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Apparent Steel Use Per Capita: Raking in the Money or Draining the Coeffers?

Kişi Başına Görünür Çelik Tüketimi: Varlıklara Katkı mı yoksa Kaynaklara Külfet mi?

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ABSTRACT

This study uses an econometric decision model to examine the relationship between apparent steel use per capita in the Republic of Korea and the monetary and economic structures of individuals and the country. South Korea is one of the leading countries in terms of apparent steel use per capita. The analysis considers 1,496 indicators from the World Bank's World Development Indicators series. These indicators are classified at the individual and country levels according to the research scope and data constraints. The CRITIC method is used to select the variables without external intervention in the time series. The selection relies on the intrinsic algorithmic structure of the series. NARDL and Hatemi-J asymmetric causality methods are used in the econometric analysis. The ALWAS method is used to assess integrated performance. The findings indicate that the usage intensity hypothesis, which has been present in the literature for over fifty years, requires reconsideration and revision. The results also show the significance of apparent steel use per capita for individuals and the state in terms of socio-economic, socio-technical and political metallurgy dimensions.

ÖZ

Kişi başına görünür çelik tüketimi sosyo-ekonomik gelişmişlik göstergeleri arasında yer almaktadır. Bu nedenle bu çalışma, önde gelen çelik tüketen ve üreten ülkelerden biri olan Güney Kore'de kişi başına görünür çelik tüketiminin vatandaş ve devlet açısından ekonomik yapılarla ilişkisini ekonometrik bir karar modeli aracılığıyla incelemektedir. Araştırma tasarımı Dünya Bankası'nın Kalkınma Göstergeleri serisinden yazarlar tarafından hem bireysel hem de ulusal düzeyde sınıflandırılan 1496 gösterge üzerine kurulmuştur. Çalışmada zaman serilerine herhangi bir dış müdahale yapılmaksızın serilerin içsel algoritmik yapıları kullanılarak değişkenlerin belirlenmesi için CRITIC yöntemi uygulanmıştır. Analizler NARDL ve Hatemi-J asimetric nedensellik yöntemleriyle gerçekleştirilmiş ve bütünleşik performans değerlendirmesi için ise ALWAS yöntemi kullanılmıştır. Bulgular, elli yılı aşkın süredir literatürde yer alan metal kullanım yoğunluğu hipotezinin revize edilmesi gerektiğine işaret etmektedir. Ayrıca sonuçlar kişi başına görünür çelik tüketiminin vatandaşlar kadar sosyo-ekonomik, sosyo-teknik ve politik metalurji boyutları itibariyle devletler açısından da kritik öneme sahip olduğunu ortaya koymaktadır. Çalışma politika önerileri ve gelecek çalışmalar vizyonu ile sonlandırılmıştır.

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Introduction

Iron has been a fundamental material in human production and consumption since the Chalcolithic Age. In early periods, meteoric iron was considered sacred. Its value was also increased by the difficulty of extraction. In Mesopotamia, iron was traded at roughly twice the value of gold and five times that of silver. Iron craftsmen therefore held a social position comparable to that of priests (Pounds, 1959; Spoerl, 2007; Stefanescu, 2005). The development of steelmaking gave iron a major place in the Industrial Revolution. The Bessemer process made large-scale and relatively low-cost steel production possible. It is widely regarded as a turning point in the Second Industrial Revolution (He & Wang, 2017; World Steel Association [WSA], 2012). Over time, steel became a symbol of technological progress. It also became indispensable for housing, transportation and energy systems (Conejo et al., 2020; Cullen et al., 2012; Wang et al., 2022). From the late Middle Ages onward, iron and steel production shaped specialized industrial regions and import-dependent economies across Europe (Starley, 1999). Metals have long been associated with industrial development and rising living standards. The traditional sequence of metal ages reflects this view. Economic thought from Adam Smith onward also linked material progress with institutional and moral advancement (McCloskey, 1981). Steel has both socio-technical and socio-economic dimensions. Dwivedi et al. (2023) connect successful sustainability transitions with structural economic change in which steel plays a central role. The iron and steel industry has also often served as a model sector in nation-building strategies. Jawaharlal Nehru, Mustafa Kemal Atatürk, Joseph Stalin and Park Chung-Hee placed steel at the heart of their industrial policies (Clark, 1956; Rao, 1987; Szyliowicz, 1991; Woodcock & Burtin, 2003; Gemici, 2013; Kim & Sorensen, 2011). This reflects the idea of political metallurgy, where steel is treated as a matter of state policy and national strategy. We focus on the Republic of Korea in this study. South Korea is among the world's leading steel producers and exporters. It also records exceptionally high apparent steel use per capita. China accounts for more than half of global steel production (Lin et al., 2021; Song, 2023). Yet according to WSA (2024), its per capita steel use in recent years has been about 40 percent lower than that of South Korea. South Korea therefore offers a particularly relevant case for examining steel consumption at both national and individual levels.

Apparent steel use per capita is often discussed using the intensity of use hypothesis, also known as the inverted *U* hypothesis (Coccia, 2012; Evans, 1996; Ghosh, 2006; Huh, 2011; Tcha, 2019; Wårell, 2014). It links steel intensity with different stages of economic development and rejects a simple linear pattern. During early industrialization, steel consumption typically grows faster than overall economic output. Consumption later weakens in more mature economies as services and high-technology activities expand. The inverted *U*-shaped pattern has been reported in a substantial body of research (Crompton, 1999; Guzmán et al., 2005; Fernandez, 2018; Malenbaum, 1978; Malenbaum et al., 1973; Wandebori & Murtyastanto, 2023). The connection between the steel industry and economic growth has also been studied in different national contexts (Song et al., 2020; Paul & Mitra, 2024). South Korea is an unusual case because its very high per capita steel use coincides with an unconventional development trajectory. Steel consumption in the country cannot be read directly from GDP trends. Economic crises, pandemics, trade disputes and geopolitical tensions affect national indicators and household conditions in uneven ways. These shocks often blur the relationship between macroeconomic performance and industrial activity. Steel demand nevertheless moves closely with infrastructure investment, construction and manufacturing cycles. Interest rates, inflation and exchange rates also influence investment choices and steel purchasing. In this study, indicators were selected through algorithm-based procedures rather than manual selection. Each indicator was weighted according to its relative importance before entering the analysis.

The steel sector faces growing scrutiny because of its high energy use and carbon emissions (Xiao et al., 2023; Wang & Sun, 2024). EUROFER (2023) stresses the strategic value of scrap steel in recycling-based production. International efforts also seek to curb excess steel capacity through initiatives such as the Global Forum on Steel Excess Capacity. Trade frictions continue to alter established steel flows (Ahmad & Ahmad, 2023; Rogers et al., 2024). These developments are changing steel production, trade and consumption. We examine how steel demand relates to economic conditions, industrial structures and external shocks using national and individual-level data.

Materials and Methods

South Korea's position in steel production and consumption provides an interesting setting for examining apparent steel use per capita together with economic indicators. Its high level of apparent steel use per capita becomes particularly noticeable given the country's position in total crude steel production. For this reason, we examined South Korea's place among the major steel producers before constructing the dataset. Figure 1 shows apparent steel use per capita and crude steel production for South Korea and other major steel-producing countries.

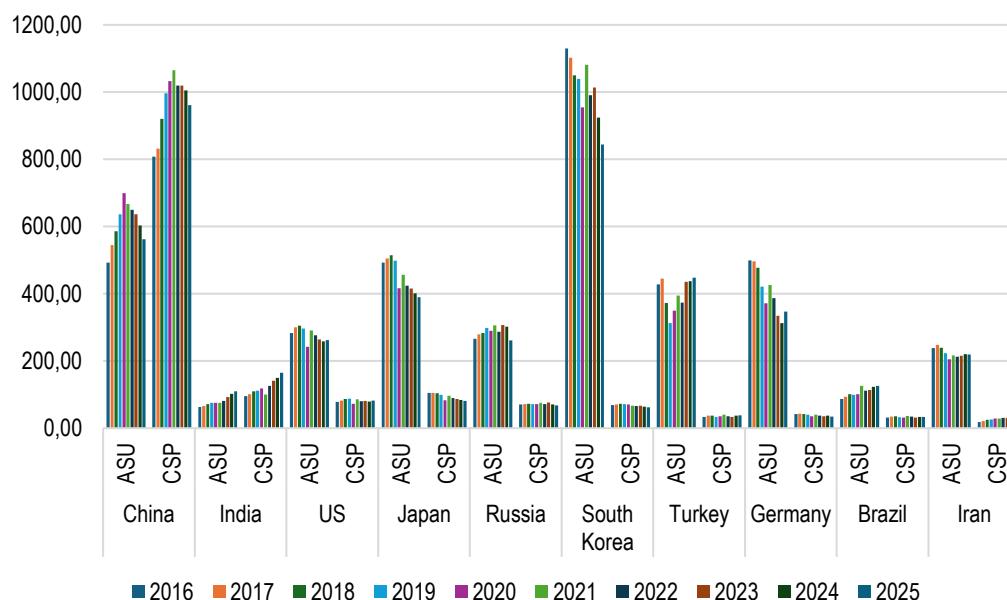


Figure 1. ASU (Apparent Steel Use per Capita, kg) and CSP (Crude Steel Production, mmt) Values of the Top 10 Steel-Producing Countries

As shown in Figure 1, South Korea has a notable position in terms of steel production and consumption. This makes it interesting to examine apparent steel use per capita together with economic indicators. South Korea's apparent steel use per capita was 1,130.2 kg in 2016 and 843.7 kg in 2025. Despite this decline, the 2025 level was still well above China's 562.1 kg and Japan's 389.5 kg. In the same year, South Korea produced 62.2 million tonnes of crude steel, behind China, India, and Japan. These figures provide a basis for examining steel use per capita in South Korea together with economic and monetary indicators. Based on this setting, the data used to examine the economic and monetary conditions accompanying steel use were obtained mainly from the World Bank's World Development Indicators database. We initially identified 1,496 indicators for the Republic of Korea. Of these, 457 had complete annual data from 1980 to 2023. We used 1980 as the starting year of the dataset. This period marked a major shift in South Korea's economic trajectory. The country moved toward heavy industry, adopted more liberal economic policies and underwent substantial structural restructuring (Heo et al., 2008; Jung, 2011; Kim, 1999; Kwon, 1997). We grouped the 457 indicators according to economic and monetary dimensions at the national and individual levels. The classification was based on the existing literature and measures of per capita apparent steel consumption. Many World Bank indicators are available in several formats, so careful selection was required. Exports Goods and Services, for instance, are reported as annual percentage growth, constant local currency units, constant 2015 United States (US) dollars, current local currency units, current US dollars and as a share of Gross Domestic Product (GDP). We consistently used the current US dollar version in these cases. After filtering the data, we retained 15 indicators for South Korea's economic and monetary conditions at the country level. We also selected 7 indicators for economic and monetary conditions at the individual level within South Korea.

H_1 ; There is a long-run relationship between apparent steel use per capita and country-level economic and monetary indicators in South Korea.

H_2 ; There is a long-run relationship between apparent steel use per capita and individual-level economic and monetary indicators in South Korea.

H_3 ; The relationship between positive and negative changes in economic and monetary indicators and apparent steel use per capita is asymmetric.

To test these hypotheses, the variables selected in the study were analyzed separately at the country and individual levels. Data processing and analysis were carried out using Microsoft Excel 2016, GAUSS 14, NonStat and EViews 11.0.

Table 1. Information on defined indicators

Country Indicators			Individual Indicators		
Indicators	Unit	Abb.	Indicators	Unit	Abb.
Broad money to total reserves ratio	ratio	BMT_{rr}	Inflation, consumer prices	annual %	INF_{cp}
Current account balance	BoP current US\$	CUR_{ab}	Gross National Income (GNI) per capita, Atlas method	current USD	GNI_{pc}
Domestic credit to private sector	% of GDP	DOC_{ps}	Broad money growth	annual %	BRO_{mg}
Exports of goods and services	current USD	EOG_{as}	GDP per capita	current USD	GDP_{pc}
Foreign direct investment, net inflows	BoP, current US\$	FDI_{ni}	Age dependency ratio	% of working age population	AGE_{dr}
GDP	current USD	GDP_{rk}	Unemployment, total	% of total labor force	UNE_{to}
General government final consumption expenditure	current USD	GGF_{ce}	Employment to population ratio, 15+, total	% (national estimate)	EPR_{rk}
GNI	current USD	GNI_{rk}			
Gross capital formation	current USD	GCA_{fo}			
Gross domestic savings	current USD	GRS_{ds}			
Gross fixed capital formation	current USD	GFC_{fo}			
Gross national expenditure	current USD	GNA_{ex}			
Manufacturing, value added	current USD	MAN_{va}			
Net primary income	BoP, current US\$	NPI_{us}			
Net trade in goods and services	BoP current US\$	NTG_{se}			

Source: Table by authors

After preparing the dataset, we used the CRITIC method to identify the independent variables according to their relative importance. We use CRITIC for variable selection within a time series econometric framework. The method is a weighting approach widely used in empirical research (Bhadra et al., 2022; Dwivedi et al., 2021; Khan et al., 2024; Peng et al., 2020; Tavosi et al., 2025; Varshney et al., 2024; Zafar et al., 2021). It was originally introduced by Diakoulaki et al. (1995). CRITIC works with data that include negative values. It also captures variation across criteria and the relationships between them (Krishnan et al., 2021; Zhang et al., 2024). This makes it suitable for datasets containing economic and monetary indicators with different statistical properties. We followed the procedure used in earlier applications of the CRITIC method (Bhadra et al., 2022; Diakoulaki et al., 1995). Consider a finite set A of n alternatives and a system of m evaluation criteria f_j , general form of the multicriteria problem is:

$$\text{Max}\{f_1(a), f_2(a), \dots, f_m(a) / a \in A\} \quad (1)$$

For every criterion f_j of this multicriteria problem, a membership function x_j is defined, mapping the values of f_j to the interval $[0,1]$.

$$x_{aj} = \frac{f_j(a) - f_j^*}{f_j^* - f_j^*} \quad (2)$$

The value x_{aj} , express the degree to which the alternative a close to the ideal value f_j^* , which is the best performance in criterion j and far from the anti-ideal value f_j^* , which is the worst performance in criterion j . By examining the j th criterion in isolation, a vector x_j is generated, denoting the scores of all n alternatives considered.

$$Max\{f_1(a), f_2(a), \dots, f_m(a)/a \in A\} \quad (3)$$

Each vector x_j is characterized by the standard deviation, σ_j which quantifies the contrast intensity of the corresponding criterion. Next, a symmetric matrix is constructed, with dimension $m \times m$ and a generic element r_{jk} , which is the linear correlation coefficient between the vectors x_j and x_k . It can be seen that the more discordant the scores of the alternatives in criteria j and k . The sum shown in formula (4) represents a measure of the conflict created by criterion j with respect to the decision situation defined by the rest of criteria.

$$\sum_{k=1}^m (1 - r_{jk}) \quad (4)$$

Spearman rank correlation coefficient R_{jk}^s can replace r_{jk} to offer a more general measure of the relationship between the rank orders of elements in vectors x_j and x_k . The information C_j , emitted by the j th criterion is determined using a multiplicative aggregation formula.

$$C_j = \sigma_j \sum_{k=1}^m (1 - r_{jk}) \quad (5)$$

Objective weights result by normalizing C_j to unity according to the following equation:

$$w_j = \frac{C_j}{\sum_{k=1}^m C_k} \quad (6)$$

Following the determination of variables using the CRITIC method, the Z-score transformation was employed to ensure data standardization and methodological consistency in the subsequent analyses.

$$Z_{ij} = \frac{x_{ij} - \bar{x}_j}{S_j} \quad (7)$$

Where Z_{ij} was the normalized index of sample i in data category j , x_{ij} was the value of sample i in data category j , $\bar{x}_j$ and S_j were the mean and standard deviation of data category j (Wang et al., 2025). The multiple linear regression model representation of time series, assuming k variables, is presented in Equation 7.

$$\hat{Y}_i = \hat{\beta}_0 + \hat{\beta}_1 X_{i,1} + \hat{\beta}_2 X_{i,2} + \dots + \hat{\beta}_k X_{i,k} + e_i \quad (8)$$

Equation 8 presents the basic regression framework used in the study. Y is the dependent variable and the X terms are the explanatory variables. The parameter vector is represented by β and e is the residual term. Stationarity is an important issue in time series analysis. Non-stationary series often produce misleading statistical relationships, as first documented by Granger and Newbold (1974). We therefore conducted several unit root tests before further estimation. We first applied the Augmented Dickey-Fuller test (Dickey & Fuller, 1979). It includes lagged terms to control for autocorrelation and uses the same critical values as the standard Dickey-Fuller procedure. We also used the approach proposed by Elliott et al. (1996). The ERS-Point Optimal test removes deterministic trends before estimation. Another test was the KPSS procedure developed by Kwiatkowski et al. (1992). KPSS uses stationarity as the null hypothesis. It tests this against non-stationarity using a non-parametric estimate of long-run variance. Two further tests were used for more complex dynamics. The Sollis (2009) test allows for smooth or exponential transition autoregressive behavior. It accommodates symmetric and asymmetric adjustments (Omay et al., 2020). We also implemented the Lee-Strazicich (2013) test. It incorporates potential structural breaks linked to policy changes and uses an LM -based procedure similar

in spirit to the KPSS test. The results of these stationarity checks determined the subsequent econometric methods. The series had different orders of integration. We therefore used the Autoregressive Distributed Lag bounds testing approach developed by Pesaran et al. (2001). The approach permits a mixture of $I(0)$ and $I(1)$ variables as long as none are integrated of order two (Abbas et al., 2024; Shahbaz & Mubarak 2023; Qu et al., 2024). We also used the nonlinear extension proposed by Shin et al. (2014) to capture possible asymmetries. This Nonlinear ARDL model has been increasingly used in recent empirical work (Ahmed et al., 2023; Ghosh, 2022; Jang et al., 2022; Quan et al., 2024). Equation 9 gives the form of the NARDL model used in the study.

$$\Delta y_t = \phi_0 + \phi_1 y_{t-1} + \phi_2 x_{t-1}^+ + \phi_3 x_{t-1}^- + \sum_{i=1}^{k-1} \phi_4 \Delta y_{t-i} + \sum_{i=1}^{k-1} \phi_5 \Delta x_{t-i}^+ + \sum_{i=1}^{k-1} \phi_6 \Delta x_{t-i}^- + \varepsilon_t \quad (9)$$

In Equation 9, Δ denoting difference operator, ϕ_1, ϕ_2 and ϕ_3 are the long-run parameters and ϕ_4, ϕ_5 and ϕ_6 are short-run parameters. For cointegration testing in NARDL framework, the null hypothesis of no cointegration is tested as $\phi_1 = \phi_2 = \phi_3 = 0$. A relationship between two variables does not imply causation. Causality tests that assume symmetric effects of shocks are used to determine causal links (Hsiao, 1981; Sims, 1972; Toda & Yamamoto, 1995). Granger and Yoon (2002) introduced the distinction between positive and negative changes. This distinction led to asymmetric tests (Hatemi J, 2012). Hatemi J (2012) developed the Asymmetric Causality Test to reveal hidden relationships. The test has been widely applied (Ajmi et al., 2015; Bahmani-Oskooee et al., 2019; Soon & Baharumshah, 2021). It has also been used together with the NARDL method (Akinlo, 2021; Dar & Nain, 2024; Gritli & Charfi, 2023; Khanday & Tarique, 2023). In the Hatemi J (2012) asymmetric causality test, the information criterion is denoted as HJC. The following information criterion is used to select the optimal lag order: (p):

$$HJC = \ln(|\hat{\Omega}_j|) + j \left(\frac{n^2 \ln T + 2n^2 \ln(\ln T)}{2T} \right), j = 0, \dots, p \quad (10)$$

Where $|\hat{\Omega}_j|$ is the determinant of the estimated variance-covariance matrix of the error terms in the VAR model based on lag order j , n is the number of equations in the VAR model and T is the number of observations (Hatemi J, 2012). We compare the dependent variable with variables that exhibit asymmetric or causal relationships based on the NARDL and Hatemi J (2012) tests. Multi-criteria decision-making methods were then used to determine integrated performance values. The time series contain negative values, so we applied the T-Score transformation developed by Kırdar and Aytakin (2024). The transformed series were prefixed with *ts*.

$$t_{ij} = 10 \frac{(x_{ij} - \mu_j)}{\sigma_j} + 50 \quad (11)$$

No issues were detected in equilibrium shifts after the transformations. We determined the criterion weights for the new decision problem using the CRITIC method. Performance values were assessed using the Aczél-Alsina Weighted ASsessment (ALWAS) method introduced by Pamucar et al. (2023) (Deveci et al., 2024; Gokasar et al., 2023; Işık et al., 2024). The ALWAS method uses Aczél-Alsina nonlinear functions to define weighted alternative strategies. These strategies are used to assess the preliminary impact of alternatives and determine their final evaluation scores. ALWAS ranks alternatives through nonlinear information processing. This allows decision-making to be simulated under different levels of risk. The method also has a high degree of robustness and flexibility. The ALWAS methodology introduces a novel algorithm for information standardization. The algorithm ensures consistency between natural and normalized attribute values. It also prevents range violations based on attribute types (Pamucar et al., 2023). Suppose that an evaluation of m alternatives A_i ($i = 1, 2, \dots, m$) under n criteria C_j ($j = 1, 2, \dots, n$) was performed. Then, a home matrix can be formed $\mathfrak{R} = [\zeta_{ij}]_{m \times n}$, where ζ_{ij} represents an estimated i th alternative under the j th criterion; $i = 1, \dots, m; j = 1, \dots, n$. Since the criteria presented in different units of measurement were used to evaluate the alternatives, it is necessary to standardize the information in the home matrix $\mathfrak{R} = [\zeta_{ij}]_{m \times n}$. Standardization of information implies translating all elements ζ_{ij} into the interval between zero and one, i.e.,

$\zeta_{ij} \in [0,1]$. The standardization of the home matrix was performed using Equation 12, which defined the standardized home matrix $\mathfrak{R}^s = [\hat{\zeta}_{ij}]_{m \times n}$.

$$\hat{\zeta}_{ij} = \begin{cases} \zeta_{ij} = \frac{\zeta_{ij}}{\zeta'_{ij}}, & \text{if } j \in B \\ \zeta_{ij} = -\frac{\zeta_{ij}}{\zeta'_{ij}} + \frac{\max_{1 \leq i \leq m} \left(\frac{\zeta_{ij}}{\zeta'_{ij}} \right) + \min_{1 \leq i \leq m} \left(\frac{\zeta_{ij}}{\zeta'_{ij}} \right)}{2}, & \text{if } j \in C \end{cases} \quad (12)$$

Where $\zeta'_j = \max_{1 \leq i \leq m} (\zeta_{ij})$. Based on Aczél–Alsina norms, weighted nonlinear functions are defined to describe and integrate final strategies for combining alternatives, with two weighted strategies outlined in the following section (Aczél & Alsina, 1982). Aczél–Alsina weighted averaging strategy of association $(\mathbb{R}_i^{(1)\xi}, i = 1, \dots, m)$. Let $\hat{\zeta}_{ij}$ be a set of elements of the matrix $\mathfrak{R}^s = [\hat{\zeta}_{ij}]_{m \times n}$ and let $w_j = (w_1, w_2, \dots, w_3)^T$ be the vector of weight coefficients of the criteria, then, by applying $\mathbb{R}_i^{(1)\xi}$.

$$\mathbb{R}_i^{(1)\xi} = \sum_{j=1}^n \hat{\zeta}_{ij} \left(1 - e^{-\left(\sum_{j=1}^n w_j \left(-\ln(1 - f(\hat{\zeta}_{ij})) \right)^\xi \right)^{1/\xi}} \right) \quad (13)$$

Where $f(\hat{\zeta}_{ij}) = \hat{\zeta}_{ij} / \sum_{j=1}^n \hat{\zeta}_{ij}$ and $\xi \geq 0$. Then $\mathbb{R}_i^{(2)\xi}$ represents the Aczél–Alsina weighted geometric averaging strategy $\mathbb{R}_i^{(2)\xi}, i = 1, \dots, m$.

$$\mathbb{R}_i^{(2)\xi} = \sum_{j=1}^n \hat{\zeta}_{ij} \cdot e^{-\left(\sum_{j=1}^n w_j \left(-\ln(f(\hat{\zeta}_{ij})) \right)^\xi \right)^{1/\xi}} \quad (14)$$

The integration of weighted strategies for aggregation Equation 13 and 14 was performed as follows:

$$\mathfrak{J}_i = \frac{\mathbb{R}_i^{(1)\xi} + \mathbb{R}_i^{(2)\xi}}{1 + \left\{ \emptyset \left(\frac{1 - f(\mathbb{R}_i^{(1)\xi})}{f(\mathbb{R}_i^{(1)\xi})} \right)^\theta + (1 - \emptyset) \left(\frac{1 - f(\mathbb{R}_i^{(2)\xi})}{f(\mathbb{R}_i^{(2)\xi})} \right)^\theta \right\}^{1/\theta}} \quad (15)$$

Where $\theta > 0, \emptyset \geq 0, f(\mathbb{R}_i^{(1)\xi}) = \frac{\mathbb{R}_i^{(1)\xi}}{\mathbb{R}_i^{(1)\xi} + \mathbb{R}_i^{(2)\xi}}$, and $f(\mathbb{R}_i^{(2)\xi}) = \frac{\mathbb{R}_i^{(2)\xi}}{\mathbb{R}_i^{(1)\xi} + \mathbb{R}_i^{(2)\xi}}$. The ranking of alternatives is done based on integrated weighted strategies of alternatives ($\mathfrak{J}_i$) where the alternative with a higher value $\mathfrak{J}_i$ has a better ranking. Stability and sensitivity analysis is important in optimization and decision making at both theoretical and practical levels (Tanino, 1999). Demir et al. (2024) note that only 9.5% of studies assess MCDM robustness through sensitivity analysis. Sensitivity analysis changes the weights to test ranking stability and method efficiency (Markatos et al., 2023). It ensures decision reliability and reduces uncertainty (Da Silva et al., 2022). We use logarithmic, square-root and exponential scaling normalization to adjust the weights.

$$wc'_i = \frac{\ln(wc_i + 1)}{\sum \ln(wc_i + 1)} \quad (16)$$

$$wc'_i = \frac{\sqrt{wc_i}}{\sum \sqrt{wc_i}} \quad (17)$$

$$wc'_i = \frac{e^{wc_i}}{\sum e^{wc_i}} \quad (18)$$

Equation 16 prevents excessive increases in large weights. Equation 17 reduces disparities among the weights for testing. With Equation 18, small weights increase slightly and increases in large weights remain limited.

Results and Discussion

This section presents the results of the analyses conducted separately at the citizen and state levels, as explained in the methodology section.

Variable Selection as a Decision Problem: CRITIC

The criterion weights were determined separately at the country and individual levels. The resulting values are presented below. As stated earlier, the weights were determined by the method without intervention from the authors.

Table 2. Weights according to the CRITIC

Country Indicators			Individual Indicators		
Criteria	Weights	Importance	Criteria	Weights	Importance
BMT_{rr}	0.2605	High	BRO_{mg}	0.1884	High
NTG_{se}	0.0758	High	GNI_{pc}	0.1601	High
CUR_{ab}	0.0661	High	GDP_{pc}	0.1588	High
FDI_{ni}	0.0625	High	UNE_{to}	0.1474	High
NPI_{us}	0.0595	High	Average 0.1429		
DOC_{ps}	0.0592	Medium	AGE_{dr}	0.1263	Low
EOG_{as}	0.0507	Medium	EPR_{rk}	0.1099	Low
MAN_{va}	0.0476	Medium	INF_{cp}	0.1099	Low
GNA_{ex}	0.0466	Medium			
GCA_{fo}	0.0466	Medium			
GDP_{rk}	0.0458	Low			
GNI_{rk}	0.0456	Low			
GFC_{fo}	0.0453	Low			
GRS_{ds}	0.0445	Low			
GGF_{ce}	0.0438	Low			

In the CRITIC results for countries, the number of criteria is fifteen, so the classification is based on the principle of divisibility into low, medium and high; for citizens, the CRITIC results are based on the average value.

Source: Table by authors

Table 2 shows that BMT_{rr} receives the highest weight in the country-level analysis with a value of 0.2605. This variable reflects the relationship between money in circulation and bank reserves. Changes in money supply affect credit conditions and broader economic activity, which in turn influence GDP_{rk} growth (Odumisor, 2019; Qaseem, 2024). For this reason, its prominent weight in the CRITIC results is understandable. The next most influential criterion is NTG_{se} . This indicator carries particular relevance for the Asia-Pacific region. The United Nations projects a continued expansion of merchandise trade in this area (ESCAP, 2020). Evidence from South Korea suggests that the goods-producing sector has expanded more rapidly than services (Choi & Bang, 2019). This pattern aligns with higher per capita visible finished steel consumption. Following NTG_{se} , the results highlight CUR_{ab} and FDI_{ni} . Since the 1998 currency crisis, South Korea has maintained a persistent current account surplus. Research indicates that demographic dynamics explain a substantial share of this pattern (Han & Shin, 2018). At the same time, the role of foreign direct investment in economic growth has attracted sustained scholarly interest (Labidi et al., 2024; Saleem et al., 2024; Shin & Park, 2024). In South Korea's case, this relationship cannot be assessed in isolation from its development trajectory. Limited domestic mineral and energy resources pushed the country toward an export-oriented growth strategy. Over time, manufacturing came to represent a large share of national output. South Korea's transition from developing to developed status in 2021 reflects this structural transformation (Lee, 2020; Wang et al., 2023). Within this context, the strong performance of the FDI_{ni} indicator in the CRITIC weighting is reasonable. The high importance assigned to NPI_{us} is also consistent with South Korea's deep integration into global markets. The economy relies heavily on international trade and foreign capital flows (Milani & Park, 2015; Kang et al., 2022). These linkages make external price and investment conditions particularly relevant for domestic industrial activity. Taken together, the findings suggest that per capita visible

finished steel consumption is closely tied to South Korea's monetary and external economic environment. Indicators such as BMT_{rr} , FDI_{ni} and CUR_{ab} move in ways that correspond with changes in steel use. The relevance of NTG_{se} reinforces this interpretation. South Korea's industrial structure and external dependence continue to shape its steel demand, while the persistent current account surplus signals the durability of this model.

Table 2 shows that BRO_{mg} receives a high weight in the individual-level analysis, similar to the country-level results. Ongan and Gocer (2021) also find an asymmetric structure in South Korea's money supply dynamics. This finding matches the design used in our study. Expansions and contractions in the monetary base have asymmetric effects on changes in the money supply. This prominence of BRO_{mg} relates to the continuity of South Korea's monetary and fiscal policies. Layman (1988) argues that this continuity supported the government's long-term development strategy and helped maintain policy credibility during industrialization. The analysis also assigns considerable weight to GNI_{pc} and GDP_{pc} . Such indicators are generally important across countries, a point reflected in the broader literature (CSO, 2024; Picardo et al., 2024; The World Bank, n.d.). Focusing specifically on South Korea, however, calls for a historical reading. In the 1960s the country was among the poorest in the world, with GNI_{pc} below 100 dollars. Subsequent industrial policies contributed to a rapid and sustained transformation (Koo, 2013). Economic growth in South Korea progressed cumulatively. Major interruptions occurred mainly during the oil shock and the assassination of Park Chung Hee. Unemployment therefore did not fluctuate as sharply as in many other economies (Chang et al., 2004). Keeping unemployment low alongside strong growth remains a central macroeconomic objective worldwide. The South Korean labor market also has a dual structure. Legal distinctions between regular and irregular employment create clear differences in job security and working conditions (Jo et al., 2023). These institutional arrangements affect how economic shocks pass through to workers and firms. The results suggest that stable growth and industrial policy contributed to rising steel demand in South Korea. Per capita visible steel consumption moves closely with industrial expansion and construction activity. Relatively low unemployment and consistent macroeconomic management appear to support this stability in steel use. We reassess these results later using additional models.

Time Series Analysis of Monetary and Economic Value Responses at Country and Individual Levels

In the econometric models of this study, apparent steel use per capita (finished steel products), denoted as $zASU_{pc}$ is used as the dependent variable.

$$(\hat{y}_t)zASU_{pc} = \hat{\beta}_0 + (\hat{\beta}_1)zBMT_{rr} + (\hat{\beta}_2)zNTG_{se} + (\hat{\beta}_3)zCUR_{ab} + (\hat{\beta}_4)zFDI_{ni} + z(\hat{\beta}_5)NPI_{us} + \varepsilon \quad (19)$$

$$(\hat{y}_t)ASU_{pc} = \hat{\beta}_0 + (\hat{\beta}_1)BRO_{mg} + (\hat{\beta}_2)GNI_{pc} + (\hat{\beta}_3)GDP_{pc} + (\hat{\beta}_4)UNE_{to} + \varepsilon \quad (20)$$

We used two main specifications in the analysis. Equation 19 examines individual-level effects and Equation 20 examines country-level dynamics. Model selection was based on the Akaike Information Criterion. The regression framework included fixed effects and time trends since all series had p-values below 0.005. We therefore used models with both intercept and trend terms. Correlations among the variables in these equations were then examined. A particularly strong correlation emerged between $zCUR_{ab}$ and $zNTG_{se}$, as well as between $zGDP_{pc}$ and $zGNI_{pc}$. To reduce multicollinearity concerns, the individual-level relationships were re-estimated using Equations 21 and 22. The country-level analysis was subsequently revisited with Equations 23 and 24.

$$(\hat{y}_t)zASU_{pc} = \hat{\beta}_0 + (\hat{\beta}_1)zFDI_{ni} + (\hat{\beta}_2)zCUR_{ab} + \varepsilon \quad (21)$$

$$(\hat{y}_t)ASU_{pc} = \hat{\beta}_0 + (\hat{\beta}_1)zBMT_{rr} + (\hat{\beta}_2)zNTG_{se} + z(\hat{\beta}_3)NPI_{us} + \varepsilon \quad (22)$$

$$(\hat{y}_t)zASU_{pc} = \hat{\beta}_0 + (\hat{\beta}_1)zGDP_{pc} + (\hat{\beta}_2)zUNE_{to} + \varepsilon \quad (23)$$

$$(\hat{y}_t)ASU_{pc} = \hat{\beta}_0 + (\hat{\beta}_1)zGNI_{pc} + (\hat{\beta}_2)zBRO_{mg} + \varepsilon \quad (24)$$

Based on the unit root tests examined at the country level, the ADF results show that the null hypothesis of a unit root is rejected for $zBMT_{rr}$ and $zFDI_{ni}$ at all significance levels in levels. After first differencing, the null is rejected for all variables. The ERS-PO test in levels yields results similar to the ADF test at the 10 percent level. However, $zNPI_{us}$ retains a unit root after first differencing. The KPSS test, which reverses the null hypothesis, classifies $zFDI_{ni}$ and $zNTG_{se}$ as stationary at all significance levels. According to the Sollis (2009) test, $zASU_{pc}$ is symmetric or asymmetric ESTAR stationary for F_{AE} and $F_{AE,\mu}$. The variable $zBMT_{rr}$ is

ESTAR stationary in all model specifications and at all significance levels. For this reason, structural break unit root tests were also implemented. The Lee-Strazicich test indicates that $zNPI_{us}$ contains a unit root with structural breaks at the 1 and 5 percent levels in levels, while the remaining variables do not. After first differencing, the null hypothesis of a unit root with breaks is rejected for all series. Structural breaks concentrate around 1997-1998 and 2010-2012 for most economic variables, while $zASU_{pc}$ shows a break in 2006. The 2006 break is more closely related to sectoral dynamics, particularly fluctuations in Asian commodity prices (Cavalcanti et al., 2012; Cheung & Morin, 2007). The 1997-1998 breaks align with the Asian and South Korean financial crises (Chang et al., 2009; Yoo & Moon, 1999) and with import price shocks (Kim, 2014). The 2010-2012 period reflects the delayed effects of the 2008 global crisis, slower growth in China and the European Debt Crisis (Mascitelli & Park, 2012; Dinda, 2017; Cashin et al., 2016). Overall, South Korea's economic and monetary indicators bear the imprint of earlier shocks, many of which show persistent effects over time.

At the individual level, based on the unit root tests conducted the ADF test shows that $zASU_{pc}$ and $zGNI_{pc}$ contain a unit root at all significance levels in levels, whereas $zBRO_{mg}$ is stationary at all levels. ERS-PO results indicate that $zBRO_{mg}$ and $zUNE_{to}$ are stationary at the 5 and 10 percent levels, while the remaining variables retain a unit root in other cases. KPSS results classify $zBRO_{mg}$ and $zUNE_{to}$ as stationary at all significance levels. After first differencing, unit root problems largely disappear across all tests, particularly at the 5 and 10 percent levels. According to the Sollis (2009) test, $zBRO_{mg}$ is symmetric or asymmetric ESTAR stationary at all significance levels. The variable $zUNE_{to}$ is also ESTAR stationary in most cases, except for the 10 percent level of the $F_{AE,t}$ statistic. The Lee-Strazicich test identifies structural breaks in 1996, 1998, 2003 and 2004. The series $zGNI_{pc}$ contains a unit root with structural breaks at the 1 percent level, while all other variables do not. After first differencing, the null of a unit root with breaks is rejected for all series at all significance levels. For $zUNE_{to}$, the break year is 1996, a period better characterized as the peak of economic growth with historically low unemployment rather than a crisis year. South Korea at this time combined rapid growth with a highly organized labor market and relatively homogeneous workforce structure (Hahn, 1996; Kwon, 1999). Consistent with country-level findings, the break in $zBRO_{mg}$ occurs in 1998 and is linked to the Asian Debt and Development Crisis (Wade, 1998; Kwon, 1999). Breaks in $zGDP_{pc}$ and $zGNI_{pc}$ appear in 2003 and 2004, coinciding with Chaebol reforms, policies of the Roh Moo-Hyun administration and the SARS outbreak that disrupted regional trade and production (Kalinowski, 2009; Li & Kwok, 2009; Tanaka, 2022). Overall, the results suggest that individual-level economic and monetary indicators in South Korea bear persistent effects of past shocks.

In the applied VAR analysis, the lag lengths were determined based on the Akaike Information Criterion (AIC), resulting in a lag of 3 for Equation 21 and a lag of 1 for Equation 22. The results of the NARDL cointegration test for Equation 21 are presented in Table 3.

Table 3. NARDL results for Eq. 21

$f(zASU_{pc} zCUR_{ab}^+, zCUR_{ab}^-, zFDI_{ni}^+, zFDI_{ni}^-)$				F-critical values asymptotic n=1000		F-critical values finite sample n=45	
NARDL(1, 1, 0, 1, 1)				I(0)	I(1)	I(0)	I(1)
k	Max. lag	F-stat.					
4	3	4.543318	10%	2.45	3.52	2.638	3.772
			5%	2.86	4.01	3.178	4.45
			2.5%	3.25	4.49		
			1%	3.74	5.06	4.394	5.914

R-squared: 0.978478, Adj. R-squared: 0.973260, F-statistics: 187.5352, Prob (F-statistics): 0.0000, Durbin-Watson stat: 2.034799, C's coefficient: -0.272181, C's probability: 0.0381. The Akaike Information Criterion (AIC) was used in determining the lag length.

Source: Table by authors

The results of the NARDL cointegration test for Equation 22 are presented in Table 4.

Table 4. NARDL results for Eq. 22

$f\left(\begin{matrix} zASU_{pc} zNTG_{se}^+, zNTG_{se}^-, zBMT_{tr}^+, zBMT_{tr}^- \\ zNPI_{us}^+, zNPI_{us}^- \end{matrix}\right)$			F-critical values asymptotic n=1000		F-critical values finite sample n=45		
NARDL(1, 0, 1, 0, 0, 1, 0)							
k	Max. lag	F-stat.	I(0)	I(1)	I(0)	I(1)	
6	1	4.435834	10%	2.12	3.23	2.327	3.541
			5%	2.45	3.61	2.764	4.123
			2.5%	2.75	3.99		
			1%	3.15	4.43	3.79	5.411
<i>R-squared: 0.979104, Adj. R-squared: 0.973227, F-statistics: 166.5971, Prob (F-statistics): 0.0000, Durbin-Watson stat: 1.934773, C's coefficient: -0.715689, C's probability: 0.0206. The Akaike Information Criterion (AIC) was used in determining the lag length.</i>							

Source: Table by authors

Table 3 and 4 present the number of independent variables (k) and the number of observations (n). The F-bound test statistic reported in Table 4 is calculated as 4.4358. When this result is compared with the critical values of $I(0)$ and $I(1)$ for 1,000 observations, it is found to exceed the upper bound at the 10% significance level. The results also account for the lag lengths. The test statistic is greater than the critical value at the 10% significance level. Based on the bounds test results, the nonlinear combinations of the variables converge to an equilibrium point. This indicates that they move together in the long run. Table 5 presents the long-term coefficient estimates for Equations 21 and 22.

Table 5. Long-run estimation results.

	Coefficient	Std. Error	t-Statistics	Prob.
for Equation 21				
$LzCUR_{ab}^+$	0.049512	0.159867	0.309709	0.7587
$LzCUR_{ab}^-$	-1.902290	0.377716	-5.036298	0.0000
$LzFDI_{ni}^+$	-1.003871	0.369870	-2.714118	0.0105
$LzFDI_{ni}^-$	0.307983	0.305185	1.009168	0.3202
for Equation 22				
$LzNTG_{se}^+$	-0.377006	0.268696	-1.403094	0.1702
$LzNTG_{se}^-$	0.988963	0.582162	1.698776	0.0991
$LzBMT_{tr}^+$	0.569406	0.300127	1.897221	0.0669
$LzBMT_{tr}^-$	-0.283646	0.173804	-1.631990	0.1125
$LzNPI_{us}^+$	0.844913	0.502548	1.681258	0.1024
$LzNPI_{us}^-$	-0.383220	0.647553	-0.591797	0.5581

The 'L' symbol preceding the variable names represents the long-run.

Source: Table by authors

For Equation 21, the model used for long-term coefficient estimation is presented in Equation 25, while for Equation 22, it is presented in Equation 26

$$EC = zASU_{pc} - (0.0495 * zCUR_{ab_pos} - 1.9023 * zCUR_{ab_neg} - 1.0039 * zFDI_{ni_pos} + 0.3080 * zFDI_{ni_neg}) \quad (25)$$

$$EC = zASU_{pc} - (0.3770 * zNTG_{se_pos} - 0.9890 * zNTG_{se_neg} - 0.5694 * zBMT_{tr_pos} - 0.2836 * zBMT_{tr_neg} + 0.8449 * zNPI_{us_pos} - 0.3832 * zNPI_{us_neg}) \quad (26)$$

According to the long-term coefficient results presented in Table 5 and Equation 25, it can be observed that the long-term coefficient of the $zCUR_{ab}^-$ variable is also negative. In this context, a one-unit decrease in the $zCUR_{ab}$ variable is expected to increase the $zASU_{pc}$ variable by approximately 1.9 units. In another case, a potential one-unit increase in the $zFDI_{ni}$ variable is expected to decrease the $zASU_{pc}$ variable by approximately one unit. Equation 26, the long-term coefficient of the variable $zNTG_{se}^-$ is obtained as 0.9890. Based on this result, it is stated that a one-unit decrease in $zNTG_{se}$ would lead to a decrease of approximately

0.9890 in $zASU_{pc}$. Furthermore, the coefficient result for the variable $zBMT_{tr}^+$ is obtained as 0.5694. In this case, a one-unit increase in $zBMT_{tr}$ is expected to lead to an increase of approximately 0.5694 in $zASU_{pc}$. Both results are statistically significant at the 10% significance level. The long-term Wald Test results for the model are presented in Table 6.

Table 6. NARDL long-run Wald Test results for Eq. 21 and 22.

	Test-statistics	Value	df	Prob.
for Equation 21				
$W_{LR,zCUR_{ab}}$	t-statistics	-3.827005	35	0.0005
$W_{LR,zFDI_{ni}}$	t-statistics	3.725740	35	0.0007
for Equation 22				
$W_{LR,zNTG_{se}}$	t-statistics	2.900807	33	0.0066
$W_{LR,zNPI_{us}}$	t-statistics	-1.546808	33	0.1314
$W_{LR,zBMT_{tr}}$	t-statistics	-2.719629	33	0.0103

The 'W' symbol preceding the variable names represents the Wald Test, while the 'LR' index corresponds to the long-run term.

Source: Table by authors

For Equation 21, according to the results of the Wald test, the null hypothesis H_0 is rejected at all significance levels in the long run. This indicates that the effects of decreases in the variable $zCUR_{ab}$ and increases in the variable $zFDI_{ni}$ on the variable $zASU_{pc}$ are not symmetric. For Equation 22, the null hypothesis H_0 is also rejected at all significance levels for the variables $zNTG_{se}$ and $zBMT_{tr}$ in the long term. Accordingly, it can be concluded that the effects of decreases in $zNTG_{se}$ and increases in $zBMT_{tr}$ on $zASU_{pc}$ are not symmetric. The results of the NARDL cointegration test for Equation 23 are presented in Table 7.

Table 7. NARDL results for Eq. 23

$f(zASU_{pc} zGDP_{pc}^+,zGDP_{pc}^-,zUNE_{to}^+,zUNE_{to}^-)$				F-critical values		F-critical values finite	
$NARDL(1,1,0,2,0)$				asymptotic n=1000		sample n=42	
k	Max. lag	F-stat.		I(0)	I(1)	I(0)	I(1)
4	2	4.742180	10%	2.45	3.52	2.638	3.772
			5%	2.86	4.01	3.178	4.45
			2.5%	3.25	4.49		
			1%	3.74	5.06	4.394	5.914

R-squared: 0.975074, Adj. R-squared: 0.968843, F-statistics: 156.4751, Prob (F-statistics): 0.0000, Durbin-Watson stat: 2.266735, C's coefficient: -0.975623, C's probability: 0.0160. The Akaike Information Criterion (AIC) was used in determining the lag length.

Source: Table by authors

The results of the NARDL cointegration test for Equation 24 are presented in Table 8.

Table 8. NARDL results for Eq. 24

$f(zASU_{pc} zBRO_{mg}^+,zBRO_{mg}^-,zGNI_{pc}^+,zGNI_{pc}^-)$				F-critical values		F-critical values finite	
NARDL(1,3,3,0,1)				asymptotic n=1000		sample n=42	
k	Max. lag	F-stat.		I(0)	I(1)	I(0)	I(1)
4	3	2.021961	10%	2.45	3.52	2.66	3.838
			5%	2.86	4.01	3.302	4.544
			2.5%	3.25	4.49		
			1%	3.74	5.06	4.428	6.25

R-squared: 0.715760, Adj. R-squared: 0.675154, F-statistics: 17.62708, Prob (F-statistics): 0.0000, Durbin-Watson stat: 2.307322, C's coefficient: -0.177949, C's probability: 0.0107. The Akaike Information Criterion (AIC) was used in determining the lag length.

Source: Table by authors

The F-Bounds Test value is 4.7421 and is reported in Table 7. Compared with the $I(0)$ and $I(1)$ values for 1000 observations, this value exceeds the upper bound at the 10% significance level. The results based on the lag lengths also show a large test value at the 10% significance level. Based on the boundary test results, the nonlinear combinations of the variables converge to an equilibrium point. This means that they move together in the long run. The results in Table 8 indicate that the variables do not exhibit a long-run relationship, as suggested by the bounds test. Table 9 presents the long-term coefficient estimates.

Table 9. Long-run estimation results for Eq. 23

	Coefficient	Std. Error	t-Statistics	Prob.
$LzGDP_{pc}^+$	0.498552	0.224739	2.218366	0.0337
$LzGDP_{pc}^-$	2.347829	0.749544	3.132345	0.0037
$LzUNE_{to}^+$	-0.152194	0.130559	-1.165703	0.2523
$LzUNE_{to}^-$	-0.538200	0.137327	-3.919109	0.0004

The 'L' symbol preceding the variable names represents the long-run.

Source: Table by authors

The model for the long-term coefficient estimation is provided in Equation 27.

$$EC = zASU_{pc} - (0.4986 * zGDP_{pc_pos} + 2.3478 * zGDP_{pc_neg} - 0.1522 * zUNE_{to_pos} - 0.5382 * zUNE_{to_neg}) \quad (27)$$

According to the long-term coefficient results presented in Table 9 and Equation 27, the long-term coefficients of the variables $zGDP_{pc}^+$ and $zGDP_{pc}^-$ are found to be positive. In this context, it is stated that a unit increase in the $zGDP_{pc}$ variable will lead to an approximate increase of 0.50 units in the $zASU_{pc}$ variable, while a unit decrease in the $zGDP_{pc}$ variable will decrease the variable by approximately 2.35 units. On the other hand, the long-term coefficient of the variable $zUNE_{to}^-$ is obtained as negative. This implies that a potential unit decrease in the $zUNE_{to}$ variable will result in an approximate increase of 0.54 units in the $zASU_{pc}$ variable. The results of these variables under consideration are significant at the 10% significance level. The long-term Wald test results for the model are presented in Table 10.

Table 10. NARDL long-run Wald Test results for Eq. 23

	Test-statistics	Value	df	Prob.
$W_{LR,zGDP_{pc}}$	t-statistics	2.058282	32	0.0478
$W_{LR,zUNE_{to}}$	t-statistics	-2.005287	32	0.0535

The 'W' symbol preceding the variable names represents the Wald Test, while the 'LR' index corresponds to the long-run term.

Source: Table by authors.

The Wald Test results, the H_0 is rejected for the variables $zGDP_{pc}$ and $zUNE_{to}$ at all significance levels in the long term. This indicates that the effects of decreases in the $zUNE_{to}$ variable and both increases and decreases in the $zGDP_{pc}$ variable on the $zASU_{pc}$ variable are not the same.

Causality analysis of monetary and economic value responses at national and individual levels

The outcomes of the asymmetric causality test can be found in Table 11.

Table 11. Hatemi-J (2012) asymmetric causality test results

		Crit. Val.			
Causality structure	Test Stat.	1%	5%	10%	Determining causality
Eq.21					
$zASU_{pc}^+ \rightarrow zCUR_{ab}^+$	13.290	8.316	4.343	3.055	Causality exist
$zCUR_{ab}^+ \rightarrow zASU_{pc}^-$	20.217	19.662	4.764	2.814	Causality exist
$zCUR_{ab}^- \rightarrow zASU_{pc}^-$	8.188	9.952	4.712	3.266	Causality exist
$zCUR_{ab}^- \rightarrow zASU_{pc}^+$	15.099	13.463	4.447	2.591	Causality exist
$zASU_{pc}^+ \rightarrow zFDI_{ni}^-$	20.999	21.469	13.153	9.410	Causality exist
$zFDI_{ni}^+ \rightarrow zASU_{pc}^+$	31.752	25.655	11.883	8.210	Causality exist

$zFDI_{ni}^+ \rightarrow zASU_{pc}^-$	19.820	38.505	18.845	12.806	Causality exist
$zFDI_{ni}^- \rightarrow zASU_{pc}^-$	648.986	37.133	15.731	10.195	Causality exist
$zFDI_{ni}^- \rightarrow zASU_{pc}^+$	14.110	20.999	11.007	7.573	Causality exist
Eq.22					
$zASU_{pc}^+ \rightarrow zNTG_{se}^+$	13.185	8.235	4.272	2.971	Causality exist
$zNTG_{se}^+ \rightarrow zASU_{pc}^-$	24.001	17.835	4.457	2.754	Causality exist
$zNTG_{se}^- \rightarrow zASU_{pc}^-$	6.487	9.142	4.450	3.223	Causality exist
$zNTG_{se}^- \rightarrow zASU_{pc}^+$	15.924	13.156	4.657	2.621	Causality exist
$zASU_{pc}^- \rightarrow zBMT_{tr}^+$	8.260	10.475	4.897	3.144	Causality exist
$zBMT_{tr}^+ \rightarrow zASU_{pc}^-$	32.441	18.019	7.523	3.374	Causality exist
$zASU_{pc}^- \rightarrow zNPI_{us}^-$	6.671	8.204	4.077	2.762	Causality exist
$zASU_{pc}^- \rightarrow zNPI_{us}^+$	4.817	8.029	4.366	3.049	Causality exist
$zNPI_{us}^+ \rightarrow zASU_{pc}^+$	8.063	10.666	5.096	3.314	Causality exist

The +/- signs in the superscripts of the variables represent positive and negative shocks. Critical values (1%, 5% and 10%) were determined using the Leveraged Bootstrap. The HQC information criterion was taken into account.

Source: Table by authors.

Other directional relationships not included in Table 11 did not exhibit asymmetric causality. According to Table 11 the effects of shocks to $zCUR_{ab}$ on $zASU_{pc}$ are bidirectional and asymmetric. Furthermore, it is stated that the effect of $zASU_{pc}$ on $zCUR_{ab}$ is positive. Additionally, there is an asymmetric and strong bidirectional relationship between $zASU_{pc}$ and $zFDI_{ni}$ with the effect of negative shocks being more pronounced. Table 11, it is observed that increases in $zASU_{pc}$ have positive effects on $zNTG_{se}$, while negative shocks do not show any causality. Additionally, both negative and positive changes in $zNTG_{se}$ have significant effects on $zASU_{pc}$. The impact of $zASU_{pc}$ on $zBMT_{tr}$ is found to be limited only to negative shocks, whereas the effect of $zBMT_{tr}$ on $zASU_{pc}$ is more pronounced. Negative shocks in $zASU_{pc}$ are shown to have both positive and negative effects on $zNPI_{us}$, while positive shocks in $zNPI_{us}$ have a supportive impact on $zASU_{pc}$. The results of the asymmetric causality test are provided in Table 12.

Table 12. Hatemi-J (2012) asymmetric causality test results

		Crit. Val.			
Causality structure	Test Stat.	1%	5%	10%	Determining causality
Eq.23					
$zASU_{pc}^+ \rightarrow zGDP_{pc}^-$	6.974	18.573	9.886	6.937	Causality exist
$zGDP_{pc}^+ \rightarrow zASU_{pc}^-$	14.094	33.030	10.486	7.140	Causality exist
$zGDP_{pc}^- \rightarrow zASU_{pc}^-$	10.645	31.296	14.068	9.951	Causality exist
$zGDP_{pc}^- \rightarrow zASU_{pc}^+$	9.583	17.235	8.257	5.887	Causality exist
$zASU_{pc}^+ \rightarrow zUNE_{to}^+$	6.366	15.144	8.316	6.127	Causality exist
$zASU_{pc}^+ \rightarrow zUNE_{to}^-$	14.868	15.243	8.494	5.970	Causality exist
$zUNE_{to}^+ \rightarrow zASU_{pc}^+$	9.755	21.593	10.907	8.005	Causality exist
$zUNE_{to}^+ \rightarrow zASU_{pc}^-$	3.439	37.842	7.246	3.115	Causality exist
$zUNE_{to}^- \rightarrow zASU_{pc}^-$	66.651	20.914	10.010	6.254	Causality exist
Eq.24					
$zASU_{pc}^+ \rightarrow zBRO_{mg}^-$	3.127	9.910	4.782	3.036	Causality exist
$zBRO_{mg}^- \rightarrow zASU_{pc}^+$	29.218	52.686	24.454	14.935	Causality exist
$zASU_{pc}^- \rightarrow zGNI_{pc}^+$	13.149	8.854	4.389	2.786	Causality exist
$zGNI_{pc}^+ \rightarrow zASU_{pc}^-$	22.267	23.699	11.568	8.573	Causality exist

The +/- signs in the superscripts of the variables represent positive and negative shocks. Critical values (1%, 5% and 10%) were determined using the Leveraged Bootstrap. The HQC information criterion was taken into account.

Source: Table by authors.

No asymmetric causality relationship was found for any other directions not included in Table 12. The primary interpretation is that causality relationships among the variables yield different outcomes depending on positive and negative shocks. In this context, causality from $zASU_{pc}$ to $zGDP_{pc}$ becomes significant under negative shocks, while causality from $zGDP_{pc}$ to $zASU_{pc}$ appears to be more pronounced in the presence of negative shocks. Additionally, the negative shocks of $zUNE_{to}$ are observed to have a strong impact to $zASU_{pc}$, further reinforcing the asymmetric relationship among the relevant variables. Another noteworthy aspect is that to $zASU_{pc}$ does not influence the positive shocks of $zGDP_{pc}$. Based on the results obtained from Table 12, it is possible to state that the relationship between $zBRO_{mg}$ and $zASU_{pc}$ is asymmetric. In this context, while declines in $zBRO_{mg}$ are observed to contribute to increases in $zASU_{pc}$, it is also noted that increases in $zASU_{pc}$ have a negative impact on $zBRO_{mg}$. Additionally, the results indicate that increases in $zBRO_{mg}$ have no significant effect on $zASU_{pc}$. Furthermore, it is assessed that negative shocks to $zASU_{pc}$ may have an increasing effect on $zGNI_{pc}$, whereas positive shocks to $zGNI_{pc}$ could lead to negative changes in $zASU_{pc}$.

Economic indicators and apparent steel use per capita: A CRITIC-ALWAS approach

The analysis combined the results of the NARDL model and the Hatemi-J asymmetric causality test with the CRITIC-based ALWAS method for both countries and individuals. The focus was to track how asymmetric economic and monetary indicators evolved in relation to $zASU_{pc}$ over time. To apply the ALWAS procedure, the relevant variables were first weighted using the CRITIC method and treated as decision criteria. The weighted results were then used to construct overall performance patterns and examine their temporal movements.

Table 13. Determination of criterion weights using the CRITIC method for country.

	$tsBMT_{rr}$	$tsCUR_{ab}$	$tsFDI_{ni}$	$tsNPI_{us}$	$tsNTG_{se}$
w_j	0.3421	0.1600	0.1875	0.1375	0.1729

The 'ts' symbol preceding the variables represents the T-Score transformation.

Source: Table by authors

In the variable selection process, as presented in Table 13, the highest importance weight is assigned to $tsBMT_{rr}$, while the lowest importance weight corresponds to the $tsNPI_{us}$ criterion, similar to the findings in Table 2. Other differences are associated with the algorithmic structure of the series and the applied transformation. The results obtained from the ALWAS method, implemented using these weights, are presented in Table 14.

Table 14. Findings of the ALWAS method

	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
$\mathfrak{J}_i$	0.5667	0.5985	0.6204	0.6787	0.6559	0.6618	0.6705	0.7164	0.5718	0.5679
	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
$\mathfrak{J}_i$	0.5742	0.6052	0.5870	0.5863	0.5698	0.5600	0.5508	0.6504	0.5885	0.5852
	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
$\mathfrak{J}_i$	0.5777	0.5843	0.5848	0.5841	0.6215	0.6028	0.5819	0.5956	0.6169	0.6143
	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
$\mathfrak{J}_i$	0.6219	0.6190	0.6649	0.7136	0.7162	0.7291	0.7497	0.7421	0.7325	0.7059
	2020	2021	2022	2023						
$\mathfrak{J}_i$	0.7247	0.8072	0.7477	0.7417						

The parameters related to the ALWAS method were selected in accordance with the original paper as $e=2.718282$, $\theta=1$ and $\Phi=0.5$. In line with expectations, theory and time series causality analyses, ξ was set to 4 and this value was found to be consistent with the original paper's consistency range, where $1 \leq \xi \leq 5$ (Pamucar et al. 2023).

Source: Table by authors

The $\mathfrak{J}_i$ values presented in Table 14 represent the annual integrated performance values of the relevant economic and monetary variables specific to this study. The annual variation of this performance is compared with the annual variation of $zASU_{pc}$ in Figure 1.

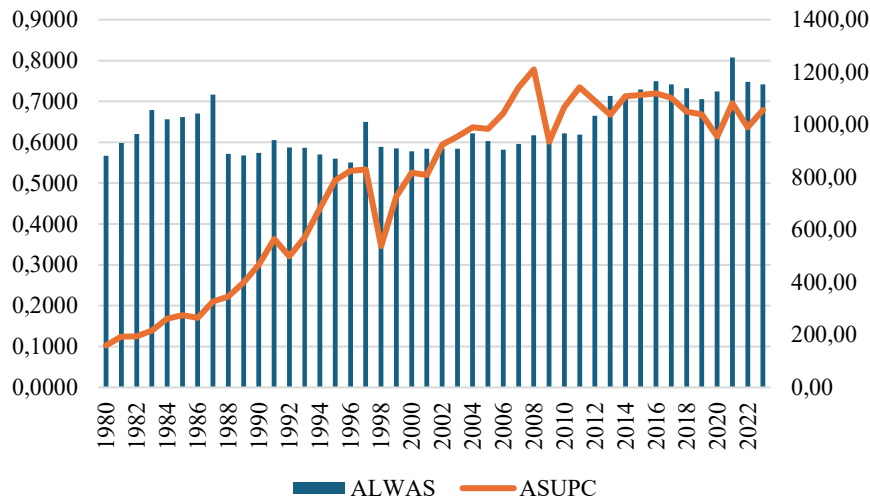


Figure 2. Annual changes in ALWAS performance: Variation graph based on apparent steel use per capita (finished steel products).
Source: Figure by authors

Figure 2 shows that economic performance diverged from $zASU_{pc}$ in 1997-1998 and again between 2006 and 2013. Before 1996, $zASU_{pc}$ moved broadly in line with the pattern described by Malenbaum et al. (1973). The figure also indicates that per capita steel consumption fluctuated more than the main economic indicators, especially during crisis years. At the country level, ALWAS results reveal that outside major shock periods, $zASU_{pc}$ and overall economic performance tended to peak in the same years. The most common peak years were 2014, 2015, 2016, 2017 and 2021. For the individual-level analysis, the relevant variables were first weighted with the CRITIC method and then used as criteria in the ALWAS procedure.

Table 15. Determination of criterion weights using the CRITIC method

	$tsBRO_{mg}$	$tsGNI_{pc}$	$tsGDP_{pc}$	$tsUNE_{to}$
w_j	0.2435	0.2727	0.3735	0.2104

The 'ts' symbol preceding the variables represents the T-Score transformation.

Source: Table by authors

The weights reported in Table 15 do not follow exactly the same ranking as in Table 2. $tsUNE_{to}$ again receives the lowest weight. The change in ordering reflects differences in the data transformation and the way the algorithm processes the series. The ALWAS results based on these revised weights are shown in Table 16.

Table 16. Findings of the ALWAS method

	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
$\mathfrak{J}_i$	0.5691	0.5864	0.5945	0.5843	0.5787	0.5896	0.6025	0.6315	0.6615	0.6626
	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
$\mathfrak{J}_i$	0.6665	0.6839	0.6693	0.6657	0.6905	0.7071	0.7145	0.6911	0.5760	0.6047
	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
$\mathfrak{J}_i$	0.6667	0.7897	0.6784	0.6447	0.6658	0.6818	0.7182	0.7329	0.7309	0.7034
	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
$\mathfrak{J}_i$	0.7030	0.7173	0.7247	0.7335	0.7503	0.7420	0.7394	0.7406	0.7566	0.7613
	2020	2021	2022	2023						
$\mathfrak{J}_i$	0.7627	0.7961	0.7670	0.7696						

The parameters related to the ALWAS method were selected in accordance with the original paper as $e=2.718282$, $\theta=1$ and $\Phi=0.5$. In line with expectations, theory and time series causality analyses, ξ was set to 4 and this value was found to be consistent with the original paper's consistency range, where $1 \leq \xi \leq 5$ (Pamucar et al., 2024).

Source: Table by authors

The $\mathfrak{J}_i$ values presented in Table 16 represent the annual integrated performance values of the related economic and financial variables in the context of this study. A comparison of the annual changes in this performance with the annual changes in $zASU_{pc}$ is presented in Figure 3.

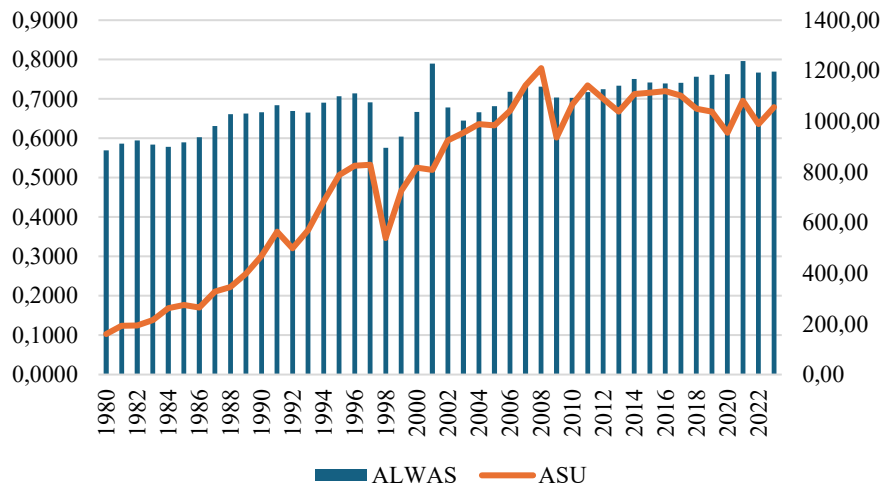


Figure 2. Annual changes in ALWAS performance: Variation graph based on apparent steel use per capita (finished steel products).

Source: Figure by authors

Figure 3 indicates that economic performance diverged from $zASU_{pc}$ in 1997-1998, 2000-2002 and 2018-2020. Before 1996, the path of, $zASU_{pc}$ follows Malenbaum's (1973) argument fairly closely. The 1997-1998 gap coincides with the Asian crisis, while the 2018-2020 divergence overlaps with the pandemic. During 2000-2002, overall economic activity slowed, yet per capita steel consumption continued to rise. This period involved strong state incentives, industrial restructuring, infrastructure investment and export-oriented production, which appear to have offset the broader slowdown. At the individual level, the ALWAS results show that 2014, 2015, 2017 and 2021 were shared peak years for both, $zASU_{pc}$ and economic performance, outside major shock periods. These patterns suggest that per capita steel consumption cannot be understood only through personal economic and financial indicators.

Diagnostics Tests and Sensitivity Analyses

Diagnostic test results for Equation 21 and 22 are presented in Table 17 and Figure 3.

Table 17. Results of diagnostic tests

Diagnostic Test	Eq. 21		Eq. 22	
	Test Val.	Prob.	Test Val.	Prob.
Breusch-Godfrey Serial Corr. LM test $\chi^2 SC$	0.231392	0.8907	1.113178	0.5732
Breusch-Pagan-Godfrey Het. test $\chi^2 HET(BPG)$	4.995816	0.7580	5.399416	0.7982
ARCH Heteroskedasticity $\chi^2 HET(ARCH)$	0.318950	0.5722	0.448995	0.5028
Jarque-Bera Normality test $\chi^2 NORM$	0.652670	0.7215	2.418090	0.2984
Ramsey RESET test $\chi^2 FF$	1.284264	0.2083	1.316615	0.1976

Source: Table by authors

According to Table 17, since the p-value $\chi^2 SC$ is greater than 10%, there is no autocorrelation problem in the model. Additionally, considering the 10% significance level, the p-values of the $\chi^2 HET(BPG)$ and $\chi^2 HET(ARCH)$ tests indicate that there is no heteroscedasticity issue. The $\chi^2 NORM$ test confirms that the normality assumption is satisfied and the $\chi^2 FF$ test shows that there are no issues in model specification.

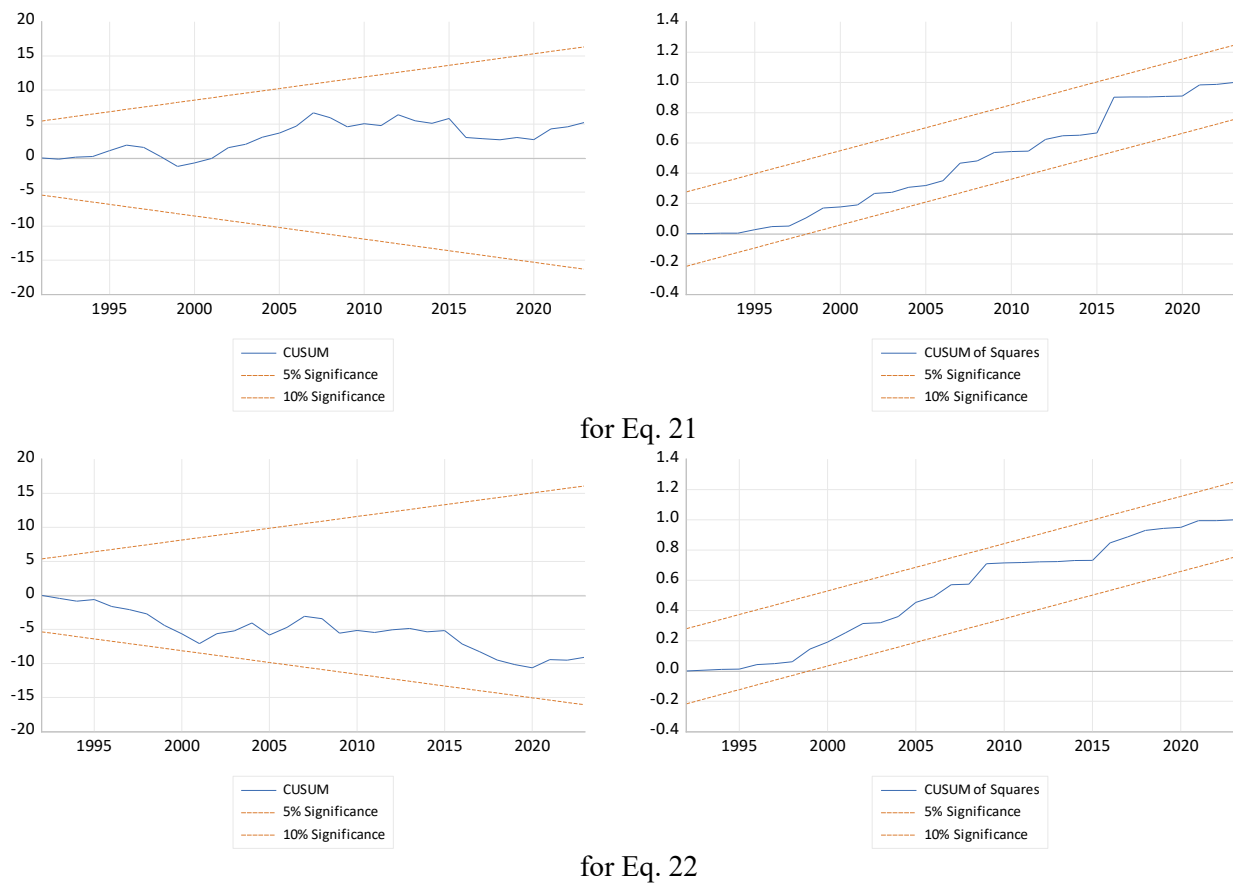


Figure 4. CUSUM and CUSUM of squares graphs

Source: Figure by authors.

Figure 4 shows that the CUSUM and CUSUM of squares graphs remain within the desired bounds at the 90% confidence level. This suggests that the model is stable. Table 18 and Figure 5 present the diagnostic test results for Equation 25.

Table 18. Results of diagnostic tests for Eq. 25

Diagnostic Test	Test Val.	Prob.
Breusch-Godfrey Serial Corr. LM test $\chi^2 SC$	2.413402	0.2992
Breusch-Pagan-Godfrey Heteroskedasticity test $\chi^2 HET(BPG)$	10.99753	0.2018
ARCH Heteroskedasticity $\chi^2 HET(ARCH)$	2.265248	0.1323
Jarque-Bera Normality test $\chi^2 NORM$	0.167541	0.9196
Ramsey RESET test $\chi^2 FF$	0.008736	0.9931

Source: Table by authors.

According to Table 18, since the p-value $\chi^2 SC$ is greater than 10%, there is no autocorrelation problem in the model. Additionally, considering the 10% significance level, the p-values of the $\chi^2 HET(BPG)$ and $\chi^2 HET(ARCH)$ tests indicate that there is no heteroscedasticity issue. The $\chi^2 NORM$ test confirms that the normality assumption is satisfied and the $\chi^2 FF$ test shows that there are no issues in model specification.

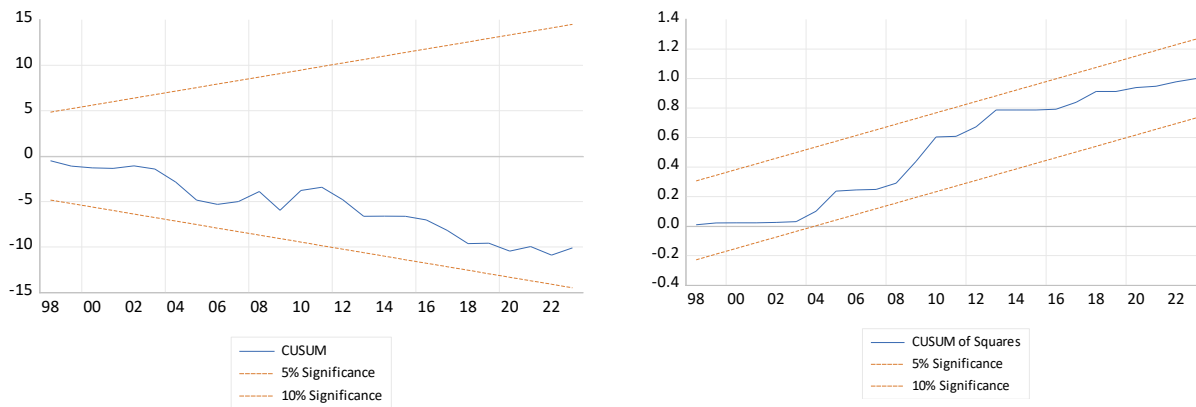


Figure 5. CUSUM and CUSUM of squares graphs
Source: Figure by authors.

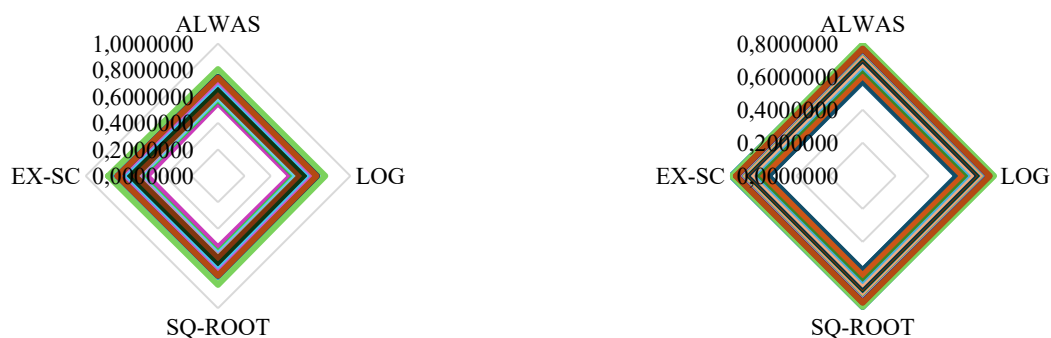
Figure 5 shows that the CUSUM and CUSUM of squares graphs remain within the acceptable limits at the 90% confidence interval. This suggests that the model is stable. We conducted the sensitivity analyses by reweighting the criteria. Table 19 presents the new weights calculated separately at the country and individual levels.

Table 19. Change in criterion weights according to CRITIC

		$tsBMT_{rr}$	$tsCUR_{ab}$	$tsFDI_{ni}$	$tsNPI_{us}$	$tsNTG_{se}$
Logarithmic normalization	w_j	0.3260	0.1641	0.1906	0.1429	0.1764
Square-root normalization	w_j	0.2654	0.1815	0.1965	0.1682	0.1884
Exponential scaling normalization	w_j	0.2300	0.1917	0.1970	0.1874	0.1940
		$tsBRO_{mg}$	$tsGNI_{pc}$	$tsGDP_{pc}$	$tsUNE_{to}$	
Logarithmic normalization	w_j	0.2444	0.2704	0.2711	0.2141	
Square-root normalization	w_j	0.2471	0.2614	0.2618	0.2297	
Exponential scaling normalization	w_j	0.2483	0.2556	0.2558	0.2402	

Source: Table by authors

Figure 5 presents the radar charts comparing the results of the ALWAS method re-applied three times considering the new weights, with the country-level results shown on the left and the individual-level results on the right.



In the figures, ALWAS represents the original solution, LOG represents logarithmic normalization, SQ-ROOT represents square-root normalization and EX-SC represents exponential scaling normalization

Figure 5. Sensitivity analysis radar chart according to Table 19 and Table 20.

Source: Figure by authors

The two radar charts show similar patterns across different runs of the method. The results remain stable across these runs and do not appear to reflect random fluctuations. We applied the ALWAS approach in several settings to examine its behavior with different data structures. The method produced consistent results in these applications and proved practical for performance assessment. Based on these applications, ALWAS can be

used with existing techniques to evaluate economic and monetary performance.

Conclusion

We examine the relationship between per capita steel consumption and the economic well-being of individuals and countries in South Korea from 1980 to 2023. South Korea was selected because of its notably high per capita apparent steel use based on finished steel products. The dataset was built mainly from the World Bank's World Development Indicators. We used the CRITIC technique within the MCDM framework to select variables for the econometric models. The selection was based on the statistical properties of the series and the practical limits of the available data. No manual variable selection was used. The CRITIC results were grouped into different importance levels at the country and individual scales. Different criteria were used for each level. Only variables with high importance weights were included in the econometric analysis. At the country level, these variables were the broad money to total reserves ratio, net trade in goods and services, the current account balance, net foreign direct investment inflows and primary income. At the individual level, we used broad money growth, GNI per capita, GDP per capita and total unemployment. The unit root tests indicate that many economic and monetary indicators in South Korea carry traces of earlier shocks. Their adjustment is not immediate. The structural break dates identified by the tests also match patterns reported in previous studies.

The analysis also considered correlations among the independent variables. At each level, two upper and four lower NARDL models were estimated. We used a 10 percent significance level to allow for broader confidence intervals in the econometric tests, following Yue and Hashino (2003) and Kodra et al. (2011). At the country level, current account balance and foreign direct investment had asymmetric and negative long-run relationships with apparent steel use per capita. Net trade in goods and services and the broad money to total reserves ratio had asymmetric and positive relationships. Large current account surpluses reduce reliance on foreign borrowing by increasing domestic savings (Allegret et al., 2014; Griffin, 1978). They support export-oriented production but do not automatically increase domestic steel consumption. Deficit periods are often accompanied by slower industrial investment, weaker infrastructure spending and lower steel use per capita. In export-driven economies such as South Korea, rising trade surpluses are usually associated with stronger industrial activity and higher steel consumption. A higher broad money to reserves ratio tends to expand credit and coincides with greater steel use. Tighter liquidity is typically associated with weaker industrial output and steel demand (Lardy, 2012; Nguyen et al., 2019). At the individual level, GDP per capita had an asymmetric relationship with apparent steel use per capita. Increases in GDP per capita were associated with higher steel consumption. Declines produced sharper reductions in steel use. This differs from the usage intensity hypothesis commonly discussed in the literature. It also fits South Korea's export-led growth model (Cho, 1985; Nam, 1994). Manufacturing and construction activity strengthens during expansionary periods and steel demand rises. During downturns, industrial output and investment slow quickly. Steel consumption falls at least as fast. Much of South Korea's growth relies on steel-intensive sectors such as shipbuilding, automobiles, construction and infrastructure (Hong et al., 2024; Sohal & Ferme, 1996). Postponed investment in these sectors leads to a disproportionate decline in steel use. Firms tend to use existing inventories instead of placing new orders. The NARDL models did not reveal significant short-run asymmetries at conventional lag lengths because of the properties of the series used in this study. We therefore applied asymmetric causality tests. The integrated performance of the related variables was evaluated with the ALWAS method and compared with the time path of apparent steel use per capita. The identified decomposition periods matched both the structural breaks and causality results. The years with the best performance in both sets of variables also largely overlapped. These results suggest that apparent steel use per capita is related to economic conditions at both the individual and country levels.

The steel industry faces growing pressure to decarbonize. At the same time, it has to deal with limited scrap supply, production capacity and trade restrictions such as tariffs and quotas. These pressures affect steel-producing and exporting countries as well as final users. Steel policy is also closely linked to developments in energy, construction and manufacturing. Steel prices are not transparent and vary widely across regions. This

makes risk management difficult for firms and governments. Global uncertainties add to these difficulties. Persistent imbalances between supply and demand continue to create volatility in steel production and prices (Beddows 2000). Long-term planning therefore needs to consider decarbonization requirements, scrap availability and capacity constraints. Digital trading platforms could improve price transparency, reduce regional price gaps and improve risk management. Consumers and investors may also benefit from considering energy efficiency, low-carbon alternatives and market trends in decisions related to steel use. Pauliuk et al. (2013) describe the late 21st century as the “era of steel scrap.” More research is needed on the economics of scrap markets, product life cycles and local scrap management projects in addition to existing material flow analyses. This work could improve our understanding of the economic and social dimensions of apparent steel use per capita. Per capita consumption of high quality steel and stainless steel could also be examined. These indicators could offer further information on development patterns for researchers and industrial organizations.

Additional Information and Declarations

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