

# Estimating the Underground Economy Using Fuzzy Indexation and the MIMIC Model within a SEM Framework

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**Abstract:** The present study aimed to estimate the size and trend of the underground economy in Iran using fuzzy indexation and the Multiple Indicators Multiple Causes (MIMIC) model within a Structural Equation Modeling (SEM) framework and to examine the effects of selected macroeconomic determinants on underground economic activity. This applied, descriptive-survey study employed a hybrid methodological framework combining fuzzy logic and structural equation modeling. In the first stage, a fuzzy inference system based on Mamdani logic was developed to estimate the underground economy using seven macroeconomic indicators categorized into monetary, financial, and real-sector dimensions. The monetary dimension included liquidity growth and the relative price of non-tradable to tradable goods; the financial dimension included the ratio of oil revenues to GDP and the ratio of oil revenues to government budget revenues; and the real-sector dimension included the non-oil trade balance, the ratio of agricultural value added to non-oil GDP, and the ratio of construction value added to non-oil GDP. Triangular membership functions with five linguistic levels were defined using six-year moving averages and standard deviations. After fuzzification, rule construction, inference, and defuzzification, annual underground economy indices were estimated for the period 1996–2025. In the second stage, the estimated underground economy was modeled as a latent construct using Partial Least Squares Structural Equation Modeling (PLS-SEM) in SmartPLS. Gross Domestic Product, Money Supply, Activity Rate, Direct Tax Burden, and Gross Fixed Capital Formation were incorporated as explanatory variables. Reliability and validity were assessed through Composite Reliability and Average Variance Extracted, while hypothesis testing was conducted using standardized path coefficients and bootstrapping procedures. The results confirmed the adequacy of the measurement model, with Composite Reliability values ranging from 0.821 to 0.894 and AVE values ranging from 0.631 to 0.702. Kolmogorov–Smirnov tests indicated non-normality of all variables, supporting the use of PLS-SEM. Path analysis revealed that Gross Domestic Product had a significant negative effect on the underground economy ( $\beta = -0.360$ ,  $t = 15.369$ ,  $p < 0.01$ ). Money Supply exerted a significant positive effect ( $\beta = 0.776$ ,  $t = 28.960$ ,  $p < 0.01$ ). Direct Tax Burden showed a significant negative relationship with underground economic activity ( $\beta = -0.109$ ,  $t = 2.195$ ,  $p < 0.05$ ). Activity Rate also had a significant negative effect ( $\beta = -0.048$ ,  $t = 11.457$ ,  $p < 0.01$ ). Furthermore, Gross Fixed Capital Formation demonstrated a strong negative effect on the underground economy ( $\beta = -0.607$ ,  $t = 9.527$ ,  $p < 0.01$ ). The fuzzy estimation indicated that the underground economy followed an upward trend after 2011 and averaged approximately 37% of GDP during the study period.

**Keywords:** Underground Economy; Fuzzy Logic; MIMIC Model; Structural Equation Modeling; Shadow Economy; Money Supply; Economic Growth; Iran.

## 1. Introduction

The underground economy has become one of the most complex and persistent challenges in contemporary economic governance because it includes activities that generate income, exchange, employment, and capital circulation while remaining partly or wholly outside official measurement, taxation, regulation, or legal supervision. Although the underground economy is often discussed through the language of tax evasion, informal production, illicit trade, smuggling, money laundering, and unregistered enterprise, its analytical significance is broader than these categories. It affects the accuracy of national accounts, weakens fiscal capacity, distorts monetary and financial indicators, reduces the transparency of labor and product markets, and complicates the design of macroeconomic policy. Recent studies show that shadow economic activity is not limited to developing economies or fragile states; rather, it appears in different forms across developed, transitional, and developing economies, depending on institutional quality, enforcement capacity, financial transparency, trade openness, corruption control, technological development, and the incentives created by taxation and regulation [1-3].

One of the central difficulties in studying the underground economy is that it cannot be directly observed. By definition, many of its components are hidden from official records, deliberately concealed by economic agents, or embedded in transactions that appear legal at the surface but contain informal or illicit dimensions. This problem has encouraged researchers to adopt indirect estimation methods that infer the size and dynamics of the underground economy from observable causes and indicators. In this regard, approaches such as currency-demand models, electricity-consumption approaches, structural equation modeling, and MIMIC models have become important tools for estimating latent economic activity. The MIMIC model is especially useful because it treats the underground economy as an unobserved latent construct that is influenced by several causal variables and reflected through several observable indicators. This logic corresponds closely with the empirical reality of hidden economic activity, in which the phenomenon itself cannot be directly measured but can be inferred from macroeconomic, monetary, fiscal, and institutional signals [4-6].

The underground economy is closely related to financial crime, tax evasion, illicit financial flows, and money laundering. These activities weaken the formal economy not only by reducing government revenue but also by creating parallel circuits of capital accumulation and exchange. Money laundering is particularly important because it allows income generated through illegal or informal sources to be integrated into formal financial systems. Studies on money laundering describe it as a staged process through which illicit proceeds are concealed, transferred, layered, and legitimized, often through complex financial, commercial, or cross-border arrangements [7-9]. In this sense, money laundering is not merely a criminal act but also a structural mechanism that connects hidden markets to formal financial institutions, thereby increasing the difficulty of estimating the real size of the underground economy.

The expansion of global trade and financial technology has further transformed the mechanisms through which underground economic activities are organized. Trade-based money laundering, digital payment systems, financial technology platforms, and cross-border transaction networks have created new opportunities for concealment, misreporting, and regulatory arbitrage. Structured reviews of money laundering in global trade emphasize that financial technology can play a dual role: it can increase transparency and detection capacity, but it can also facilitate faster and more complex illicit transactions when regulatory systems are weak or fragmented [10, 11]. Similarly, the digital development of financial systems has raised new challenges for controlling the legalization of proceeds from drug trafficking and other criminal markets, as illicit actors increasingly exploit digital channels,

cryptocurrencies, and transnational financial infrastructures [12]. These developments highlight the need for estimation models that can handle uncertainty, nonlinearity, and hidden relationships among variables.

Illicit trade constitutes another major channel through which the underground economy expands. It may appear in the form of smuggling, illegal extraction, informal logistics, counterfeit goods, prohibited commodities, wildlife trafficking, pharmaceutical crime, or shadow supply chains. Research on illicit trade during wartime has shown that conflict conditions, weakened institutions, and disrupted markets can create favorable environments for illegal trade networks [13]. Other studies have examined illicit trade in specific sectors, including crab harvesting and international seafood markets, illegal pharmaceutical trade during the COVID-19 pandemic, and wildlife trafficking under large infrastructure and trade initiatives [14-16]. These sectoral studies are important because they show that the underground economy is not an abstract macroeconomic residual; it is produced through concrete sectoral practices that interact with regulation, demand, enforcement, and profit opportunities.

The relationship between illicit economies and political or security conditions is also significant. In fragile, conflict-affected, or post-conflict settings, shadow economies may provide income and survival opportunities, but they may also strengthen criminal networks, finance violence, and undermine state authority. Research on illicit economies in peace processes suggests that hidden markets can affect the stability of peace settlements and the incentives of armed or criminal actors [17]. Studies on peacekeeping operations and shadow economy growth further indicate that international interventions may interact with host-country informal markets in complex ways [5]. Moreover, the nexus between terrorism and the shadow economy in developing countries demonstrates that underground economic systems may be linked to broader security risks when illicit financing, weak regulation, and informal exchange networks converge [4]. Therefore, estimating the underground economy has implications not only for economic policy but also for governance, security, and institutional resilience.

Tax evasion remains one of the most widely discussed drivers of underground economic activity. When tax systems are perceived as unfair, administratively burdensome, or weakly enforced, economic agents may shift part of their activity outside formal reporting channels. Evidence from Asian countries shows that the business environment and tax evasion are closely connected, suggesting that regulatory quality and administrative simplicity can influence the incentives to remain formal or informal [18]. However, the relationship between tax burden and the underground economy is not always linear. In some contexts, higher taxation may increase concealment, while in others, stronger fiscal institutions and more effective tax administration may reduce evasion. For this reason, empirical models must account for the possibility that fiscal variables interact with broader institutional and macroeconomic conditions.

Corruption control and institutional quality are also essential in explaining the scale of shadow economic activity. Studies on developing countries indicate that weak corruption control can intensify the shadow economy by reducing the expected cost of informal or illegal behavior and by allowing hidden transactions to operate through bribery, regulatory capture, or selective enforcement [3]. Cross-country evidence on economic and financial crime further confirms that broader social development, institutional maturity, and governance structures influence the prevalence of financial crime and hidden economic behavior [2]. Financial crime in specific industries, such as forestry, also demonstrates how weak oversight, resource dependence, and institutional gaps can create opportunities for illegal extraction, underreporting, and fraudulent trade [19]. These findings imply that the underground economy must be analyzed as a multidimensional phenomenon shaped by both economic incentives and institutional constraints.

A major body of research has also linked the underground economy with money laundering indicators and international financial risk. Studies of European Union member states have used money laundering measurement indices to cluster countries according to risk patterns, revealing that national differences in financial transparency, enforcement, and vulnerability matter substantially [20]. Research on laundered funds destination theory, using the Walker–Unger gravity model, shows that launderers’ country preferences are influenced by economic size, financial openness, distance, regulation, and perceived safety [21]. Evidence from UK regulatory data further indicates that cross-jurisdictional financial crime risks can be detected through systematic analysis of regulatory information [6]. These studies support the methodological argument that hidden economic behavior can be estimated indirectly through carefully selected indicators and causal variables.

The underground economy also has clear implications for sustainable development. Money laundering and illicit financial flows can obstruct progress toward development goals by reducing public revenue, encouraging corruption, weakening institutional trust, and diverting resources from productive investment [22]. Illicit trade and shadow supply chains similarly interfere with sustainable development by undermining lawful markets, encouraging environmental harm, and reducing accountability in production and distribution networks [23]. In rural and resource-based settings, informal or illegal enterprise may coexist with local livelihoods, tourism development, and shadow infrastructures, creating a complex relationship between economic survival, illegality, and development policy [24, 25]. These complexities require empirical strategies that do not reduce the underground economy to a single observable activity but instead conceptualize it as a latent system reflected in multiple economic and institutional signals.

The literature also emphasizes that intelligence capacity, information systems, and data-driven financial monitoring are increasingly important in detecting hidden economic activity. National intelligence and illicit trade are related because the ability of states to collect, process, and act upon information affects their capacity to prevent illicit flows [26]. Financial intelligence management has been presented as a mechanism for improving economic security by using information algorithms and structured monitoring systems [27]. Legal frameworks against the legalization of criminal proceeds are also central to economic security, particularly where organized criminal groups use formal economic channels to conceal illegal income [28, 29]. These studies show that the underground economy is not only an economic measurement problem but also a problem of information asymmetry, legal design, and institutional detection.

From a methodological perspective, conventional econometric models often face limitations when applied to the underground economy because the phenomenon is uncertain, multidimensional, and partially qualitative in nature. Fuzzy logic offers an appropriate complementary approach because it allows variables to belong to different conceptual categories by degree rather than forcing them into rigid binary classifications. This is especially useful when economic indicators do not have sharp thresholds separating formal from informal or legal from illegal behavior. Through fuzzy indexation, monetary, fiscal, and real-sector variables can be transformed into graded membership functions, allowing the researcher to model uncertainty more realistically. When fuzzy indexation is integrated with the MIMIC framework, the analysis can benefit from both flexible classification and structural estimation of latent relationships. This combination is particularly useful in contexts where data limitations, macroeconomic volatility, sanctions, inflationary pressures, and institutional complexity make direct estimation of the underground economy difficult.

For Iran, estimating the underground economy is especially important because the economy has experienced long-term structural changes, oil-revenue dependence, inflationary pressures, sanctions, exchange-rate instability,

fiscal constraints, and regulatory challenges. Such conditions may increase incentives for informal transactions, unregistered production, currency substitution, smuggling, tax avoidance, and hidden financial circulation. Studies on shadow and illicit economic activity in various national contexts suggest that underground markets expand when formal institutions cannot fully absorb economic pressures or provide stable incentives for lawful participation [30, 31]. At the same time, macroeconomic variables such as GDP, money supply, labor-force activity, tax burden, and capital formation can function as observable signals of deeper hidden dynamics. Therefore, a model that combines fuzzy indexation with MIMIC-based structural equation modeling can provide a more comprehensive and analytically sensitive estimate of Iran's underground economy.

The present study was conducted to estimate the underground economy in Iran using fuzzy indexation and the MIMIC model within a structural equation modeling framework and to examine the relationships between macroeconomic determinants and the latent underground economy over the study period.

## 2. Methodology

This study employed a descriptive-survey research design and was conducted as an applied and causal investigation aimed at estimating the size and dynamics of the underground economy in Iran. The research was considered applied because its findings can be utilized by policymakers, economists, governmental institutions, universities, and economic planning organizations to better understand hidden economic activities and their implications for national development. From a temporal perspective, the study was cross-sectional in its analytical framework, although it utilized annual time-series macroeconomic data covering the period from 1996 to 2025 (corresponding to 1375–1404 in the Iranian calendar) for estimating the underground economy index and examining its long-term trend. The theoretical foundations of the study were developed through an extensive review of books, scientific articles, research reports, dissertations, and official economic documents related to underground economic activities, fuzzy logic methodologies, MIMIC modeling, and structural equation modeling.

Unlike traditional survey-based studies involving individual respondents, the units of analysis in this research consisted of annual macroeconomic observations extracted from national economic databases and official statistical publications. The study adopted a two-stage methodological framework. In the first stage, a fuzzy logic approach was utilized to construct an underground economy index based on monetary, financial, and real-sector indicators. In the second stage, the estimated underground economy index was incorporated into a Multiple Indicators Multiple Causes (MIMIC) model within a Structural Equation Modeling (SEM) framework to examine the causal relationships between latent underground economic activity and its observable determinants and indicators. The combination of fuzzy logic and SEM was selected to capture the inherent uncertainty associated with underground economic activities while simultaneously modeling the complex relationships among latent and observed variables.

For the fuzzy logic component, three major dimensions of the underground economy were considered. The monetary sector dimension included the relative price index of non-tradable goods to tradable goods and the liquidity growth rate. The real-sector dimension consisted of the non-oil trade balance, the ratio of construction sector value added to non-oil GDP, and the ratio of agricultural value added to non-oil GDP. The financial-sector dimension included the ratio of oil revenues to GDP and the ratio of oil revenues to total government revenues. These indicators were selected based on economic theory and empirical evidence regarding the drivers and manifestations of underground economic activities.

For the structural equation modeling stage, annual observations of Gross Domestic Product (GDP), Money Supply Ratio (MS), Activity Rate (ACR), Direct Tax Burden (DTB), and Gross Fixed Capital Formation (GFCF) were

used as causal and indicator variables associated with the latent underground economy construct. The underground economy itself was treated as a latent variable that could not be directly observed and therefore had to be estimated through the relationships among these observable economic indicators.

The primary data collection instrument for estimating the underground economy index was a fuzzy inference system developed based on the principles of fuzzy set theory and fuzzy logic. The fuzzy system was designed to transform crisp macroeconomic observations into linguistic variables capable of representing the uncertainty and ambiguity inherent in underground economic activities. The system employed triangular membership functions due to their simplicity, interpretability, and widespread use in economic fuzzy modeling. Each input variable was classified into five linguistic categories, namely Very Low, Low, Normal, High, and Very High. To define the membership functions, six-year moving averages were calculated for each variable, and the upper and lower bounds of the membership functions were determined using two standard deviations above and below the corresponding moving averages. This procedure allowed the transformation of quantitative economic indicators into fuzzy sets and facilitated the evaluation of underground economic conditions under different economic scenarios.

The fuzzy inference process was based on the Mamdani inference system, which is one of the most commonly used fuzzy reasoning approaches. Expert knowledge and empirical evidence from the literature were utilized to formulate the fuzzy rule base. The decision rules were expressed in the form of "IF-THEN" statements, allowing different combinations of monetary, financial, and real-sector conditions to generate corresponding levels of underground economic activity. For the monetary and financial sub-indices, each consisting of two input variables and five linguistic categories, twenty-five fuzzy rules were generated. For the real-sector sub-index, which included three input variables with five linguistic categories each, one hundred and twenty-five fuzzy rules were constructed. An additional one hundred and twenty-five rules were developed to combine the three sub-indices into a comprehensive underground economy index. Fuzzy operators MIN and MAX were employed in place of conventional logical AND and OR operators, respectively. After the inference process, defuzzification procedures were applied to convert the fuzzy outputs into crisp values representing annual underground economy estimates. Sensitivity analysis was subsequently conducted by introducing controlled variations in the input variables and examining the resulting changes in the output index to evaluate the robustness and stability of the fuzzy model.

For the structural equation modeling phase, the MIMIC model served as the principal analytical instrument for estimating the latent underground economy construct. The MIMIC approach is particularly suitable for phenomena such as underground economic activity because they cannot be directly measured. The model simultaneously incorporates observable causes that influence underground economic behavior and observable indicators that reflect its consequences. The structural equation model was estimated using the Partial Least Squares Structural Equation Modeling (PLS-SEM) approach implemented through SmartPLS software. This method was selected because it is distribution-free, suitable for complex models, robust against multicollinearity, and capable of handling relatively limited sample sizes commonly encountered in macroeconomic time-series analyses.

Data analysis was conducted in two complementary stages. In the first stage, fuzzy logic techniques were employed to estimate the underground economy index. Initially, all selected economic indicators were normalized through the calculation of six-year moving averages. Subsequently, triangular membership functions were defined for each variable using statistical thresholds based on the mean and standard deviation of the corresponding series. The fuzzification process transformed crisp observations into linguistic values representing varying degrees of membership across the five fuzzy categories. Following fuzzification, a comprehensive fuzzy rule base was

developed according to theoretical expectations and empirical evidence regarding the relationships among monetary, financial, and real-sector variables and underground economic activity. The Mamdani fuzzy inference engine was then used to process all possible combinations of input conditions and generate fuzzy output sets. Finally, defuzzification procedures produced annual crisp estimates of the underground economy index for the period 1996–2025. Sensitivity analysis was conducted to assess the stability of the estimated index and identify the degree to which variations in each input variable influenced the final underground economy estimates.

In the second stage, Structural Equation Modeling was applied using the MIMIC framework to investigate the determinants and indicators of underground economic activity. The latent underground economy variable estimated through fuzzy logic was incorporated into a structural model linking causal variables such as GDP, money supply ratio, activity rate, tax burden, and gross fixed capital formation with the hidden economy construct. The Partial Least Squares approach was employed for parameter estimation because of its predictive orientation and its ability to estimate complex causal structures without requiring multivariate normality assumptions. The assessment of the measurement model included the evaluation of factor loadings, indicator reliability, composite reliability, Cronbach's alpha, and convergent validity through Average Variance Extracted (AVE). The structural model was evaluated using path coefficients, coefficients of determination ( $R^2$ ), effect sizes, predictive relevance statistics, and bootstrapping procedures to determine the significance of hypothesized relationships. The integration of fuzzy logic and MIMIC-based structural equation modeling provided a comprehensive framework for estimating the size of the underground economy, identifying its major determinants, and examining its evolution over the study period.

### 3. Findings and Results

The fuzzy estimation began with the fuzzification of the input variables. For each inference block, the input variables were classified into five linguistic membership levels: Very Low, Low, Normal, High, and Very High. The output set was also divided into five linguistic levels: Very Small, Small, Medium, Large, and Very Large. A six-year moving average was used as the base value for each input variable in order to reduce the effect of business-cycle fluctuations. The moving average represented the Normal level of each variable, and the fuzzification process started from 1991. After the input variables were transformed into fuzzy linguistic values, decision rules were developed in the form of IF–THEN statements. These rules determined how the membership functions of the input variables were combined to produce the output level of the underground economy. Where two input variables were used, twenty-five fuzzy rules were required, because the number of rules is obtained from  $n^t$ , where  $n$  is the number of linguistic values and  $t$  is the number of causal or independent variables. The following rule base shows the general fuzzy decision structure used for the irregular component of the underground economy.

**Table 1. General fuzzy rules for the irregular component of the underground economy**

Rule	BURDIMP	ENERGY	Irregular sector	Weight
1	Very High	Very High	Very Large	1.00
2	Very High	High	Very Large	0.80
3	Very High	Normal	Small	1.00
4	Very High	Low	Small	0.80
5	Very High	Very Low	Medium	0.80
6	High	Very High	Very Large	1.00
7	High	High	Large	1.00
8	High	Normal	Large	0.80

9	High	Low	Medium	1.00
10	High	Very Low	Small	1.00
11	Normal	Very High	Large	1.00
12	Normal	High	Large	0.80
13	Normal	Normal	Medium	1.00
14	Normal	Low	Small	0.80
15	Normal	Very Low	Small	1.00
16	Low	Very High	Large	1.00
17	Low	High	Medium	1.00
18	Low	Normal	Small	0.80
19	Low	Low	Small	1.00
20	Low	Very Low	Very Small	1.00
21	Very Low	Very High	Medium	0.80
22	Very Low	High	Small	0.80
23	Very Low	Normal	Small	1.00
24	Very Low	Low	Very Small	0.80
25	Very Low	Very Low	Very Small	1.00

In the final defuzzification stage, the linguistic values were transformed into crisp numerical values so that the trend of the underground economy could be extracted. The values 0, 0.25, 0.50, 0.75, and 1 were assigned to the levels Very Small, Small, Medium, Large, and Very Large, respectively. MATLAB was used to implement the fuzzy inference system and to produce annual outputs between zero and one, representing the annual status of the underground economy. The results showed that the household component of the underground economy followed a declining trend from the beginning of the period until approximately 2011, indicating that home production and household self-consumption declined with urbanization and the expansion of modern living patterns. However, in later years, this trend did not continue clearly, and household production may have increased under the influence of economic sanctions. The informal component showed considerable fluctuation and dispersion, although its average level remained relatively stable, suggesting that this component maintained a relatively constant share in the expansion of the underground economy. The irregular component fluctuated but showed an upward trend after 1995, indicating the increasing role of tax evasion, regulatory avoidance, and energy-related distortions. The illegal component, representing activities such as production and trade of prohibited or smuggled goods, was at its lowest level during the years after the Revolution and the war period but began to increase from the 1990s onward. Overall, the final estimate of the underground economy as a percentage of GDP showed fluctuations over the period 1991–2024 and could be divided into two distinguishable periods: 1991–2011 and 2011–2024. From 2011 onward, the underground economy followed an upward trend. On average, the size of the underground economy in Iran during 1991–2024 was estimated at approximately 37% of GDP.

For the financial component of the underground economy, the ratio of oil revenues to total public budget revenues and the ratio of oil revenues to GDP were used as input variables. MATLAB simulation generated a time-series index for the financial component. The fuzzy decision rules used for this component are presented in Table 2.

**Table 2. Fuzzy decision rules for the financial sub-index of the underground economy**

Rule	Oil revenue share of budget revenues	Oil revenue share of GDP	Financial sub-index	Weight
1	Very Low	Very Low	Very Low	1.00
2	Very Low	Low	Very Low	0.80
3	Very Low	Medium	Low	1.00
4	Very Low	High	Low	0.80
5	Very Low	Very High	Medium	0.80
6	Low	Very Low	Very Low	0.80
7	Low	Low	Low	1.00
8	Low	Medium	Low	0.80
9	Low	High	Medium	1.00
10	Low	Very High	High	1.00
11	Medium	Very Low	Low	1.00
12	Medium	Low	Medium	0.80
13	Medium	Medium	Medium	1.00
14	Medium	High	High	0.80
15	Medium	Very High	High	1.00
16	High	Very Low	Low	1.00
17	High	Low	Medium	1.00
18	High	Medium	High	0.80
19	High	High	High	1.00
20	High	Very High	Very High	0.80
21	Very High	Very Low	Medium	0.80
22	Very High	Low	Medium	1.00
23	Very High	Medium	High	0.80
24	Very High	High	Very High	0.80
25	Very High	Very High	Very High	1.00

For the monetary component of the underground economy, the relative price of non-tradable to tradable goods and liquidity growth were used as the two input variables. The results of the fuzzy estimation showed that changes in monetary conditions were reflected in the monetary underground economy index through the rule base shown in Table 3.

**Table 3. Fuzzy decision rules for the monetary sub-index of the underground economy**

Rule	Liquidity growth	Relative price of non-tradable to tradable goods	Monetary sub-index	Weight
1	Very Low	Very Low	Very Low	1.00
2	Very Low	Low	Very Low	0.80
3	Very Low	Medium	Low	1.00
4	Very Low	High	Low	0.80
5	Very Low	Very High	Medium	0.80
6	Low	Very Low	Very Low	0.80
7	Low	Low	Medium	1.00
8	Low	Medium	Low	0.80
9	Low	High	Medium	1.00
10	Low	Very High	High	1.00
11	Medium	Very Low	Low	1.00
12	Medium	Low	Medium	0.80
13	Medium	Medium	Medium	1.00
14	Medium	High	High	0.80
15	Medium	Very High	High	1.00

16	High	Very Low	Low	1.00
17	High	Low	Medium	1.00
18	High	Medium	High	0.80
19	High	High	High	1.00
20	High	Very High	Very High	1.00
21	Very High	Very Low	Medium	0.80
22	Very High	Low	Medium	1.00
23	Very High	Medium	High	1.00
24	Very High	High	Very High	0.80
25	Very High	Very High	Very High	1.00

For the real-sector component, three input variables were entered into the fuzzy inference system: non-oil trade balance, the ratio of agricultural value added to non-oil GDP, and the ratio of construction value added to non-oil GDP. Because three input variables were used and each had five linguistic levels, 125 fuzzy rules were generated. The rule base indicated that combinations of high non-oil trade imbalance, high construction activity, and different levels of agricultural value added produced different levels of the real-sector underground economy index. The full 125-rule base was used in MATLAB to extract the time-series trend of the real-sector underground economy index.

**Table 4. Fuzzy rule base for the real-sector sub-index of the underground economy**

Rule range	Input variables	Number of rules	Output structure	Weight range
Rules 1–25	Non-oil trade balance at Very High level combined with five levels of construction value added and five levels of agricultural value added	25	Mostly Very High, High, Medium, and Low real-sector sub-index values depending on the interaction of construction and agriculture	0.80–1.00
Rules 26–50	Non-oil trade balance at High level combined with all linguistic levels of construction and agricultural value added	25	Mostly High and Medium values at stronger input combinations and Low values where agricultural or construction contribution is weaker	0.80–1.00
Rules 51–75	Non-oil trade balance at Medium level combined with all linguistic levels of construction and agricultural value added	25	Mostly Medium and Low values, with Very Low values appearing when both sectoral indicators are weak	0.80–1.00
Rules 76–100	Non-oil trade balance at Low level combined with all linguistic levels of construction and agricultural value added	25	Mostly Medium, Low, and Very Low values, showing a decline in the real-sector underground economy index under weaker trade-balance conditions	0.80–1.00
Rules 101–125	Non-oil trade balance at Very Low level combined with all linguistic levels of construction and agricultural value added	25	Mostly Medium, Low, and Very Low values, with the lowest outputs occurring when the sectoral indicators are also Very Low	0.80–1.00

After estimating the monetary, financial, and real-sector sub-indices, the final underground economy index was calculated by combining these three sub-indices. Since each sub-index had five linguistic levels, 125 fuzzy rules were used to estimate the final underground economy index. The final fuzzy rule base was structured so that simultaneous high values in the monetary, real, and financial sub-indices generated a Very High underground economy index, whereas simultaneous low values generated a Low or Very Low underground economy index.

**Table 5. Fuzzy rule structure for the final underground economy index**

Rule range	Input variables	Number of rules	Final underground economy index pattern	Weight range
Rules 1–25	Monetary sub-index at Very High level combined with all levels of real and financial sub-indices	25	Mostly Very High, High, Medium, and Low values, depending on whether the real and financial sub-indices reinforce or weaken the monetary signal	0.80–1.00
Rules 26–50	Monetary sub-index at High level combined with all levels of real and financial sub-indices	25	Mostly High and Medium values, with Low values when both real and financial sub-indices are weak	0.80–1.00
Rules 51–75	Monetary sub-index at Medium level combined with all levels of real and financial sub-indices	25	Mostly Medium and Low values, reflecting intermediate underground economy conditions	0.80–1.00
Rules 76–100	Monetary sub-index at Low level combined with all levels of real and financial sub-indices	25	Mostly Medium, Low, and Very Low values, depending on the strength of financial and real-sector components	0.80–1.00
Rules 101–125	Monetary sub-index at Very Low level combined with all levels of real and financial sub-indices	25	Mostly Medium, Low, and Very Low values, with the smallest index values occurring when all three sub-indices are weak	0.80–1.00

In the structural equation modeling stage, inferential analysis was performed using reliability and validity indices, factor analysis logic, and PLS-based path analysis in SmartPLS. Before estimating the model, the normality of the data was examined through the Kolmogorov–Smirnov test. The results showed that all variables had significance values below 0.05; therefore, the assumption of normality was not supported. This finding justified the use of the PLS-SEM approach, because PLS does not require multivariate normality, is compatible with small samples, and is appropriate when the model includes complex relationships among latent variables.

**Table 6. Kolmogorov–Smirnov normality test**

Variable	Significance level	Result
Gross Domestic Product	0.012	Distribution is not normal
Money Supply	0.017	Distribution is not normal
Activity Rate	0.001	Distribution is not normal
Direct Tax Burden	0.004	Distribution is not normal
Gross Fixed Capital Formation	0.014	Distribution is not normal

The reliability and convergent validity of the latent constructs were then examined. The results showed that the Average Variance Extracted values for all constructs were greater than 0.50, indicating acceptable convergent validity. Moreover, the composite reliability values were all higher than 0.70, confirming the internal consistency reliability of the constructs. Therefore, the measurement model had acceptable reliability and validity, and the final model was considered suitable for testing the research hypotheses.

**Table 7. Model fit, convergent validity, and composite reliability indices**

Latent construct	Average Variance Extracted (AVE)	Composite reliability
Gross Domestic Product	0.661	0.894
Money Supply	0.702	0.881
Activity Rate	0.631	0.864
Direct Tax Burden	0.689	0.821
Gross Fixed Capital Formation	0.692	0.845

The SmartPLS output was examined in both the significance and standardized coefficient modes. In the significance model, path significance was evaluated using the t-statistic, and paths with t-values greater than 1.96 were considered statistically significant at the 95% confidence level. In the standardized model, the coefficients shown on the paths represented standardized beta coefficients, while the values inside the endogenous construct represented the coefficient of determination. The path analysis results showed that all five hypothesized relationships were statistically significant.

**Table 8. Results of PLS path analysis for the research hypotheses**

Hypothesis	Path	Path coefficient ( $\beta$ )	t-statistic	Direction	Result
H1	Gross Domestic Product $\rightarrow$ Underground Economy	-0.360	15.369	Negative / inverse	Supported
H2	Money Supply $\rightarrow$ Underground Economy	0.776	28.960	Positive / direct	Supported
H3	Direct Tax Burden $\rightarrow$ Underground Economy	-0.109	2.195	Negative / inverse	Supported
H4	Activity Rate $\rightarrow$ Underground Economy	-0.048	11.457	Negative / inverse	Supported
H5	Gross Fixed Capital Formation $\rightarrow$ Underground Economy	-0.607	9.527	Negative / inverse	Supported

The first hypothesis examined whether Gross Domestic Product reduces the underground economy. The results showed that the path coefficient between Gross Domestic Product and the underground economy was negative and significant ( $\beta = -0.360$ ,  $t = 15.369$ ). Since the t-statistic was greater than 1.96, the null hypothesis was rejected at the 95% confidence level. This means that, assuming other factors remain constant, a one-unit increase in Gross Domestic Product is associated with a 0.360-unit decrease in the underground economy.

The second hypothesis examined the positive effect of Money Supply on the underground economy. The path coefficient was positive and significant ( $\beta = 0.776$ ,  $t = 28.960$ ). Therefore, the hypothesis was supported, indicating that Money Supply has a direct and meaningful effect on the underground economy. In practical terms, when other variables remain constant, a one-unit increase in Money Supply is associated with a 0.776-unit increase in the underground economy.

The third hypothesis examined the effect of Direct Tax Burden on the underground economy. The results showed a negative and significant relationship between Direct Tax Burden and the underground economy ( $\beta = -0.109$ ,  $t = 2.195$ ). Since the t-statistic exceeded the critical value of 1.96, the relationship was statistically significant at the 95% confidence level. Accordingly, assuming other factors remain unchanged, a one-unit increase in Direct Tax Burden is associated with a 0.109-unit decrease in the underground economy.

The fourth hypothesis assessed the relationship between Activity Rate and the underground economy. The results indicated a negative and statistically significant path coefficient ( $\beta = -0.048$ ,  $t = 11.457$ ). Thus, Activity Rate had an inverse effect on the underground economy. This finding means that, with other variables held constant, a one-unit increase in Activity Rate is associated with a 0.048-unit decrease in the underground economy.

The fifth hypothesis examined the effect of Gross Fixed Capital Formation on the underground economy. The path coefficient was negative and statistically significant ( $\beta = -0.607$ ,  $t = 9.527$ ). Therefore, the hypothesis was supported. This result shows that Gross Fixed Capital Formation has a strong inverse effect on the underground economy, meaning that, assuming other factors remain constant, a one-unit increase in Gross Fixed Capital Formation is associated with a 0.607-unit decrease in the underground economy. Overall, the findings confirmed that the underground economy in Iran is affected by monetary expansion, production capacity, investment

formation, labor-market activity, and fiscal pressure, while the fuzzy estimates revealed that the underground economy has expanded particularly after 2011 and averaged approximately 37% of GDP during the study period.

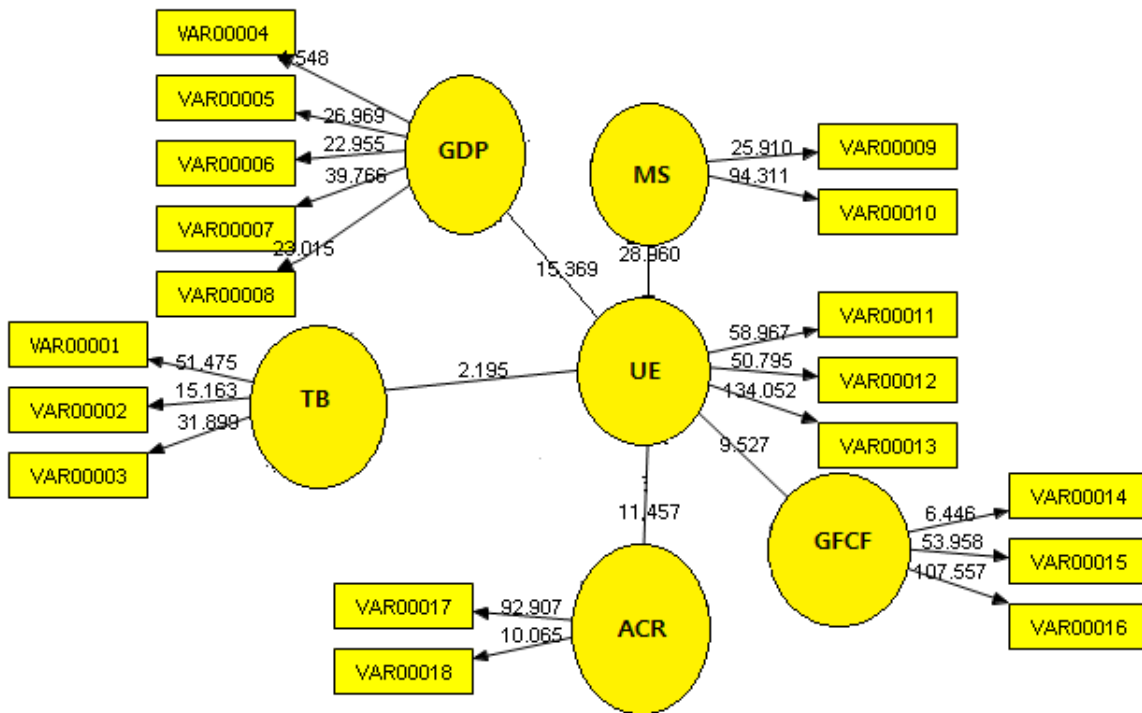


Figure 1. Model with T-Value

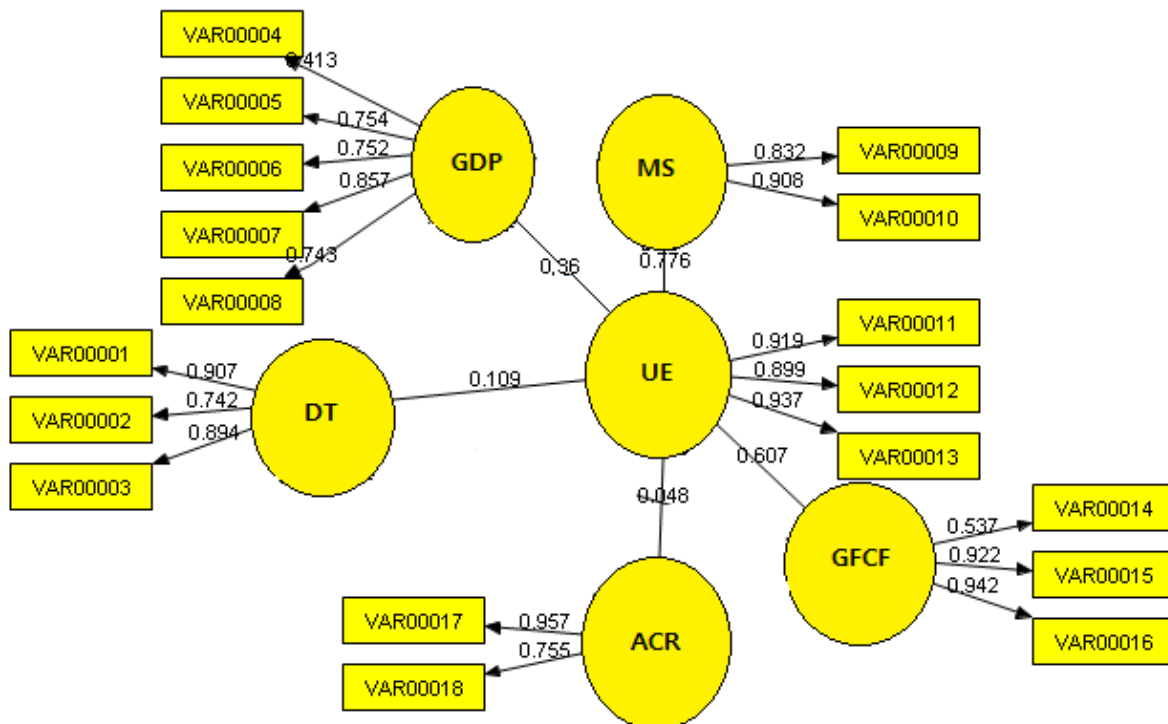


Figure 2. Model with Standardized Coefficients

#### 4. Discussion and Conclusion

The purpose of this study was to estimate the size and dynamics of the underground economy in Iran using a combined framework of fuzzy indexation and the MIMIC model within structural equation modeling. The fuzzy estimation results demonstrated that the underground economy has experienced substantial fluctuations over the study period and has followed a generally upward trajectory since approximately 2011. The findings further indicated that the average size of the underground economy was approximately 37% of GDP, suggesting that a considerable proportion of economic activity occurs outside official monitoring, taxation, and regulatory systems. The fuzzy analysis also revealed heterogeneous trends across the household, informal, irregular, and illegal sectors of the underground economy. While the household component generally declined during the earlier years of the study period, the irregular and illegal sectors exhibited increasing tendencies over time. These findings are consistent with the argument that structural economic pressures, institutional weaknesses, regulatory burdens, and changing market incentives may gradually shift economic activity toward hidden or semi-hidden channels. Previous studies have similarly reported that underground economic activities tend to expand when formal institutions face difficulties in maintaining transparency, monitoring compliance, and enforcing economic regulations [1, 3, 30].

One of the most important findings of the study was the significant negative relationship between Gross Domestic Product and the underground economy. The results showed that increases in GDP were associated with reductions in underground economic activity. This finding can be explained through the expansion of formal economic opportunities that typically accompanies economic growth. As production increases, labor markets become more active, formal employment opportunities expand, and businesses have stronger incentives to operate within legal and institutional frameworks. Economic growth also improves government capacity to provide services and strengthen enforcement mechanisms, thereby reducing the attractiveness of underground activities. This interpretation aligns with studies suggesting that economic development and institutional maturation contribute to reducing financial crime and informal economic behavior by improving governance quality and increasing participation in formal markets [2, 6]. Moreover, evidence from cross-country analyses indicates that stronger economic performance is often associated with greater transparency and lower dependence on hidden economic activities [20, 22].

The results further revealed that Money Supply exerted a strong positive effect on the underground economy. This was the strongest positive relationship identified in the structural model. The positive coefficient suggests that monetary expansion may create conditions that facilitate hidden transactions, particularly in environments characterized by inflationary pressures, exchange-rate instability, and imperfect financial monitoring. Increased liquidity can make it easier for economic actors to conduct transactions outside formal reporting systems, especially when cash-based activities remain prevalent. Furthermore, excess liquidity may encourage speculative activities, unreported transactions, and informal market exchanges that are difficult to monitor through official channels. This finding is consistent with studies emphasizing the role of financial systems and monetary conditions in facilitating money laundering, illicit trade, and hidden financial flows [10, 32]. Research on money laundering mechanisms similarly indicates that expanding financial channels may increase opportunities for concealing illicit proceeds when regulatory oversight is insufficient [7, 8, 11]. Therefore, the positive relationship between money supply and underground economic activity appears theoretically and empirically plausible.

Another important result concerned the relationship between Direct Tax Burden and the underground economy. Contrary to the conventional expectation that higher tax burdens necessarily stimulate tax evasion and underground activity, the present findings showed a significant negative relationship. This result suggests that increases in effective tax burden may coincide with stronger tax administration, improved monitoring, and more effective fiscal governance. In such circumstances, the deterrent effect of enforcement may outweigh the incentive effect of taxation. It is also possible that periods characterized by higher tax collection reflect broader institutional improvements that simultaneously reduce opportunities for hidden economic activity. Similar findings have been reported in studies emphasizing the role of governance quality and corruption control in moderating the relationship between taxation and informal economic behavior [3, 18]. Research on economic security and anti-money laundering frameworks further supports the view that stronger fiscal and legal institutions can reduce incentives for economic concealment even when tax obligations increase [28, 29]. Thus, the findings suggest that tax burden should not be evaluated independently of the institutional context within which taxation is implemented.

The study also found a significant negative relationship between Activity Rate and the underground economy. Although the magnitude of this effect was smaller than that observed for GDP and Gross Fixed Capital Formation, it remained statistically significant. This finding indicates that higher labor-force participation is associated with lower levels of underground economic activity. A possible explanation is that active labor markets provide greater access to formal employment opportunities, reducing the need for individuals to engage in unregistered or informal economic activities. When labor-market participation increases, workers may gain greater access to social protection, legal income sources, and institutional support mechanisms, all of which decrease dependence on underground markets. Similar arguments have been advanced in studies examining the relationship between economic inclusion, institutional development, and hidden economic activities [1, 2]. Furthermore, labor-market integration may improve the effectiveness of taxation and regulatory oversight because a larger proportion of economic transactions occur through formal channels.

The negative and statistically significant relationship between Gross Fixed Capital Formation and the underground economy represents another important contribution of the study. The relatively large coefficient suggests that investment plays a crucial role in reducing hidden economic activity. Increased capital formation is often associated with industrial expansion, infrastructure development, technological modernization, and enhanced productivity. These developments tend to strengthen the formal economy by increasing the scale and visibility of economic transactions. Large-scale investments typically require compliance with legal, financial, and regulatory standards, making it more difficult for economic activities to remain hidden. Consequently, investment-led growth may encourage the transition from informal to formal economic structures. This interpretation is supported by research indicating that sustainable development, institutional modernization, and economic formalization are interconnected processes [22, 24]. Studies of illicit economies have also shown that underdeveloped investment environments may encourage the persistence of informal and illegal activities because economic actors face fewer opportunities within the formal sector [23, 25].

The fuzzy analysis provided additional insights regarding the composition of the underground economy. The upward trend observed in the irregular and illegal sectors is particularly noteworthy. The expansion of these sectors may reflect increasing incentives for tax avoidance, regulatory circumvention, smuggling, and other forms of illicit economic activity. Similar developments have been documented in studies of illicit trade, criminal supply chains, and hidden commercial networks operating across national and international markets [23, 25, 26]. Research on

shadow infrastructures and criminal networks highlights how underground economic systems adapt to changing regulatory environments and exploit gaps in enforcement mechanisms [25]. Moreover, studies of wartime economies and conflict-affected regions demonstrate that uncertainty and institutional disruption often accelerate the growth of hidden markets [5, 13].

The estimated average underground economy size of approximately 37% of GDP indicates that a substantial share of economic activity remains outside official measurement. Such a magnitude has important implications for fiscal policy, monetary policy, economic forecasting, and development planning. When a large portion of economic activity is hidden, official statistics may underestimate production, employment, income generation, and financial flows. This can reduce the effectiveness of policy interventions because decision-makers rely on incomplete information. Furthermore, large underground sectors create opportunities for money laundering, corruption, illicit trade, and criminal enterprise. Research on money laundering consistently emphasizes the strong connection between hidden economic activity and broader financial crime risks [6, 21, 30]. Bibliometric evidence further demonstrates that money laundering, tax evasion, corruption, and underground economic activity constitute interconnected research themes within the broader literature on economic crime [33].

The findings also have implications for economic security and governance. Studies focusing on financial intelligence systems argue that improving information management and analytical capacity is essential for identifying hidden economic activities and protecting economic security [27]. Similarly, efforts to combat money laundering, illicit trade, and criminal financial networks increasingly rely on advanced monitoring technologies, artificial intelligence systems, and cross-border information sharing [11, 12]. The present findings support these perspectives by demonstrating that underground economic activity is strongly associated with macroeconomic and institutional variables that can be monitored through systematic analytical frameworks.

Another noteworthy aspect of the study is the methodological contribution of combining fuzzy logic with the MIMIC model. Traditional estimation techniques often struggle to capture the uncertainty and ambiguity inherent in underground economic activities. Fuzzy logic addresses this limitation by allowing economic indicators to possess varying degrees of membership across different conceptual categories rather than forcing binary classifications. When integrated with structural equation modeling, this approach provides a more flexible representation of latent economic phenomena. The consistency between the fuzzy estimation results and the SEM findings suggests that the combined methodology offers a robust framework for analyzing hidden economic activity. This methodological integration may be particularly useful in countries where data limitations, institutional complexity, and economic volatility complicate direct measurement approaches.

The overall pattern of results suggests that the underground economy in Iran is influenced simultaneously by monetary conditions, investment dynamics, labor-market participation, fiscal structures, and broader economic performance. While monetary expansion appears to stimulate underground activity, economic growth, investment accumulation, labor-force participation, and stronger fiscal capacity appear to constrain it. These findings reinforce the multidimensional nature of the underground economy and support the view that effective policy responses require coordinated interventions across monetary, fiscal, regulatory, and institutional domains rather than reliance on any single policy instrument.

One limitation of the present study is the reliance on macroeconomic time-series indicators as proxies for a latent phenomenon that cannot be directly observed. Although the fuzzy-MIMIC framework provides a sophisticated approach to estimating underground economic activity, the results remain dependent on the quality and availability of official data. In addition, the study focused on a limited set of monetary, financial, and real-sector

indicators and did not incorporate institutional variables such as governance quality, regulatory effectiveness, corruption perception, or judicial efficiency. Another limitation concerns the use of annual observations, which may not fully capture short-term fluctuations in underground economic behavior.

Future studies may expand the model by incorporating institutional, political, technological, and social variables that influence underground economic activity. Researchers may also compare the fuzzy-MIMIC framework with alternative estimation approaches such as dynamic factor models, Bayesian estimation methods, machine learning algorithms, and hybrid econometric techniques. Comparative studies across countries or regions could provide additional insights into the determinants of underground economic activity under different institutional environments. Furthermore, future research may investigate the effects of digital finance, cryptocurrencies, fintech innovations, and electronic payment systems on the evolution of underground economies.

Policymakers should strengthen economic transparency through integrated information systems linking taxation, banking, customs, labor-market databases, and business registration systems. Efforts to promote investment, expand productive employment, and improve economic growth should be considered essential components of strategies aimed at reducing underground economic activity. Regulatory agencies should enhance monitoring of financial transactions while minimizing unnecessary administrative burdens that encourage informality. Governments should also invest in advanced analytical technologies, risk-monitoring systems, and interagency coordination mechanisms to improve the detection of hidden economic activities and support evidence-based economic policymaking.

#### **Authors' Contributions**

Authors equally contributed to this article.

#### **Ethical Considerations**

All procedures performed in this study were under the ethical standards.

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#### **Conflict of Interest**

The authors report no conflict of interest.

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