intervals, which limits their practical applicability in volatile economic conditions. The findings support the use of flexible nonlinear models like GAM for understanding and forecasting economic activity when structural complexity is present.

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ADVANCED PERMUTATION ENTROPY METRICS FOR BITCOIN: TOWARDS ROBUST EARLY WARNING INDICATORS OF MARKET INSTABILITY

Permutation entropy (PEn) is a widely recognized nonlinear statistical measure used to quantify the complexity inherent in time series data [1]. Despite its widespread adoption due to conceptual simplicity and computational efficiency, classical PEn exhibits certain limitations, notably its insensitivity to amplitude variations within the time series and its simplified handling of observations with equal values. While various modified PEn methods have been developed, their efficacy as early-warning indicators for cryptocurrency market downturns remains largely unexplored. This research addresses these deficiencies by presenting a comparative analysis of classical PEn and three of its extended versions: weighted permutation entropy (WPEn) [2], amplitude-aware permutation entropy (AAPEn) [3], and uniform quantization-based permutation entropy (UPEn) [4].

We specifically apply these entropy metrics to scrutinize the Bitcoin market crash that occurred between December 2017 and February 2018. Our findings suggest that these enhanced PEn methods offer a more nuanced understanding of market dynamics by capturing subtle changes in data complexity and amplitude distribution that classical PEn might overlook. The superior sensitivity of these advanced metrics, particularly AAPEn, to pre-crash market conditions highlights their potential in serving as robust early-warning signals for impending market instability in the volatile cryptocurrency landscape. The analysis reveals that the variations in these entropy measures can provide valuable insights into shifts in market efficiency and the emergence of irregular patterns preceding significant price corrections. This study contributes to the development of more sophisticated analytical tools for financial risk management in digital asset markets.

Specifically, the AAPEn metric considers not only the order but also the amplitude of values in the time series, allowing it to better reflect significant fluctuations that may indicate increasing uncertainty or panic in the market. Classical PEn, operating only on rank orders, may not respond to substantial amplitude changes that do not alter ranks. For example, two time series with identical rank orders but different amplitude fluctuations would yield the same classical PEn. However, if the second series has significantly larger amplitude spikes, this could be a sign of increasing turbulence. This is where AAPEn demonstrates its advantage, as it adds a weight to the entropy estimation proportional to the amplitude differences between elements.

Fig. 1 illustrates an example of AAPEn calculation.

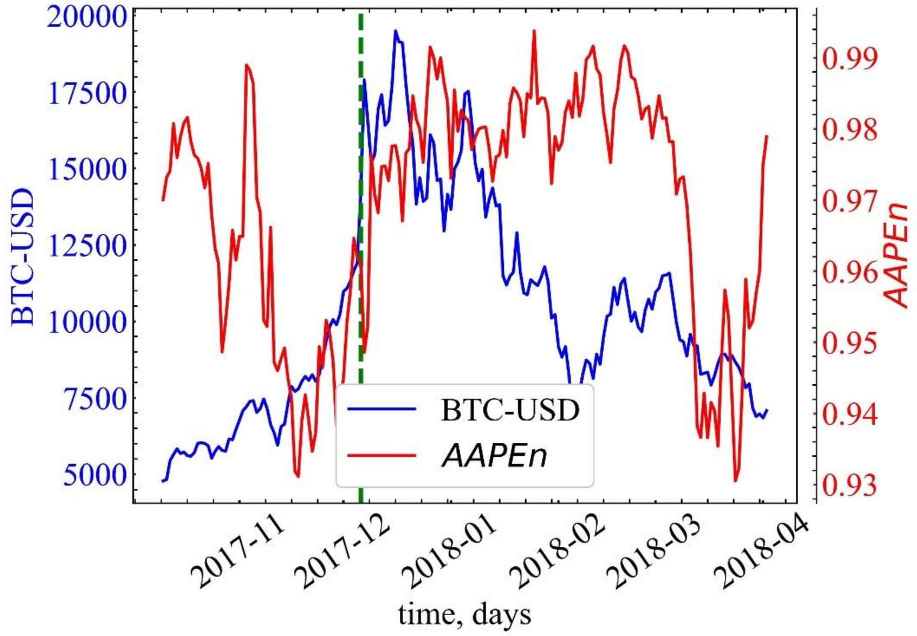

Fig. 1. Comparative dynamics of the Bitcoin during the market crash of 2018 and AAPEn.

In conclusion, the application of advanced permutation entropy methods, especially AAPEn, presents a compelling opportunity to augment early-warning mechanisms for cryptocurrency market instability. Such entropy metrics contribute not only to improved forecasting of market downturns but also afford critical insights for policymakers and market actors, thereby facilitating a more data-driven approach to decision-making.

Our previous studies have also emphasized the importance of multifractal analysis and cross-correlations for understanding the interconnections between different financial markets, which can be complemented by the application of advanced entropy metrics.

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MODELING UKRAINE'S OPEN ECONOMY UNDER WAR-INDUCED UNCERTAINTY

Modern geopolitical conflicts pose unprecedented challenges for economic analysis, as traditional models often fail to capture the complexity and non-linearity arising from wartime conditions. This is particularly acute for open economies, deeply integrated into global markets, yet simultaneously facing direct aggression. Russia's full-scale invasion of Ukraine in 2022 has transformed Ukraine's economy into a critical case study for modeling under war-induced uncertainty, demonstrating both devastating consequences and remarkable resilience. Within the context of the "Digital Economy" conference and the "Modeling and Data Analysis in Economics" track, the role of digital technologies and data analysis in enhancing resilience, adaptation, and effective recovery is of particular interest. These theses aim to highlight key aspects of modeling Ukraine's open economy during wartime, including the nature of uncertainty, theoretical approaches, empirical findings on impact and adaptation, and prospects for modeling and data analysis to support policy and recovery.

Economic uncertainty in wartime is a multifaceted phenomenon, often taking the form of "radical uncertainty" where probabilities cannot be quantified (Londono et al.,