

**STATISTICAL ANALYSIS OF THE COMPLIANCE
OF THE DISTRIBUTION OF STOCK EXCHANGE DATA
FROM THE MAIN MARKET OF THE WSE
WITH THE NEWCOMB-BENFORD LAW**

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Purpose: The aim of the study is to verify the compliance of the empirical distribution of closing prices of companies listed on the Main Market of the Warsaw Stock Exchange (GPW) with the theoretical Newcomb-Benford law. In addition, it was investigated whether the degree of conformity with the Benford distribution differs between companies with high and low liquidity. The analysis aimed to identify potential statistical anomalies in market data that may indicate irregularities in price formation or signal potential manipulations of stock prices.

Research limitations/implications: The research sample included a total of 1.456.671 observations (real numbers representing the daily closing price of 421 analyzed companies listed on the main market of GPW between 1991-2022). To verify whether the empirical distribution of data representing the daily closing prices of shares listed on the Main Market of GPW conforms to the theoretical Newcomb-Benford distribution, first-digit, second-digit and first-two-digit tests were applied. To quantitatively assess the degree of fit of the empirical distribution to the theoretical one, statistical tests and the mean absolute deviation (MAD) measure were used. The research focuses on the Polish market. Future research suggests conducting a comparative analysis of foreign exchanges.

Practical implications: The results may be used by financial market regulators, auditors, and market analysts as a tool to support the detection of anomalies in stock trading.

Social implications: The research findings are important for society because a properly functioning stock market can attract more investors and issuers. In turn, any market anomalies, especially those involving manipulation, can lead to a decline in trust in capital market institutions. Furthermore, they can lead to asset mispricing and, in extreme cases, to losses for market participants.

Originality/value: This study represents one of the first applications of the Newcomb-Benford law to analyze long-term closing price data of companies on the Main Market of GPW in Warsaw (Central and Eastern Europe). The originality of the study lies in combining multiple tests of empirical-theoretical distribution fit and considering the liquidity differentiation of companies.

Keywords: Newcomb-Benford law (distribution), Main Market GPW, distribution conformity tests, MAD.

Category of the paper: Research paper.

1. Introduction

Modern finance requires comprehensive methods to detect irregularities and verifying data reliability. In this context, the Newcomb-Benford law is considered a useful mathematical tool, connected to big data analysis and statistical methods. The Newcomb-Benford law describes the relative frequency distribution of the leading digits in data sets. For individual datasets, the distribution of digits in certain significant positions aligns with the theoretical distribution known as the Newcomb-Benford law, Benford's law, or the law of the first significant digits.

In 1881, the Canadian astronomer and mathematician S. Newcomb discovered that the frequencies of first digits in randomly selected numbers are not uniformly distributed but follow a natural logarithmic decreasing pattern. While in the United States Naval Observatory library, Newcomb observed that the earlier pages of logarithmic tables were more worn than the later ones. Based on this observation, Newcomb hypothesized that users of logarithmic tables more frequently consulted numbers beginning with lower digits, which appeared at the start of the tables (Newcomb, 1938). However, his discovery did not initially attract much attention. Only in 1938 did Frank Benford, unaware of Newcomb's previous work, independently observe the same regularity by examining the wear on logarithmic tables. Empirically testing this thesis, he found that numbers in various datasets more often start with lower digits. Benford analyzed the first-digit distribution in approximately 300 data sets from different scientific fields and confirmed the pattern. Applications of the Newcomb-Benford law include natural sciences (e.g., river areas), mathematics and statistics (e.g., numerical data in newspapers or statistical yearbooks) and economics and finance (e.g., transaction prices, market data) (Benford, 1995). It is also applied in market data analysis and auditing (Corazza et al., 2010; Grammatikos, Papanikolaou, 2021). In the literature, the Newcomb-Benford law is used, among other things, to detect financial anomalies, accounting fraud, and analyze capital market data in various countries. Previous research has focused primarily on the American and Western, and Southern European markets, while analysis of long-term data from the Warsaw Stock Exchange (WSE), accounting for differences in company liquidity, remains limited.

The aim of this article is to verify the consistency of the empirical distribution of closing prices of companies listed on the Main Market of the Warsaw Stock Exchange (WSE) with the theoretical distribution of the Newcomb-Benford law. Additionally, we examined whether the degree of consistency with the Newcomb-Benford law varies depending on the companies' liquidity. The following research question was formulated: Does the empirical distribution of the first, second, and first two significant digits of the daily closing prices of companies listed on the Main Market of the Warsaw Stock Exchange (WSE) correspond to the theoretical distribution of the Newcomb-Benford law? Based on this, a research hypothesis was formulated: the empirical distribution of daily closing prices of companies listed on the Main Market of the Warsaw Stock Exchange differ significantly from the theoretical distribution of Newcomb-Benford law.

The article has a classic structure, consisting of an introduction, a literature review, including the strengths and weaknesses of the mathematical method of the Newcomb-Benford distribution discussed by the authors, a description of the research methodology, a presentation of the results, and a summary containing the main conclusions and limitations of the research, as well as future directions for potential analyses.

2. Literature Review

The Newcomb-Benford law is relatively rarely applied in Polish literature. Regarding the capital market, one study applied the first-digit test to daily trading volumes of 774 companies listed on GPW and NewConnect. A lack of conformity with the Newcomb-Benford distribution was observed in 37.38% of the public company stocks (Lesiak, 2024). Digit analysis is applied more frequently to foreign markets. Research on daily returns of the S&P 500 index from March 21, 1988, to March 21, 2018 (7,561 observations) provided empirical evidence of compliance with the Newcomb-Benford law. Short-term deviations (1 year) were associated with low risk periods and positive trends, and χ^2 test p-values relative to the Newcomb-Benford distribution showed some predictive ability for average market returns and risk levels, suggesting that deviations could serve as market risk indicators (Cerqueti, Maggi, Riccioni, 2024).

Analysis of closing prices on the Istanbul Stock Exchange showed generally significant deviations (Karavardar, 2014), as did studies on the Chinese stock market. Daily returns were more in line with the law, suggesting they may be better candidates for the Newcomb-Benford test than prices alone (Fang, 2024). Studies on daily returns of indices from selected developed and developing countries (Europe, North Africa) indicated that daily returns often corresponded to the Newcomb-Benford distribution, revealing natural regularities in financial market dynamics. Deviations from Benford's law (χ^2 p-values) were correlated with low-risk periods and positive market trends, highlighting its potential as a short-term market risk indicator (Hamida, de Peretti, Belkacem, 2024).

Riccioni and Cerqueti noted that the Newcomb-Benford analysis could serve as a market stability barometer, as deviations between empirical and theoretical distributions were correlated with periods of increased market instability (eg, crises, sharp declines or increases) (Riccioni, Cerqueti, 2018). Studies on credit default swap (CDS) prices showed that daily first-digit distributions were more stable in developed countries (USA, Germany, France), but deviations were significant in countries affected by debt crises (Greece, Ireland, Portugal) (Ausloos et al., 2016). Cano-Rodríguez found that while market-based asset valuations better comply with Newcomb-Benford law than expert valuations, differences were minor, indicating both approaches have high conformity, and digit analysis can be a useful tool for monitoring

valuation quality (2025). However, some authors point out that mathematical analysis using the Newcomb-Benford distribution can produce both false positives and false negatives. The specificity and type of the data and whether the basic conditions are met, such as a large data set and the absence of arbitrary constraints, are crucial for effectiveness (Diekmann, Jann, 2010).

Literature review demonstrates the growing application of digit analysis using Newcomb-Benford properties in economics and finance, supporting the potential for developing procedures to detect anomalies in large financial datasets. In the literature, the Newcomb-Benford law is used, among other things, to detect financial anomalies, accounting fraud, and analyze capital market data in various countries. Previous research has focused primarily on the American, Western, and Southern European markets, while analysis of long-term data from the Warsaw Stock Exchange (WSE), accounting for differences in company liquidity, remains limited. The literature review showed that the application of the Newcomb-Benford law as an analytical method is quite broad. Recent studies also show that deviations from the theoretical distribution, measured, for example, by the chi-square test, can be used as indicators of unusual market activity and predict future stock returns. At the same time, however, the authors emphasize that not every data set, including financial data, must or should satisfy the Newcomb-Benford law, suggesting caution in treating this method as a universal tool. Some studies indicate that deviations from the Benford distribution correlate with unusual market activity and can serve as a screening tool for detecting potential manipulation. At the same time, significant criticism of this mathematical method has been raised, suggesting that the Newcomb-Benford law is, at best, a screening tool and that results should be verified using other methods and contextual analysis.

3. Methods

In 1995, Hill provided a proof confirming that the Newcomb-Benford distribution can be used to identify distortions in aggregated data sets (Hill, 1995). It should be noted that this law is conceptually flexible, allowing the application of various tests, e.g. first-digit, second-digit, and first-two-digit tests (Hill, 2009).

The formulas for the distributions of the first, second, and first-two digits are as follows (Nigrini, 1996, 2012):

Probability that the first significant digit is d , where $d \in \{1, 2, 3, \dots, 9\}$:

$$P(D_1 = d) = \log_{10}\left(1 + \frac{1}{d}\right) \quad (1)$$

The probability of each first significant digit is 30.10% for 1, 17.60% for 2, 12.49% for 3, 9.69% for 4, 7.99% for 5, 6.69% for 6, 5.79% for 7, 5.11% for 8, and 4.57% for 9.

Probability that the second digit (following the first significant digit) is d , where $d \in \{0, 1, 2, \dots, 9\}$:

$$P(D_2 = d) = \sum_{k=1}^9 \log_{10} \left(1 + \frac{1}{10k+d} \right) \quad (2)$$

where k represents the first digit (from 1 to 9). The probability of each second significant digit decreases with increasing value, from 11.97% for 0 to 8.50% for 9.

Probability that the first two digits of a number are d_1, d_2 , where $d_1 \in \{1, 2, \dots, 9\}$ and $d_2 \in \{0, 1, \dots, 9\}$:

$$P(D_1 D_2 = 10d_1 + d_2) = \log_{10} \left(1 + \frac{1}{10d_1+d_2} \right) \quad (3)$$

For the first two-digit distribution, the range of possible values is larger, including combinations from 10 to 99. The highest probability is 4.14% for pair 10, and the lowest is 0.44% for the pair 99.

This article presents a statistical analysis applying the Newcomb-Benford law to verify whether the real numbers representing the daily closing prices of the Main Market of GPW conform to the theoretical law. The objective is to detect significant deviations, which could indicate anomalies in stock prices, potentially signaling speculative behavior or price manipulations on the Polish regulated market. In the study sample, closing prices were represented as real numbers, so the analysis considered the full range of price precision, which increases the reliability of the study.

The analysis used historical GPW stock price data from 1991 to 2022, sourced from www.stooq.pl. Data from 421 companies were analyzed, totaling 1 456 671 observations (real numbers representing daily closing prices). First-digit, second-digit, and first-two-digit tests were applied to verify compliance with the Newcomb-Benford distribution at the following aggregation levels:

- Daily closing prices of GPW companies for the entire period and comparison between the first full year analyzed (1992) and the last (2022).
- Daily closing prices of GPW companies grouped by high and low liquidity (low-liquidity program classification).

Based on the literature review, the article reports results of statistical tests, including (Jianu, Jianu, 2021):

- Chi-square test.
- Kolmogorov-Smirnov test.
- Chebyshev distance-based test.
- Euclidean distance-based test.
- Freedman–Watson U^2 test.
- Joensen correlation test.
- Hotelling T^2 "joint digit" test.

The use of these tests allows for a more comprehensive picture of the data's compliance with the Newcomb-Benford law, minimizing the risk of misinterpretation of the results. The selection of multiple tests is justified by the literature review, as the literature lacks a uniform methodological approach, and the selection of tests is not clear-cut. Using a set of complementary tests allows for results that are more comparable to previous studies and increases their reliability. These tests assess the null hypothesis that the distribution of digits (or digit combinations) conforms to the Newcomb-Benford distribution versus the alternative hypothesis of nonconformity. Statistical significance levels of $p = 0.05$, $p = 0.01$, and $p = 0.001$ were used; p values below 0,001 are reported as $p < 0,001$. In large samples (as in this study), even small deviations may be statistically significant; therefore, analyzes are complemented by visual comparisons of empirical and theoretical distributions (Kossovsky, 2021).

In addition, the mean absolute deviation (MAD) measure was used to evaluate the fit between empirical and theoretical distributions (David, 1998; Wilcox, 2003; Larsen, 2017). Critical values to identify significant deviations are (Nigrini, 2012):

- First-digit test: MAD exceeds 0,015.
- First-two-digit test: MAD exceeds 0,0022.

Nonconformity with the theoretical Newcomb-Benford distribution may indicate market anomalies such as potential speculative or manipulative actions during the analyzed period or reflect the presence of heuristics in the market.

Visualizations were created to show the values taken from the distributions of daily closing prices over the subsequent years. In Chart 1, the y-axis represents the stock closing price (PLN), and the x-axis represents the year.

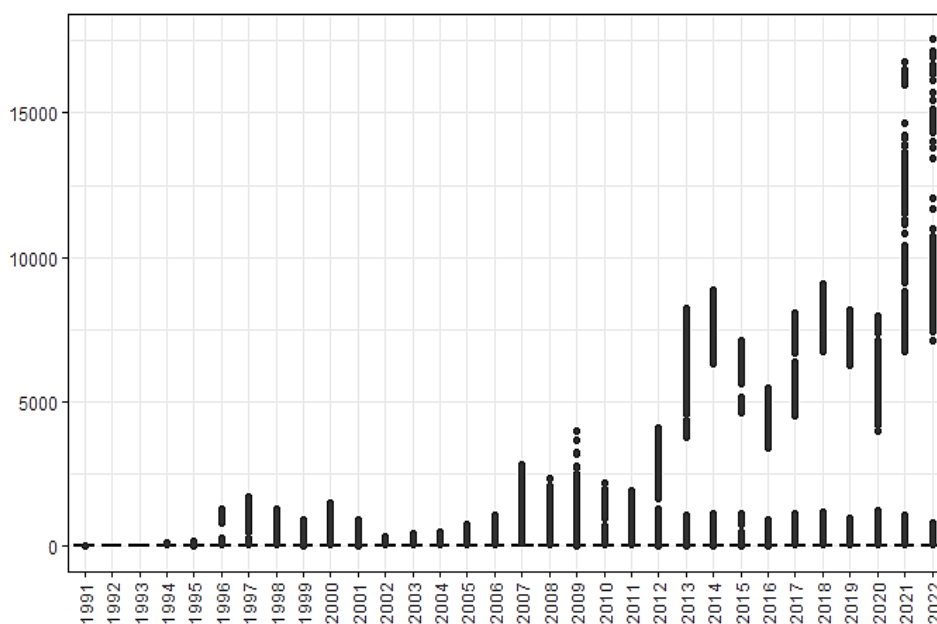


Figure 1. Distribution of closing prices from 1991 to 2022.

Source: own elaboration based on www.stooq.pl

An upward trend in closing prices can be observed over the analyzed period. Furthermore, as the market developed, the dispersion (spread) of prices increased, especially after 2010, when the range of prices (interquartile range and number of outliers) expanded. Some companies exhibited occasionally exceptionally high prices. The lower bound of closing prices remained relatively low throughout the study period, which may indicate the persistence of a segment of low-capitalization and low-liquidity companies.

4. Research Results

4.1. Tests of Empirical Data Conformity with the Newcomb-Benford Distribution: Entire Study Period

The hypothesis of conformity between the empirical data distribution (daily closing prices of companies listed on the Main Market of GPW) and the theoretical Newcomb-Benford distribution was tested, similarly to other studies, using several different tests as described in the methodology section.

Table 1.

Results of tests for Conformity of Empirical Data with the Newcomb-Benford distribution

Distribution Type	Chi ² Test	Kolmogorov-Smirnov Test	Chebyshev Distance Test	Euclidean Distance Test	Friedman U Test	Joensen Correlation Test	Hotelling T ² Test
First Digit	<0,001	<0,001	<0,001	<0,001	<0,001	0,999	<0,001
Second Digit	<0,001	<0,001	<0,001	<0,001	<0,001	0,999	<0,001
First Two Digits	<0,001	<0,001	<0,001	<0,001	<0,001	0,992	<0,001

Source: own elaboration based on www.stooq.pl.

As shown in Table 1, most of the tests for the conformity of the digit distributions with the Newcomb-Benford law indicated deviations from the expected distribution, except for the Joensen correlation test. This test only checks the consistency of the sign of the correlation between empirical data and the theoretical distribution. For the complete data set, the MAD value was 0,001 for the first digit and below 0,001 for the first two digits. This indicates that although statistical tests formally showed significant differences between the compared distributions, which, as noted in the methodology section, may result from the large sample size, the practical level of these differences is marginal and does not indicate a substantial distortion of the data. This is also confirmed by figure 2, which shows that the largest differences occur in the frequencies of higher digits, which may reflect the relatively small number of high closing prices.

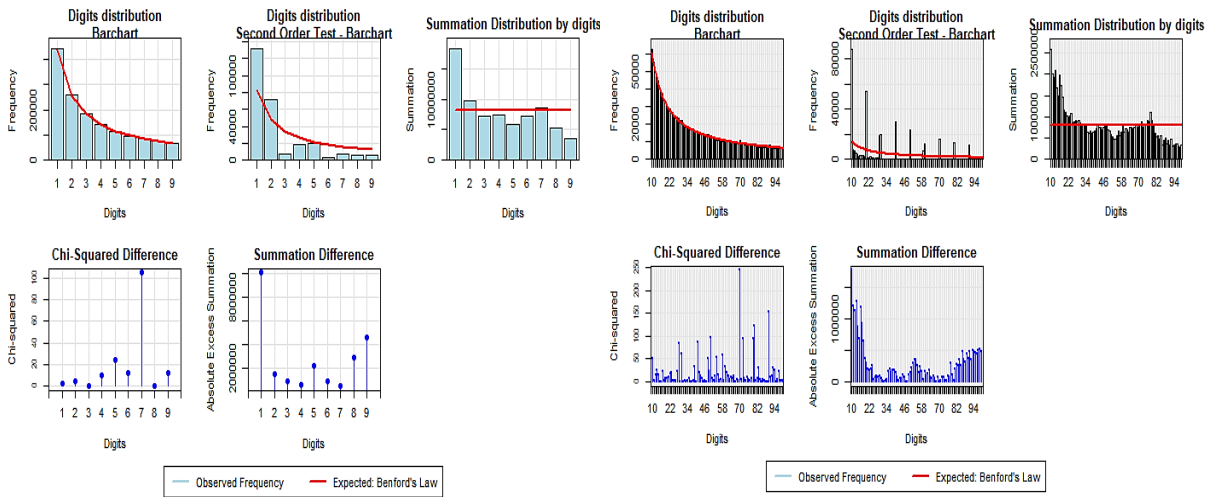


Figure 2. Visualization of the Conformity of Closing Prices with the Newcomb-Benford Distribution for the First Digit Second Digit, and First Two Digits.

Source: own elaboration based on www.stooq.pl.

A comparison of results was also made for the initial and final periods, namely 1992 (the first full year) and 2022. In the case of 1992, for closing prices, the MAD value was 0,107 for the first digit and 0,013 for the first two digits.

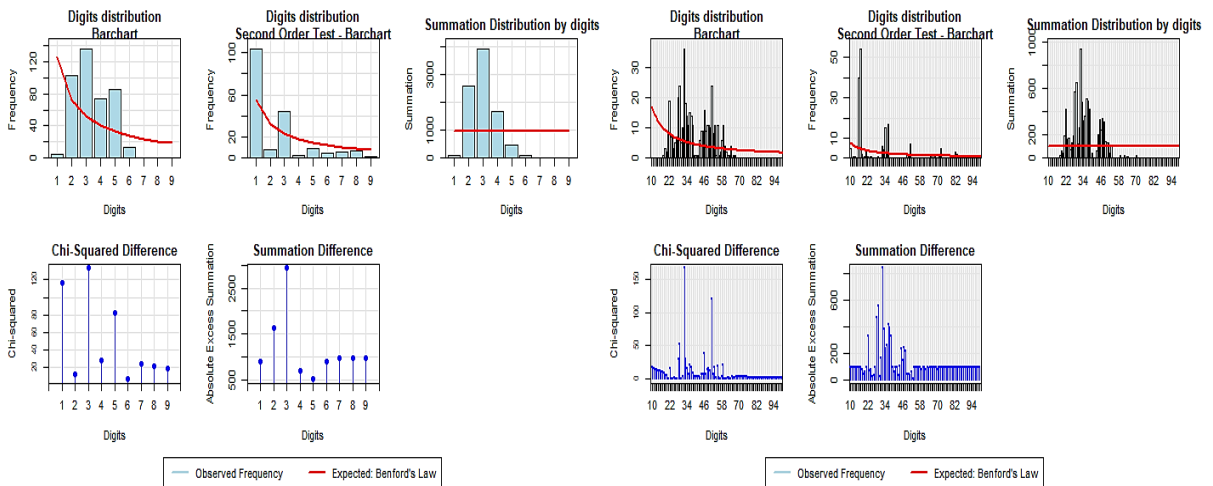


Figure 3. Visualization of the Conformity of Closing Prices with the Newcomb-Benford Distribution for the First Digit, Second Digit, and First Two Digits in 1992.

Source: own elaboration based on www.stooq.pl.

These results were compared with those from 2022. In the case of 2022, the MAD value was 0,008 for the first digit and 0,001 for the first two digits.

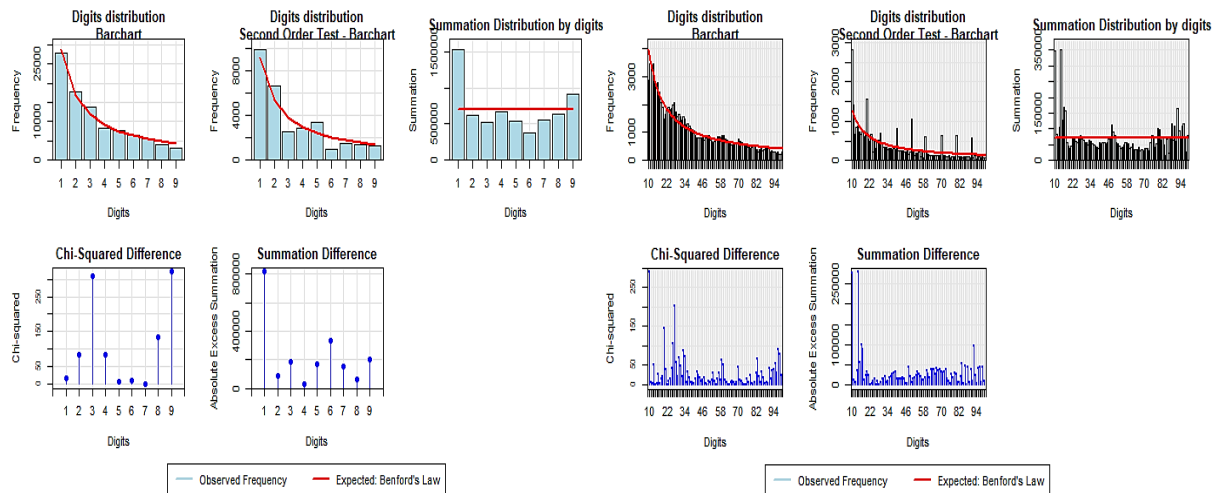


Figure 4. Visualization of the Conformity of Closing Prices with the Newcomb-Benford Distribution for the First Digit, Second Digit, and First Two Digits in 2022.

Source: own elaboration based on www.stooq.pl.

Based on graphs 3 and 4, it was observed that, compared to 2022, in the early period of the modern stock exchange (1992), there were significant deviations of the empirical data from the theoretical distribution. This can probably be attributed to the low efficiency, limited liquidity, and the small number of listed companies (16) (www 1). A substantial decrease in the MAD value - from 0,107 to 0,008 for the first digit and from 0,013 to 0,001 for the first two digits - indicates an increase in the conformity of the stock closing prices with the Newcomb-Benford distribution for three decades of the Main Market of the Warsaw Stock Exchange (GPW).

4.2. Tests of Conformity with the Newcomb-Benford Distribution: Low- and High-Liquidity Companies

In the next stage of analysis, the research sample was divided into two groups. The aim was to determine, based on stock price data, whether companies classified as belonging to the low-liquidity segment exhibit higher deviations from the theoretical distribution than those outside of this segment. According to the assumption adopted, low-liquidity companies are defined as those whose closing price does not exceed 1 PLN (www 2; www 3). The purpose was to compare these two groups. Therefore, the hypothesis of conformity between the closing price distribution and the Newcomb-Benford distribution was also tested for this company division.

Table 2.
Results of Goodness-of-Fit Tests for Empirical Data Distributions of Low- and High-Liquidity Companies Compared to the Newcomb-Benford Distribution

High-Liquidity Companies							
Distribution Type	Chi ² Test	Kolmogorov-Smirnov Test	Chebyshev Distance Test	Euclidean Distance Test	Friedman U Test	Joenssen Correlation Test	Hotelling T ² Test
Second Digit	<0,001	<0,001	<0,001	<0,001	<0,001	0,999	<0,001
First Two Digits	<0,001	<0,001	<0,001	<0,001	<0,001	0,999	<0,001
First Digit	<0,001	<0,001	<0,001	<0,001	<0,001	0,999	<0,001
Low-Liquidity Companies							
Distribution Type	Chi ² Test	Kolmogorov-Smirnov Test	Chebyshev Distance Test	Euclidean Distance Test	Friedman U Test	Joenssen Correlation Test	Hotelling T ² Test
First Digit	<0,001	<0,001	<0,001	<0,001	<0,001	<0,001	<0,001
Second Digit	<0,001	<0,001	<0,001	<0,001	<0,001	<0,001	<0,001
First Two Digits	<0,001	<0,001	<0,001	<0,001	<0,001	<0,001	<0,001

Source: own elaboration based on www.stooq.pl.

The results indicate that the low- and high-liquidity company groups exhibit similar deviation patterns from the Newcomb-Benford distribution. For low-liquidity companies, the MAD value for closing prices was 0,081 for the first digit and 0,008 for the first two digits. Both values exceed the critical thresholds specified in the methodological section, suggesting a lack of conformity between the compared distributions. On the contrary, for high-liquidity companies, the MAD value for closing prices was 0,008 for the first digit and 0,001 for the first two digits. These results fall below the critical thresholds, indicating that the structure of the closing price digits in the group of more liquid companies is closer to the theoretical Newcomb-Benford distribution. Charts 5 and 6 allow for verification of whether the deviations from the Newcomb-Benford distribution are indeed substantial and identify in which cases these discrepancies occur.

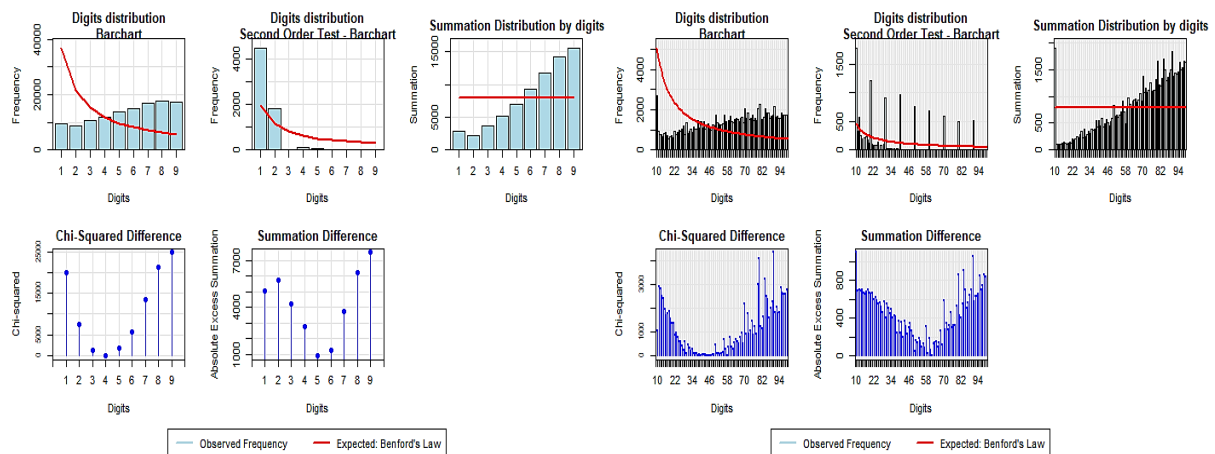


Figure 5. Visualization of the Conformity of Closing Price Distributions for Low-Liquidity Companies with the Newcomb-Benford Distribution for the First Digit, Second Digit, and First Two Digits.

Source: own elaboration based on www.stooq.pl.

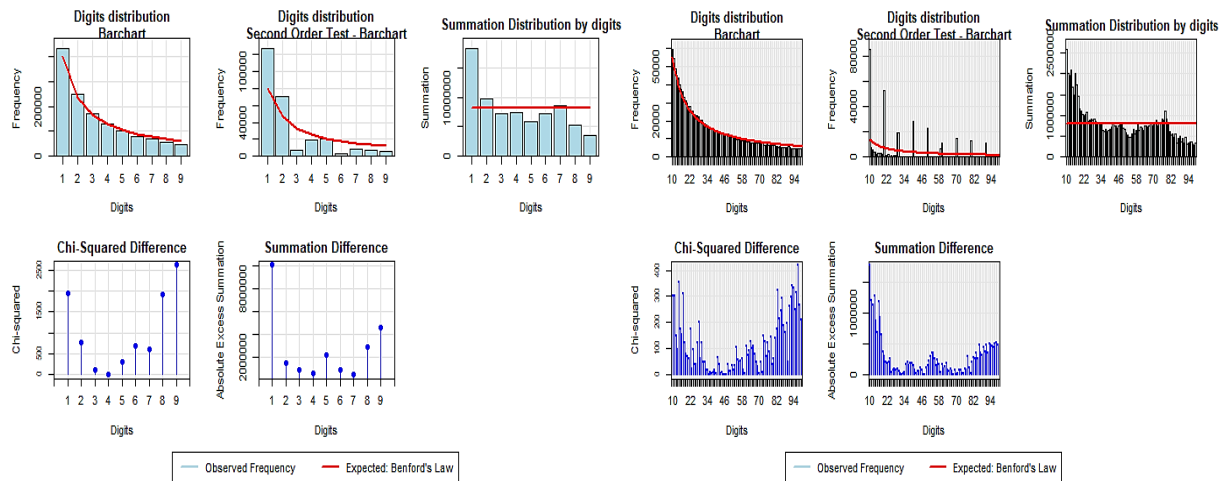


Figure 6. Visualization of the Conformity of Closing Price Distributions for High-Liquidity Companies with the Newcomb-Benford Distribution for the First Digit, Second Digit, and First Two Digits.

Source: own elaboration based on www.stooq.pl.

The visualizations presented in graphs 5 and 6 confirm the conclusions drawn from the statistical tests and the MAD measure. They indicate that a clear deviation between the compared distributions is observed for low-liquidity companies, where the discrepancies appear significant and more pronounced in closing prices compared to high-liquidity companies.

5. Summary

There are studies in the literature indicating that deviations from the Benford distribution correlate with unusual market activity and can serve as a screening tool for detecting potential manipulation. At the same time, there is also significant criticism of this mathematical method, indicating that the Newcomb-Benford law is, at best, a screening tool and that the results should be verified with other methods and contextual analysis.

In this statistical analysis, the combination of statistical tests, visualizations, and the MAD measure enabled a comprehensive assessment of the conformity of stock market data from the Main Market of the Warsaw Stock Exchange (GPW) with the Newcomb-Benford distribution. The results indicate that the Newcomb-Benford law can serve as a useful tool for supporting financial data analysis, assess market efficiency, and identifying potential anomalies in stock quotations.

The results of the statistical test suggest that the structure of the digits in integer values representing daily closing prices is not entirely random, therefore, the research hypothesis was positively verified. This stems from the specific mechanisms of market price formation, which are influenced by regulations, supervisory decisions, and investor behavior. At the same time,

the visualizations and MAD results revealed a more nuanced picture of the conformity between the compared distributions.

The findings provide grounds for concluding that deviations from the theoretical Newcomb-Benford distribution are greater in the early stages of market operation (1992 compared to 2022) and among low-liquidity companies. These deviations may result from limited investor activity, a low number of transactions, and the specific characteristics of stock quotes. The results are consistent with previous research, confirming that low-liquidity markets are characterized by a higher risk of data anomalies, which in practice may increase susceptibility to speculative or manipulative behavior. The research focuses on the Polish market. Future research suggests conducting a comparative analysis between each country. The obtained results are significant from both theoretical and practical perspectives. Theoretically, the study demonstrates that the long-term closing prices of companies listed on the WSE Main Market exhibit statistically significant deviations from the Newcomb-Benford distribution, regardless of the companies' liquidity category. This means that the classical assumption of the universality of the Newcomb-Benford distribution for a range of stock market data is not fully met in the case of the Polish stock market. From a practical perspective, the observed deviations cannot be automatically interpreted as evidence of market manipulation, as the Newcomb-Benford law primarily serves as a screening tool. These observations open an interesting avenue for further research, involving the analysis of the relationship between deviations from the Newcomb-Benford distribution and periods in which market manipulation or abuse were actually detected by the supervisory authority.

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