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Examining the Relationship Between Primary Aluminium Production and Accident Rates

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ABSTRACT

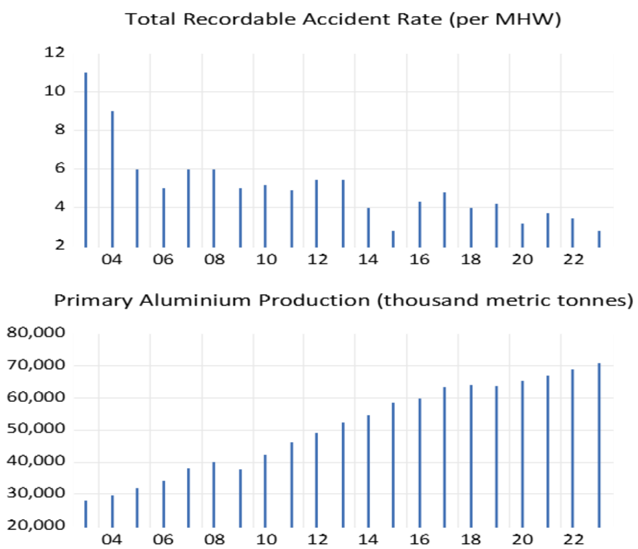
This paper examines the relationship between primary aluminum production and workplace safety, with a focus on accident rates per megawatt-hour (MWh) in the aluminum industry. As global aluminum production expands, it not only introduces economic and environmental challenges but also raises significant safety concerns inherent to heavy industry operations. Given the complexity of aluminum manufacturing and its associated risks, this study conducts a comprehensive safety analysis. Utilizing various cointegration techniques, including the Autoregressive Distributed Lag (ARDL) model, Fully Modified Ordinary Least Squares (FMOLS), Dynamic Ordinary Least Squares (DOLS), Cointegrated Regression (CCR), and the Engle-Granger and Phillips-Ouliaris tests, the research investigates the long-term relationship between production levels and accident rates. The findings reveal a significant cointegration between the variables, with the ARDL model estimating that a 1% increase in global aluminum production is associated with a 0.843% decrease in total accident rates. These results highlight the potential to enhance workplace safety through process optimization, providing valuable insights for industry stakeholders and policymakers focused on reducing risks in aluminum production.

1. INTRODUCTION

Aluminum is becoming increasingly important on a global scale due to its unique physical properties and industrial adaptability. Growing demand in sectors such as construction and automotive has contributed to a continuous rise in production, with worldwide aluminum output expected to exceed 70 million tonnes by 2023. While the rapid expansion of aluminum production presents significant opportunities for both producers and consumers, its environmental and social impacts cannot be overlooked. The industry, responsible for emitting around 1.1 billion tons of CO_2 annually, underscores the critical need for decarbonizing the supply chain to remain competitive and diversify resources [1]. The Asia region has a profound impact on global aluminum production, playing a crucial role in the industry's dynamics. With China contributing over 60% of the world's total output, this substantial production capacity has inevitably been associated with workplace accidents. Nevertheless, the implementation of safety measures has fostered a positive trend, leading to a consistent decline in accident rates.

Aluminum production is classified as a heavy industry due to its demanding operational processes and the extensive machinery utilized throughout the manufacturing stages. Historically, one of the significant challenges within this sector has been the frequent occurrence of workplace accidents, which have often been deemed unavoidable. This is largely attributable to the intricate nature of the production process, which involves the handling of hazardous raw materials and the operation of large, complex machinery. As a result, these factors have contributed to a persistent issue of safety risks, necessitating continuous efforts to improve safety measures and risk mitigation strategies within the industry. Unfortunately, such incidents are still prevalent in contemporary times. For example, in 2007, a catastrophic event involving the spillage of molten aluminum occurred at the aluminum casting division of Shandong Weiqiao Venture Group, leading to 16 fatalities and 59 injuries [2]. Such occurrences not only emphasize the ongoing dangers associated with aluminum production but also reinforce the urgent need for the implementation of stringent safety protocols. To address these safety concerns, various risk analysis methodologies have been developed. Among these, Bayesian networks (BNs) emerge as a robust tool for cause-effect analysis within probabilistic systems that are characterized by uncertain knowledge [3]. BNs facilitate the modeling of complex relationships between variables, allowing for a systematic assessment of potential risks and their interdependencies, thus contributing to enhanced decision-making processes in safety management. Due to the technological advancements and regulatory measures implemented in recent years, the frequency of accidents has markedly declined when compared to historical levels. These initiatives have enhanced safety protocols and operational practices within the aluminum production sector, fostering a safer workplace environment.

Figure 1 presents two graphs demonstrating that the total recordable accident rate declines with an increase in aluminum production in the world. This observation implies that elevated production levels may be linked to enhanced safety measures or more efficient operational processes that lower the probability of accidents. It suggests that as production increases, firms may allocate more resources towards safety protocols, employee training, and equipment upgrades to foster a safer work environment.



Data source: International Aluminium Institute.

Figure 1. Total recordable accident rates and primary aluminum production worldwide (2003-2023)

This study aims to examine the relationship between primary aluminum production levels and accident rates, employing econometric techniques such as cointegration methods to analyze trends over time. By investigating this relationship, the research will provide a robust understanding of how fluctuations in production levels may correlate with changes in accident rates. Utilizing these analytical approaches will enable the identification of long-term equilibrium relationships between the two variables, contributing to a comprehensive assessment of safety dynamics within the aluminum production industry. The primary hypothesis of this study is to reveal the long-term cointegration relationship between accident rates and primary aluminum production levels. By establishing this relationship, the research seeks to determine whether sustained changes in production are associated with corresponding variations in accident rates over time. By examining this relationship, the research intends to provide insights that can inform policy decisions, further reduce accident rates, enhance safety practices, and ultimately foster a safer working environment in the aluminum production industry.

2. LITERATURE REVIEW

Due to the specialized nature of the aluminum industry, research within this sector is particularly significant. In this regard, the body of scientific literature focused on primary aluminum production and the investigation of accidents associated with this process is relatively sparse. However, there have been several noteworthy studies in this area. To provide context, it is important to examine the aluminum production process itself. In a recent study, Ratvik et al. [4] detailed the complexities of primary aluminum production, covering the Hall–Héroult process and advancements in modern smelting technologies. Korneliúsdóttir [5] examined the energy-intensive nature of primary aluminium production, highlighting an increasing reliance on fossil fuels due to China's dominant market position, while also noting Iceland's commitment to renewable energy. A life cycle assessment conducted in this study compared aluminium production at Norðurál with an average European smelter, revealing that Norðurál has lower environmental impacts in categories such as global warming and eutrophication, yet still faces challenges related to energy consumption and other pollution metrics, emphasizing the importance of efficient resource management and waste reduction in the industry.

In their study of over 4,000 workers with more than five years of experience at the Soderberg aluminum plant in Canada, Spinelli et al. [6] discovered that the electromagnetic effects associated with primary aluminum production can result in various serious complications. Kjellén et al. [7] identified internal control (IC) as a vital regulatory strategy in Norway, requiring companies to implement formal safety, health, and environment (SHE) management systems. This was illustrated by a ten-year case study of an aluminum plant that experienced substantial improvements in SHE outcomes through a restructuring initiative. Although the economic advantages of IC were constrained by minimal SHE-related loss costs, the study underscored the importance of management motivation and the incorporation of IC into a broader management strategy for effective implementation. Young [8] underscores the need for additional evidence to substantiate the Zero Accident Vision (ZAV), noting that New Zealand Aluminium Smelters Limited (NZAS) has adhered to this vision for more than two decades, consistently recording fewer than ten lost-time injuries (LTIs) annually. While the ZAV has not been completely realized, NZAS is recognized as one of the safest heavy industrial sites worldwide. The study highlights the substantial decrease in LTIs, the interventions implemented, and their effectiveness, ultimately crediting NZAS's success to a rigorous application of the hierarchy of control methodology, with particular emphasis on ergonomic considerations. Research was also conducted to reduce accidents and losses during the primary aluminum production process. Kvande and Drabløs [9] provided a detailed description of the electrolysis cell technology, the raw materials used, and the health and safety implications of the process.

In alignment with the primary focus of the research, several studies have been conducted on the metric analyses connecting economic factors to accident evaluations. Li et al. [10] identify the level of economic development as a crucial determinant of production safety, stressing the necessity of balancing economic growth with accident prevention. By analyzing data on occupational accidents and economic indicators in China from 2000 to 2020, the study develops a grey working accident model and reveals a strong correlation between accidents and economic indicators. Çolak and Palaz [11] highlighted that while human, occupational, and environmental factors had been extensively studied, economic factors regarding occupational accidents in Turkey had received less attention. Their research, which examined the relationship between fatal occupational accidents and economic development from 1980 to 2012, revealed a short-run positive correlation between gross domestic product per capita and fatal accidents, transitioning to a negative relationship in the long run due to economic growth and structural changes in the economy. Similar studies addressing the issue have been conducted across various countries and industrial sectors, where cointegration and causality relationships were tested [12-14].

3. DATA AND METHODOLOGY

This empirical study focuses on two key data variables: Total Recordable Accident Rates (TRAR), quantified per million working hours (MHW), and Primary Aluminum Production (PAP). TRAR is crucial for evaluating workplace safety and operational efficiency, whereas PAP indicates the production level of the industry, offering insights into its overall performance. The choice of these variables aligns with the research objectives and is substantiated by existing data highlighting the significance of tracking accident rates in relation to production levels. Furthermore, it is important to consider potential confounding factors, such as changes in regulations and advancements in safety technologies, to achieve a thorough understanding of the interplay between production and safety in the aluminum sector. The data for these variables were obtained from the official platform of the International Aluminum Institute [15, 16], which serves as a comprehensive resource for research and statistical analysis relevant to the aluminum sector. This institute is esteemed as a principal authority in the field, offering extensive and up-to-date data that bolster the credibility of the research findings and enable a comprehensive analysis of trends and relationships within the context of aluminum production.

Table 1 presents descriptive statistics that offer essential insights into the characteristics of Total Recordable Accident Rates (TRAR) and Primary Aluminum Production (PAP) within the dataset. The differences in mean, median, and skewness underscore notable variations in workplace safety and production levels, which can guide further exploration of the relationship between these two variables.

Table 1. Descriptive statistics for variables

Statistic	TRAR	PAP	Statistic	TRAR	PAP
Mean	5.05	50760	Skewness	1.63	-0.16
Median	4.9	52291	Kurtosis	5.77	1.59
Maximum	11	70716	Jarque-Bera	16.1	1.82
Minimum	2.8	27986	Probability	0.00	0.40
Std. Dev.	1.94	14161	Sum	106	1065972
Observations	21	21	Sum Sq. Dev.	75.65	4.01E+09

To facilitate econometric analysis, the available data variables are transformed into their logarithmic forms. Figure 2 illustrates the graphical trends of the data represented in logarithmic quantities, enhancing interpretability and allowing for a more robust statistical examination of the relationships among the variables.

The methodological framework for this research is grounded in cointegration analysis, employing the Autoregressive Distributed Lag (ARDL) model alongside Fully Modified Ordinary Least Squares (FMOLS), Dynamic Ordinary Least Squares (DOLS), and Canonical Cointegrating Regression (CCR) techniques. Pesaran et al. [17] proposed a bound testing methodology for cointegration, which serves as an essential element within the Autoregressive Distributed Lag (ARDL) modeling approach. It establishes a framework for evaluating the existence of a long-run relationship between variables, regardless of their order of integration, whether they are integrated of order zero (I(0)) or order one (I(1)). The fundamental equation of the ARDL model can be expressed as follows:

$$Y_t = \alpha + \sum_{i=1}^{p} \beta_i Y_{t-i} + \sum_{j=0}^{q} \gamma_j X_{t-j} + \epsilon_t \quad (1)$$

In this equation, Y_t represents the dependent variable at time t, α denotes the intercept, βi are the coefficients associated with the lagged dependent variable Y_{t-i}, X_{t-j} signifies the independent variables along with their respective lags, γ_j are the coefficients corresponding to the lagged independent variables X_{t-j}, and ϵt represents the error term.

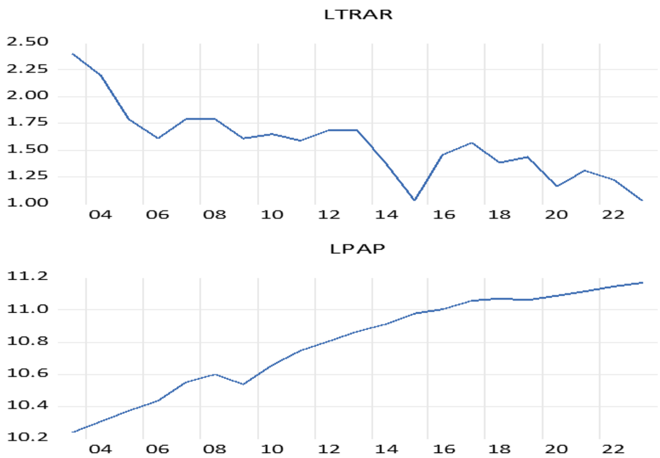


Figure 2. Graphical representation of data trends in logarithmic scale

The ARDL model, in conjunction with Engle-Granger and Phillips-Ouliaris cointegration tests, was utilized to explore the long-term relationships among the variables under consideration. Cointegration implies that while individual time series may demonstrate stochastic behavior and random fluctuations over time, their co-movement ensures that linear combinations of these series remain stationary. This principle is pivotal in econometrics and time series analysis, as it provides a robust framework for modeling long-term equilibrium relationships, thus facilitating a deeper understanding of the interconnected dynamics between the variables in the context of this study.

FMOLS [18], DOLS [19], and CCR [20] are techniques employed to estimate long-term relationships among variables in the field of econometrics. These methods are especially advantageous for addressing issues related to non-stationary data and potential endogeneity concerns. The Engle-Granger [21] and Phillips-Ouliaris [22] tests are conducted using these methodologies to evaluate the hypotheses regarding long-term cointegration relationships.

4. RESULTS

Cointegration methodologies necessitate that at least the dependent variable exhibits non-stationarity, as this characteristic is essential for elucidating the interdependence between the variables. For the ARDL model, the dependent variable must be non-stationary at its level, while it is adequate for at least one independent variable to display non-stationarity. In contrast, the FMOLS, DOLS, and CCR tests require that all variables be non-stationary at their levels and stationary at the first differenced level. In Table 2, the results of the Augmented Dickey-Fuller [23] unit root test reveal that both LTRAR and LPAP exhibit non-stationarity at their levels. However, after applying first differencing, both variables demonstrate stationarity, as indicated by their significant p-values (less than 0.05) at the first differenced level. Therefore, these variables are appropriate for application in the ARDL model, as well as in the FMOLS, DOLS, and CCR cointegration tests.

Table 2. ADF unit root test

Variables	Level	1st difference
LTRAR	-2.387 (0.157)	-5.048 (0.0009*)
LPAP	-2.202 (0.211)	-3.953 (0.0078*)

*MacKinnon (1996) one-sided p-values. Significant at 5% level.

Table 3 presents the ARDL model summary, indicating that the lagged value of LTRAR at lag 2 exhibits a significant negative relationship with current LTRAR (p-value = 0.0309). Notably, the LPAP variable is statistically significant at the 1% level (p-value = 0.0021), suggesting a strong negative association with LTRAR, which supports the observation that the rate of accidents in primary aluminium production decreases as production levels rise. The model accounts for approximately 71.3% of the variability in LTRAR (R-squared = 0.713), and the Durbin-Watson statistic of 2.066 indicates that there is no significant autocorrelation in the residuals.

Table 3. ARDL (2,0) model output

Variable	Coefficient	Std. Error	t-Statistic	Prob.
LTRAR(-1)	0.185	0.225	0.825	0.422
LTRAR(-2)	-0.491	0.207	-2.365	0.039
LPAP	-1.101303	0.296	-3.716	0.002
C (Constant)	13.93	3.608	3.861	0.001
Model summary	**R squared**	**Adj. R. squ.**	**Durbin Watson**	**Prob F st.**
	0.713	0.655	2.066	0.0002

Table 4. F-Bounds test

Test Statistic	Value	Significance	Lower Bound	Upper Bound
F-statistic	8.991	10%	3.02	3.51
k	1	5%	3.62	4.16
		1%	4.94	5.58

Table 4 reveals the results of hypothesis testing using an F-statistic of 8.991, which is significantly higher than the critical values at the 10% (3.51), 5% (4.16), and 1% (5.58) significance levels, allowing us to reject the null hypothesis and indicating that the independent variables collectively have a statistically significant effect on the dependent variable. This high F-statistic not only confirms the model's significance but also suggests the existence of long-term cointegration among the variables, indicating a strong relationship between the independent and dependent variables.

Eq. (2) and Table 5 demonstrate an inverse relationship between the logarithmic transformation of primary aluminium production (LPAP) and the total recordable accident rate (LTRAR). As LPAP rises, LTRAR declines. Specifically, a 1% increase in primary aluminium production corresponds to an approximate 0.843% reduction in the total recordable accident rate. The error correction term (EC) reflects the extent to which LTRAR deviates from its long-term equilibrium, based on the current level of LPAP. EC is expressed by the following equation:

$$EC = LTRAR - (-0.8437 \times LPAP + 10.6745) \quad (2)$$

Table 5. Levels equation

Variable	Coefficient	Std. Error	t-Statistic	P-value
LPAP	-0.843	0.106	-7.922	0.0000
C	10.674	1.159	9.202	0.0000

In Table 6, CointEq(-1) represents the rate at which the dependent variable (LTRAR) reverts to its equilibrium following a disturbance. The significant negative coefficient observed indicates that the model efficiently corrects any imbalance, preserving the long-term relationship between the variables. The significance of this term further validates the model's effectiveness in capturing the dynamic interplay between production and accident rates.

Table 6. ECM regression

Variable	Coefficient	Std. Error	t-Statistic	P-value
D(LTRAR(-1))	0.491	0.166	2.949	0.0099
CointEq(-1)*	-1.305	0.236	-5.529	0.0001

*Significant at 5% level.

The FMOLS, DOLS, and CCR methods are essential for examining long-term relationships between variables, offering reliable estimates when cointegration is present. As shown in Table 7, the Engle-Granger and Phillips-Ouliaris cointegration tests were conducted to determine the existence of a long-term equilibrium between the series. The Engle-Granger tau-statistic (-4.981, p-value 0.0042) suggests a significant cointegration relationship, leading to the rejection of the null hypothesis of no cointegration. Likewise, the z-statistic (-47.694, p-value 0.0000) further reinforces the presence of cointegration, indicating that the series move together over time despite short-term fluctuations, thus supporting the application of an Error Correction Model (ECM) for analyzing dynamic adjustments.

Table 7. Engle-Granger cointegration test result

Statistic	Value	P-value
Engle-Granger tau-statistic	-4.981	0.0042*
Engle-Granger z-statistic	-47.694	0.0000*

*This indicates that the series are cointegrated, as both the tau-statistic and z-statistic are statistically significant at the 5% level.

Table 8 demonstrates that the tau-statistic of -3.870, with a p-value of 0.033, is statistically significant at the 5% level, leading to the rejection of the null hypothesis of no cointegration and confirming that the series are cointegrated.

Although the z-statistic of -14.286, with a p-value of 0.077, does not reach significance at the 5% threshold, it suggests a potential cointegration relationship, with the tau-statistic offering more robust evidence of long-term equilibrium.

Table 8. Phillips-Ouliaris cointegration test result

Statistic	Value	P-value
Phillips-Ouliaris tau-statistic	-3.870	0.033*
Phillips-Ouliaris z-statistic	-14.286	0.077

*This indicates that the series are cointegrated, as both the tau-statistic and z-statistic are statistically significant at the 5% level.

5. CONCLUSION

This study investigates the dynamic relationship between primary aluminium production and the total recordable accident rate (TRAR), utilizing advanced econometric methods to explore the long-term connection between these variables. The results reveal a significant inverse relationship, indicating that as aluminium production increases, workplace accident rates tend to decline. This trend is likely attributed to improved safety protocols, greater operational efficiencies, and stricter adherence to regulatory standards that often accompany higher production levels.

The use of multiple cointegration methodologies, including ARDL, FMOLS, DOLS, and CCR, validates the presence of a long-term equilibrium between production and accident rates. The ARDL model, in particular, shows that a 1% increase in primary aluminium production is associated with approximately a 0.843% decrease in TRAR. With an F-statistic of 8.991, significantly above the critical values at 1%, 5%, and 10% levels, the null hypothesis is rejected, confirming that the independent variables significantly affect the dependent variable. Further validation is provided by the Engle-Granger and Phillips-Ouliaris tests, with the Engle-Granger tau-statistic of -4.981 and the Phillips-Ouliaris tau-statistic of -3.870, both confirming cointegration.

The findings give rise to several actionable recommendations for industry stakeholders. Aluminium producers should prioritize investments in advanced safety technologies, comprehensive workforce training, and the implementation of robust Health, Safety, and Environment (HSE) protocols to ensure that operational efficiencies do not compromise worker safety. Policymakers can reinforce this by enacting stricter safety regulations, including labour and union procedures, while providing incentives for companies that demonstrate measurable improvements in workplace safety. Additionally, continuous safety enhancements through regular audits, feedback systems, and strict adherence to HSE standards should be encouraged to sustain the downward trend in accident rates. Lastly, fostering collaboration between industry stakeholders, regulators, and employees is vital to ensuring that safety remains a central focus as production scales up, enabling both economic growth and enhanced worker well-being in the aluminium sector.

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