.
1996	42.04	34.74	32.02	39.01	29.23	37.41	46.81	27.24	29.35	30.00	34.79
1997	31.10	34.60	30.62	39.06	29.24	37.87	27.71	29.07	28.47	35.07	32.28
1998	30.88	34.49	37.67	37.17	28.65	38.51	23.78	30.91	27.52	36.88	32.65
1999	35.70	34.30	37.30	33.80	28.50	39.00	34.30	33.20	27.30	32.70	33.61
2000	35.55	35.62	39.88	34.75	28.12	39.89	28.11	35.89	24.76	33.49	33.61
2001	30.42	37.10	35.76	33.12	29.48	40.49	28.24	36.02	23.76	30.83	32.52
2002	30.36	36.48	22.39	30.95	29.14	41.04	22.94	35.78	23.47	28.34	30.09
2003	30.67	40.07	22.74	31.16	28.72	38.00	24.81	36.22	22.62	25.53	30.05
2004	32.63	45.34	25.10	32.29	28.95	35.22	25.52	36.76	22.34	26.58	31.07
2005	30.85	45.46	22.73	32.11	29.07	34.65	22.88	38.56	22.42	22.26	30.10
2006	35.71	46.27	21.27	31.78	28.48	36.19	19.40	39.82	22.75	21.84	30.35
2007	34.66	45.25	21.82	30.77	27.92	32.77	20.11	34.61	22.36	19.90	29.02
2008	36.38	46.71	22.06	30.41	29.14	33.26	18.61	30.96	22.14	20.27	28.99
2009	33.22	42.16	21.86	30.50	27.07	35.09	18.16	28.63	21.74	22.27	28.07
2010	32.80	41.90	21.24	33.12	28.23	36.10	17.59	28.29	22.95	22.18	28.44
2011	30.67	38.97	21.36	32.51	27.42	34.11	17.40	28.13	21.94	21.40	27.39
2012	29.48	39.56	20.55	31.22	28.12	31.45	17.31	27.77	21.14	19.24	26.59
2013	30.44	40.72	21.49	31.96	27.34	32.26	17.62	27.82	20.86	19.41	26.99
2014	30.05	40.12	21.31	32.12	26.59	32.29	16.95	26.86	20.63	19.54	26.65
2015	30.53	39.09	21.00	32.93	26.58	32.79	17.31	25.00	20.82	19.54	26.56
2016	30.04	39.37	20.76	30.93	25.61	32.55	17.44	24.57	20.28	19.16	26.07
2017	27.58	40.89	20.30	30.33	24.68	32.18	17.00	23.21	20.42	19.21	25.58
2018	28.47	42.36	20.68	30.53	24.89	31.71	17.30	22.26	20.34	20.20	25.87
2019	28.67	43.31	20.16	30.45	26.04	32.78	17.66	22.53	21.29	20.05	26.29
2020	29.70	45.80	20.98	31.87	26.43	33.31	19.01	22.72	21.84	20.77	27.24
2021	28.95	44.47	20.84	31.10	26.23	33.45	18.96	22.81	21.75	20.65	26.92
Avg.	31.83	40.58	24.76	32.54	27.69	35.17	22.04	29.83	22.89	24.13	29.15

Note: This table presents annual estimates of the IE (% of GDP) for Balkan countries from 1996 to 2021, based on the authors' MIMIC model specifications. These estimates are based on the average of six distinct MIMIC model specifications (MIMIC 1-6). The 'Avg.' column reports the cross-country average for each year, while the final row ('Avg.') shows the average level of informality for each country across the full sample period. Values represent the share of economic activity occurring outside the formal, regulated sector. Estimates are harmonised to ensure cross-country comparability over time.

encourage formalisation. The positive relationship between unemployment and informality underscores the need for policies that promote stable, formal employment opportunities. Given the heterogeneity in IE sizes across the region, policies should be tailored to country-specific contexts rather than applying a one-size-fits-all approach. The generally lower levels of informality in EU member states suggest that continued EU integration processes could help reduce informal economic activity.

All countries in the region, whether already members or seeking to join the EU, have made significant investments to improve institutions over the past decades. Candidate countries should have a functioning market economy capable of competing with the rest of the EU and of meeting all the requirements of EU membership, including adherence to the objectives of the political, economic, and monetary union. Balkan countries not already members of the EU have demonstrated substantial progress in their reforms throughout this period, which may have contributed to a reduction in the region's economic informality.

All of the variables in the MIMIC specifications reflect this advancement. The Business Freedom Index, which assesses the ease of doing business and the regulatory burden in a country, as well as the majority of other indicators that have improved across all Balkan countries, has led to a reduction in the size of the

IE. Data from the World Bank's Doing Business reports show that all Balkan nations have made substantial progress over the years. Such reforms will affect the amount of informality in the Balkan economies. As a result, the outcomes reflect this influence.

The long-term declining trend in informality across most Balkan countries can be attributed to several factors. The shift from command to market economies has gradually formalised many economic activities. EU accession processes and membership have driven institutional reforms and improved regulatory environments. Increased digitalisation of economies has made informal transactions more complex and formal transactions easier. Greater integration into the global economy has necessitated more formal business practices. However, the persistence of significant informal sectors, particularly in non-EU Balkan countries, suggests that political instability, corruption, and economic crises have partially counteracted these positive influences.

However, the 2008 financial crisis had a considerable influence on the broader economies of the Balkan countries, notably Greece. The financial crisis raised unemployment in practically all Balkan Peninsula nations and led to an overall economic depression, affecting the pace and execution of some of these countries' ongoing reforms (Jeleva, 2012; Murgasova et al., 2015; Panagiotou, 2012). Again, the MIMIC results reflect this. Even if the data show a declining trend in the size of the informal sector, the decline is not substantial in these Balkan nations, and the IE's share of GDP remains relatively high compared to that of other European countries. Figure 3 presents a map of our sample's estimated average size of the IE.

Some of our findings were unexpected and provide interesting insights. Contrary to existing literature, our results show a negative relationship between the degree of urbanisation and the size of the IE in the Balkan region. This unexpected finding might suggest that urban areas provide more opportunities for formal employment than informal activities in this context. While our study primarily focuses on the overall size of informal economies, it provides some insights into sectoral differences. The persistent significance of the agricultural sector in countries with larger informal economies, such as Albania and North Macedonia, suggests that it may be a pivotal contributor to informality in these nations.

Furthermore, grouping the countries in our study reveals interesting patterns. EU member states (Bulgaria, Croatia, Greece, Romania, and Slovenia) show consistently lower informality levels than non-EU members. This suggests that EU integration and the associated institutional reforms significantly reduce informal economic activity. Countries that have made more progress in their EU accession processes (such as Albania and Serbia) show more rapid declines in informality than those at earlier stages of the process (such as Bosnia and Herzegovina).

The policy implications are significant. Countries with stronger institutions, better governance, and more business freedom exhibit smaller informal sectors. Labour market indicators also suggest that increased employment opportunities in the formal sector help reduce informality. These findings provide guidance for EU and national policymakers seeking to formalise informal activities through institutional development rather than punitive enforcement.

Furthermore, our findings offer insights into the sectoral dynamics of informality. Agriculture and rural activities appear to sustain higher levels of informality, especially

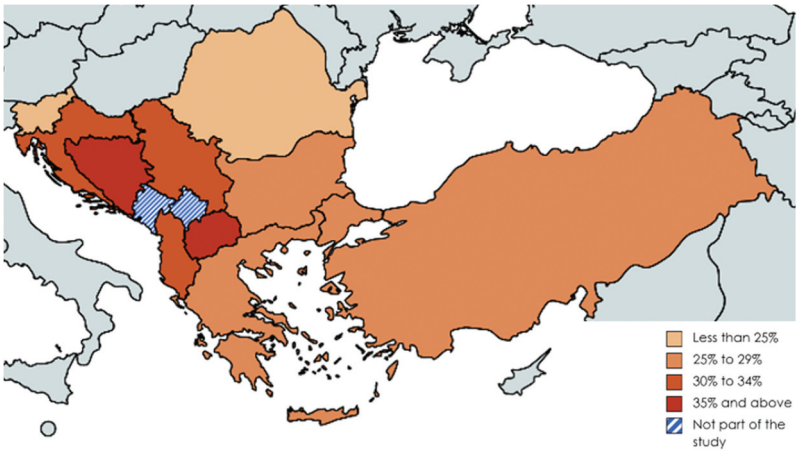

Figure 3. A map with the average size of the shadow economy in Balkan countries. **Note:** This map displays the average size of the IE (% of GDP) across Balkan countries for the period 1996–2021, based on estimates from the enhanced MIMIC model. Countries are colour-coded by average informality level: less than 25%, 25–29%, 30–34%, and 35% and above. Kosovo and Montenegro are shown with blue hatching to indicate they were not part of the study due to data limitations. The map highlights regional disparities in informality, with higher levels observed in parts of the Western Balkans.

in countries such as Albania and North Macedonia. This supports targeted policy efforts in specific sectors and geographic areas. From an SDG and EU policy perspective, our findings reinforce the need to integrate informal workers into formal systems by improving social protection, simplifying taxes, and offeringincentives for small businesses. Countries progressing in EU accession, such as Albania and Serbia, have seen more rapid declines in informality. In contrast, early-stage candidates such as Bosnia and Herzegovina, continue to face institutional bottlenecks. Finally, the results confirm that while the transition from centrally planned to market economies has led to overall formalisation, it has been uneven and strongly dependent on governance quality, external shocks, and the pace of integration with the EU and international institutions.

5. Impact of COVID-19 on the shadow economy

The COVID-19 pandemic provides a unique natural experiment for examining how external shocks affect the informal economy in the Balkans. While our analysis spanning 1996–2021 reveals a general decline in informality, the pandemic years of 2020–2021 marked a significant disruption to this trend. This section examines how the pandemic reversed the long-term decline in informality and demonstrates the counter-cyclical nature of the informal sector as a buffer during economic crises. Our findings align with the broader literature on informal economy business cycles, which shows that informal activity typically increases during economic downturns. This pattern, previously observed during the 2008 financial crisis, was dramatically reinforced during the COVID-19 pandemic. As David et al. (2023) and Roldos et al. (2019) demonstrate, informal sectors play a crucial buffering role during economic crises, providing alternative livelihoods when formal employment contracts.

The International Monetary Fund (IMF) estimated that the global economy contracted by approximately 3.5%, with most Balkan countries experiencing even larger losses (International Monetary Fund, 2021). Apart from Serbia's slight 1.1% decrease in GDP, the rest of the region recorded a larger decline than the global average, with Greece and Croatia posting the largest contractions at 8.2% and 8.4%, respectively. Unemployment increased significantly, often by more than 10%. The region's heavy reliance on the hospitality sector, which contributes significantly to GDP in countries like Greece (20%), Croatia (25%), Türkiye (12%), and Bulgaria (11%), exacerbated these economic challenges (World Tourism Organisation, 2020). As a result, we estimate a rise in the IE's average size to 27.24% of official GDP in the Balkan countries, a 18% increase from 2019 (Table 6). This marks a reversal in the long-term trend of decline and underscores the counter-cyclical nature of informality.

The informal sector provided a vital safety net for those who lost formal employment. However, this shift emphasised job insecurity, wage inequality, and poor working conditions. Informal workers often lack access to health care, social protection, and labour rights, making them particularly vulnerable during economic downturns.

Governments across the Balkans implemented various policies to minimise the economic impact of the crisis, including lockdowns, social distancing mandates, budgetary stimulus packages, and regulatory changes. While vital to slowing the spread of the epidemic and assisting affected populations, these efforts had significant consequences for the IE. Stringent lockdowns and social distancing measures forced many small firms and workers to operate informally to escape compliance costs and constraints. Economic stimulus packages, including wage subsidies and tax deferrals, often failed to reach informal-sector workers due to their unregistered status. Some governments eased regulatory restrictions and simplified procedures to facilitate business operations. Still, implementation inconsistencies sometimes led to the exploitation of regulatory gaps,

Table 6. Increase in the IE between 2019 and 2020 during COVID-19.

Country	2019	2020	Difference	Annual change
Albania	28.67	29.7	1.03	4%
Bosnia and Herzegovina	43.31	45.8	2.49	6%
Bulgaria	20.16	20.98	0.82	4%
Croatia	30.45	31.87	1.42	5%
Greece	26.04	26.43	0.39	1%
North Macedonia	32.78	33.31	0.53	2%
Romania	17.66	19.01	1.35	8%
Serbia	22.53	22.72	0.19	1%
Slovenia	21.29	21.84	0.55	3%
Türkiye	20.05	20.77	0.72	4%
Average	26.29	27.24	0.95	4%

Note: This table shows the estimated change in the size of the IE (as a percentage of GDP) between 2019 and 2020 for Balkan countries during the COVID-19 pandemic. Estimates are based on the MIMIC model. The 'Difference' column represents the percentage point increase, while the 'Annual change' column reflects the relative year-on-year growth. The average across countries indicates that the IE increased by approximately 4% on average in 2020, largely due to pandemic-induced disruptions, increased unemployment, and shifts towards informal activities amid economic uncertainty.

thereby expanding informal economic activity (European Bank for Reconstruction and Development, 2021).

The Balkan's IE provided immediate employment opportunities during the crisis. Unlike formal employment, informal jobs can be created quickly, providing instant income. However, this informal employment carries significant risks, including a lack of legal protections, poor working conditions, and job insecurity (International Labour Organisation [ILO], 2020). The IE demonstrated significant adaptability, quickly adjusting to changing market needs and operating constraints. For example, demand for home deliveries and local services increased, with these sectors exhibiting higher levels of informality. While this adaptability ensured the maintenance of essential products and services, it also exposed structural issues that could erode regulatory standards and economic stability in the long term. The increase in informality resulted in significant tax revenue losses for governments, impeding their ability to fund public services and pandemic relief. It also complicated the implementation of government policies, as informal operations often fell outside regulatory scrutiny.

Notably, the temporary surge in informality during COVID-19 highlights the limits of existing formalisation policies and the need for more inclusive strategies that extend protection to informal workers during periods of macroeconomic distress. The pandemic forced many individuals and households to seek alternative income sources in the IE. While this provided a critical lifeline for many suddenly unemployed, it increased economic vulnerability due to a lack of legal protections and social benefits.

Given the rising informality and its ramifications, Balkan governments must reconsider the role of the IE in their policymaking. Effective solutions should focus on formalising informal activities, bringing them under regulatory control and into the tax system. This can be achieved through incentives for formalisation, such as simplified registration processes, tax advantages for newly formalised enterprises, and access to financial services. Expanding social protection for informal workers is crucial to strengthening resilience against future economic crises. This involves providing access to healthcare, unemployment benefits, and retirement savings for those in informal settings.

Moreover, these reforms would support the achievement of Sustainable Development Goal (SDG) 8, particularly Target 8.3, which promotes the formalisation of work and decent work for all. By addressing the structural difficulties associated with informality, governments can improve economic resilience and ensure a more equitable distribution of recovery benefits across society (ILO, 2020; OECD, 2021).

6. Comparing our estimates with previous studies

The *MIMIC Average*, calculated as the mean of six alternative model specifications (MIMIC 1-6), provides a robust, harmonised measure of informality for the 10 Balkan countries over the period 1996–2021. These estimates, presented in Figure 4, are compared with some selected benchmark studies from the literature, including Schneider (2007, 2009), Schneider et al. (2010), Buehn and Schneider (2012), Elgin et al. (2021), and Medina and Schneider (2021), among others. These studies were chosen because they provide broad regional coverage and longer timeframes, and they estimate informality for most Balkan countries. While many other studies exist, they typically focus on individual countries or smaller subsets of the region, often with limited temporal scope.

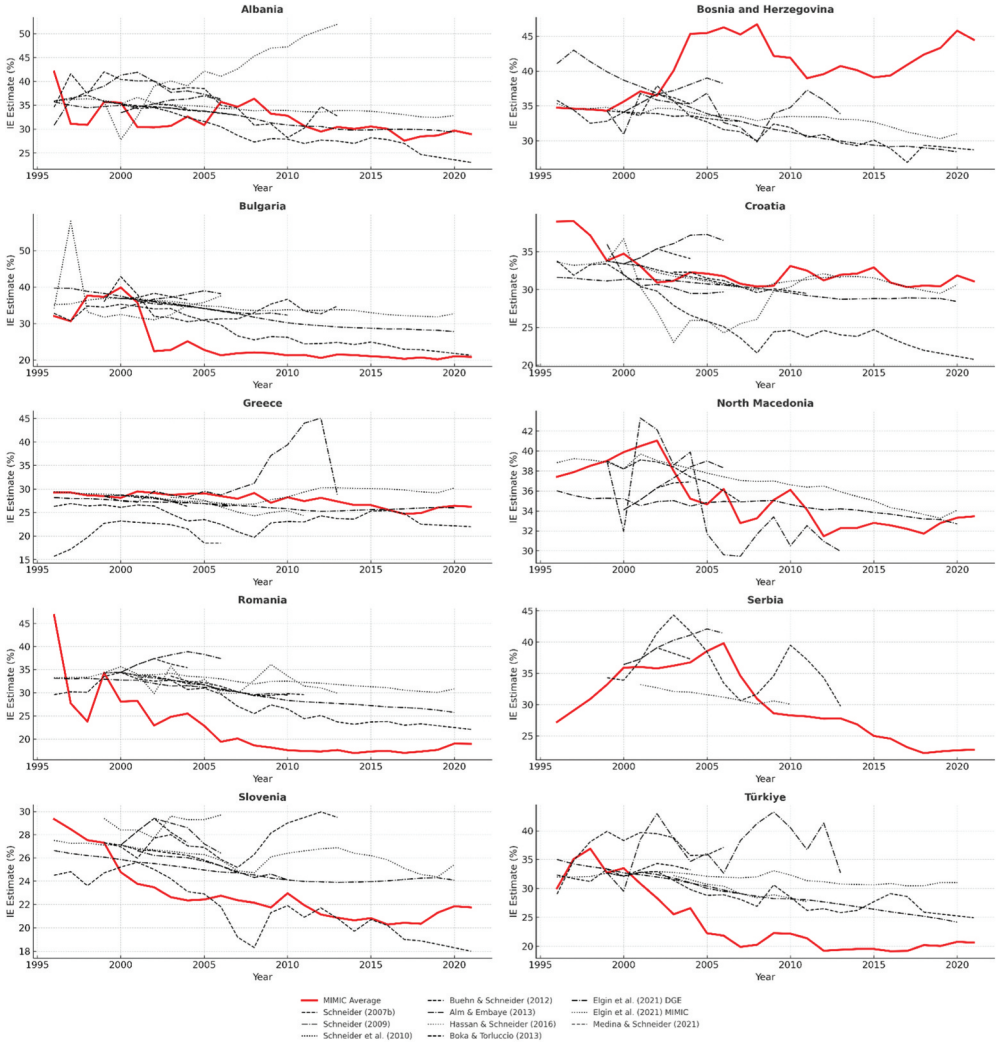

Figure 4. Comparisons of current MIMIC average estimates with existing literature for Balkan countries and Türkiye (1996–2021). **Note:** This figure presents a comparative overview of IE estimates for Balkan countries and Türkiye from 1996 to 2021. The red line in each panel represents the MIMIC Average, calculated as the average across six distinct MIMIC model specifications (MIMIC 1-6). The black dashed and dotted lines correspond to benchmark estimates from selected studies in the literature. These studies were chosen because they provide broad regional coverage and longer timeframes, and they estimate informality for most Balkan countries. While many other studies exist, they typically focus on individual countries or smaller subsets of the region, often with limited temporal scope. The MIMIC Average offers a harmonised and updated representation of informality trends across the region, facilitating comparison with existing estimates.

Compared to prior estimates, the MIMIC Average generally falls within the mid-to-upper range, smoothing out the extremes observed in individual studies and ensuring consistency across time. While some earlier works report considerably higher or lower levels for certain countries, the MIMIC Average moderates these differences and reveals more stable trends. Countries such as Albania, Bosnia and Herzegovina, and North

Macedonia consistently exhibit higher levels of informality, whereas Slovenia and Croatia tend to have lower estimates. Greece, Romania, and Bulgaria fall in the mid-range but show important variation over time, particularly in response to economic crises and institutional reforms. Türkiye's informality levels remain relatively stable and moderate compared to the rest of the region.

7. Conclusion

This study used the MIMIC approach to investigate and quantify the evolution of the IE in Balkan nations from 1996 to 2021. Our research significantly contributes to understanding the IE in the Balkans by providing a comprehensive, long-term analysis of its size and development. This study is unique in its scope, covering 25 years across countries, and in its application of the MIMIC method to this specific region. Unlike existing global estimates, such as those of the World Bank, our region-specific, harmonised approach applies a consistent MIMIC model across all countries in the sample, enabling time-consistent, policy-relevant analysis over 25 years.

Our findings reveal that the informal sector in the Balkan countries has been diminishing on average over this period, reflecting the region's significant transition and progress on reforms inspired by European Union accession policies. The IE in the Balkan nations began with an annual average of over 34% in 1996 and fell to around 27% by 2021. This downward trend can be attributed to improvements in economic and business freedom, government effectiveness, and overall government performance across most of the nations studied. We also find strong support for the idea that EU accession and alignment with EU institutions have helped reduce informality, especially in countries such as Slovenia, Romania, and Bulgaria, where EU-driven reforms have taken hold. However, it is crucial to note that despite this decrease, the total average size of the Balkan region's IE remains substantial, at just under 30% of GDP. This makes the informal sector in this part of continental Europe the largest in the EU, presenting ongoing challenges for governments in these nations.

Our analysis revealed significant variations among the countries studied. North Macedonia, Bosnia and Herzegovina, Albania, Serbia, and Croatia demonstrated the largest informal economies as a share of GDP. In contrast, Slovenia, Romania, and Greece exhibited the smallest informal sectors, ranging from 22% to 28% of GDP. Bulgaria and Türkiye showed marked reductions in their informal sectors, with averages decreasing year-on-year to between 20% and 28% of GDP across our model specifications.

Importantly, our study also captured the impact of the COVID-19 pandemic on the IE in the Balkans. We observed a notable increase in informal economic activity in 2020, with our estimates showing a 13% point increase compared to 2019. This increase underscores the informal sector's role as a safety net during economic crises. It highlights the vulnerabilities of informal workers lacking social protection and labour rights. Notably, our results also confirm that the IE behaves counter-cyclically, tending to rise during periods of economic contraction. The 2008 financial crisis and the COVID-19 pandemic both contributed to temporary increases in informality, reaffirming the informal sector's role as a shock absorber for vulnerable populations.

Our research identified several key drivers of the Balkan Peninsula's IE, including regulatory burden, monetary and financial freedom, degree of urbanisation,

macroeconomic developments, and government size. A distinctive feature of this study is the use of policy-driven causal variables and macroeconomic factors to estimate the size of the IE. This contributes to the growing body of literature that links informality not only to economic constraints but also to governance and institutional quality.

To tackle the IE effectively, we recommend a comprehensive set of reforms tailored to each country's specific circumstances. These may include institutional and regulatory reforms, as well as changes to administrative and tax laws. Based on our analysis, the most relevant policies for emerging economies include reducing administrative and regulatory burdens, fostering transparency, enhancing government performance, improving tax compliance, automating processes, and encouraging electronic payments.

Furthermore, our study highlights the importance of considering the social role of the IE, particularly in countries that depend on remittances. Policy frameworks should incorporate incentives for informal workers to transition to the formal sector while acknowledging the IE's function as a social safety net. Additionally, we recommend policies to stimulate human capital development and encourage private-sector job creation. These measures would help bring businesses and employees out of the shadows and promote more equitable and inclusive growth. Finally, we align our findings with SDG Target 8.3 and broader EU formalisation efforts, both of which promote the gradual integration of informal workers into formal employment structures rather than the elimination of informal activity. By encouraging inclusive formalisation, the Balkan region can ensure a more resilient and equitable recovery from future crises.

In conclusion, while the Balkan region has made progress in reducing its IE, significant challenges remain. Our study provides valuable insights into the dynamics of the informal sector in the Balkans, offering policymakers a foundation for targeted strategies. The use of the MIMIC model and incorporation of relevant variables closes the measurement gap in the Balkan Peninsula's post-reform IE, providing valuable insights into its size, trends, and influential factors.

Future research could build on this work by examining the long-term impacts of the COVID-19 pandemic on informality and evaluating the effectiveness of policy interventions in reducing the IE. It could also build on this work by examining the long-term impacts of business cycles on informality, evaluating the effectiveness of EU-aligned policy interventions, and comparing Balkan dynamics with those of other transitioning regions. By addressing the structural challenges of informality, governments can improve economic resilience and ensure a more equitable distribution of recovery benefits across society.

Notes

1. According to System of National Accounts 2025 (§39.2): 'The informal economy refers to the productive activities carried out by persons or economic units that are not covered by formal arrangements established by regulations and laws, such as registration, regulation, payment of taxes, and coverage of workers by social security and other labour laws and regulations.' https://unstats.un.org/unsd/nationalaccount/snaupdate/2025/2025SNA_CH39_V11.pdf
2. We focus on 10 Balkan countries: Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Greece, North Macedonia, Romania, Serbia, Slovenia, and Türkiye. Montenegro and Kosovo, although

part of the Balkan region, are not included in this study due to the unavailability of consistent data dating back to 1996.

3. The terms Turkey and Türkiye are used interchangeably throughout this paper. While Türkiye reflects the country's official name as recognised by the United Nations since 2022, Turkey appears in some data sources, charts and literature references used in this study.
4. Schneider (2007) measures the size of the IE between 1999 and 2005 for 145 countries worldwide.
5. Schneider (2009) estimates the size of the IE from 2000 to 2006/07 for 25 transition countries.
6. Schneider et al. (2010) estimate the size of the IE from 1999 to 2007 for 162 countries worldwide.
7. Schneider et al. (2013) measure the size and development of the IE from 2001 to 2010 for Serbia, Bulgaria, Romania, Slovenia and several other Eastern European countries.
8. Alm and Embaye (2013) measured the size of the IE for 111 countries worldwide (but excluding some Balkan countries such as FYR Macedonia, Bosnia and Herzegovina, Serbia and Romania) between 1984 and 2006. However, due to data availability, they do not provide estimates from 1984 to 2006 for all countries.
9. Hassan and Schneider (2016) is a study which estimates the size of the IE in 157 countries from 1999 to 2013.
10. Bitzenis et al. (2016) focus mainly on estimating the size of the IE for Greece, but in their MIMIC regression and then benchmark estimation, they estimate the size of the IE for 36 countries in Europe and North America.
11. Elgin et al. (2021) estimate the IE in 196 economies over the period 1990–2020
12. Medina and Schneider (2021) estimate the size of the shadow economy of 156 countries worldwide (including Balkan countries) over the period from 1991 to 2017.
13. Taxation burden, 'tax morality', regulation burden.
14. Effectiveness of institutions and government, political climate, institutional trust.
15. Inflation and unemployment.
16. Size of the agricultural sector, urbanisation.
17. Teobaldelli & Schneider (2012) have found that there is a statistically significant negative relationship between direct democracy and the size of the informal economy.
18. The MIMIC model has been used for the first time by Goldberger (1972). The idea of this model is to represent the IEas a latent variable or index that has caused noticeable effects, but that cannot be measured directly.
19. Where η_t denotes the value of the MIMIC index at time t according to SEM expressed above in the econometric model, $\eta_{\text{the base year}}$ is the value of the MIMIC index in the base year selected for calibration procedure, $\eta^*_{\text{the base year}}$is the exogenous value of the IEbased on a base year and usually this either is taken as a secondary value from existing literature, or it can be calculated using the currency demand method, and then a base year value used as the benchmark for calculations (Buehn & Schneider, 2012; Hassan & Schneider, 2016).
20. This measure is a one-sided test of the null hypothesis that the RMSEA equals .05, which is called a *close-fitting model*. The alternative, one-sided hypothesis is that the RMSEA is greater than 0.05. So if the *p* is greater than .05 (i.e. not statistically significant), then it is concluded that the fit of the model is 'close.' If the p is less than .05, it is concluded that the model's fit is worse than close fitting (i.e. the RMSEA is greater than 0.05) (Kenny, 2015).
21. The Model Fit Statistics presented in this table are based on the Satorra & Bentler option. A full set of Model Fit statistics has been provided in Table 4 below.
22. Also known as Noncentrality-based Indices.
23. Also known as Relative Fit Indices.
24. Also known as Noncentrality-based Indices.

Disclosure statement

No potential conflict of interest was reported by the authors.

Author contributions

CRediT: **Alban Asllani:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing; **Nikolaos Tzivanakis:** Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing; **Friedrich Schneider:** Conceptualization, Formal analysis, Methodology, Resources, Supervision, Validation, Writing – review & editing.

Data availability statement

The data supporting this study's findings are available from the corresponding author, upon reasonable request after publication.

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