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Towards a better understanding of financial and economic systems' complexities: some new evidence coming from artificial intelligence, machine learning and big data advanced technologies

Hachmi Ben Ameur[1] · **Roberto Casarin**[2] · **Massimiliano Caporin**[3,4] · **Zied Ftiti**[5] · **Bertrand B. Maillet**[2,6,7]

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Abstract

The integration of Artificial Intelligence (AI) within financial institutions has accelerated in response to mounting complexities and recurrent global crises, revealing the well-known but fair limitations of traditional economic models. Enhanced computational capacity and Big Data (BD) availability have enabled the adoption of Machine Learning (ML) across fields from banking, asset and risk management, and insurance, for tasks such as credit scoring, fraud detection, and market surveillance. AI facilitates portfolio construction and risk budgeting by synthesising historical and alternative data, while Natural Language Processing (NLP) aids in interpreting regulatory texts and central bank communications. However, the opacity of AI models introduces novel risks, including among others validation challenges and systemic vulnerabilities due to model convergence. When controlled appropriately, AI can paradoxically serve both as a risk source and a mitigation tool. This special issue presents rigorously peer-reviewed contributions that explore AI, ML, and BD applications in asset pricing, risk management, macroeconomic forecasting, and sustainable finance, offering valuable insights for academics, practitioners, and policymakers navigating financial uncertainty.

Keywords Artificial intelligence · Machine learning · Big data · Financial risks · Sustainable (ESG) finance

From Asset Pricing and Forecasting, Market Dynamics, Microstructure and Interconnectedness, Portfolio Construction, Risk Modelling and Optimization, to… Sustainable Finance and ESG criteria, Green Spreads, and Policy-maker Communications.

Extended author information available on the last page of the article

1 Introduction

The deployment of AI amongst financial institutions has quite accelerated since firms confront some complexities in economic and financial systems. Successive and recurrent crises, from international tensions (e.g., the Sub-prime crisis, the European sovereign debts, the Brexit, the COVID-19 pandemic, and the on-going Russia/Ukraine conflict) have exposed the limits of traditional and well-built models and underscored the need for tools that deep-learn, adapt, and scale, accordingly. Hopefully, BD availability and improved computing powers are enabling AI to be increasingly integrated into core financial decision-making processes. As a consequence, banks, risk and asset managers, insurance companies, now currently use ML for many purposes: credit scoring, predicting defaults, combating money laundering, and monitoring market abuse, among other tasks.

Indeed, AI facilitates signal generation, portfolio construction, and risk budgeting by combining historical prices with alternative data. In corporate finance and macroeconomics, models extract the structure of high-dimensional time-series to improve short-term forecasting and scenario analysis, whilst, at the same time, NLP helps to interpret regulatory documents and central bank communications. The added-value of AI lies in its ability to convert abundant and heterogeneous data into predictive signals and operational rational commands. These developments are also giving rise to a new class of financial and non-financial risks. De facto, the opacity of models makes them more difficult to validate and audit (since risk in basically endogenous: “fear of risks creates… a risk”). Procyclicalities and entailed systemic risk may increase, leading to a vicious circle, as main models converge using similar data and quite similar saillant (modelled) features. Furthermore, it is important to note that, when used within a framework of strict oversight and good governance, AI can be paradoxically both a source of risk (i.e., create a “model risk of risk models”), but also a useful tool for measuring as well as mitigating it, more specifically in hard times.

This special issue of *Annals of Operations Research* contains blind reviewed, carefully selected collection of articles that provide some innovative results regarding the use of AI, ML, and BD, in the context of important financial-economics concerns. These contributions enable better risk and uncertainty modelling, improve forecasting accuracy, decision-making actions, and further clarify the way financial markets and economic systems truly function, more specifically in crisis situations. Spanning asset pricing and return predictability, portfolio construction, optimization, risk management, market microstructure and interconnectedness, as well as sustainable finance and macroeconomic policies, these articles illustrate how advanced methods using big data complement theoretical modelling and traditional canonical econometrics’ methods to generate some evidence, we hope to be very relevant to researchers, practitioners (mainly investors), regulators, and policymakers.

2 AI, ML, and BD for pricing and forecasting asset returns

The results presented in this section reflect recent developments in various applications related to the analysis of the efficiency of stock and cryptocurrencies markets, the forecasting of commodity price volatility, derivatives pricing, identification of “zombie” (junk) companies, and predicting Environmental, Social, and Governance ranked (ESG) stock prices, with an increasing focus on interpreting the so-called “black box” models.

Citera and De Pretis (2025) consider the stochastic structure of cryptocurrency and stock returns based on information theory within the Quantum Response Statistical Equilibrium (QRSE) framework. The results of this article offer an alternative perspective to the classical Efficient Market Hypothesis (EMH). More specifically, they show that the apparent randomness of asset prices is not accidental but an unintended consequence of market participants' profit-seeking behavior. This fundamental point of view is complemented by Gao et al. (2024), who propose an integrated system for forecasting fluctuations in Brent crude oil prices. Their study proposes a multifractal analysis combined with volatility forecasting. The results show that long-term correlations mainly determine the multifractal characteristics of the market and that their hybrid model offers greater accuracy and stability, particularly for high-frequency data.

Anastasiou et al. (2025) use advanced predictive models to forecast the risk of bank failure by analyzing ESG-related news. The results show that this machine learning model outperforms simple regressions. Furthermore, they show that integrating ESG news with macro-financial variables significantly improves predictive performance. Funahashi (2024) focuses on derivatives pricing, an area where exact analytical solutions are rare and numerical methods are costly. This article proposes two neural network-based approaches: learning the difference between the price of a derivative and its asymptotic expansion, and learning the difference between two distinct underlying stochastic processes. It appears that these approaches significantly reduce training data requirements and computation time.

As part of identifying and analyzing the health of companies, Veganzones and Séverin (2024) identify and visualize “zombie” companies using Self-Organizing Maps (SOM) and Support Vector Machines (SVM). They document the heterogeneity of “zombie companies' financial profiles” and show that a hybrid SOM-SVM model outperforms traditional statistical methods in predicting zombification, especially in the longer term.

Awijen et al. (2024) examine the role of climate risks (transitional and physical) in predicting ESG stock prices, using eXplainable AI (XAI). The results show that incorporating climate risk variables significantly improves forecast accuracy. SHapley Additive exPlanations (SHAP) reveal significant influence of inflation, recession, and pollution on the S&P 500 ESG Index. Similarly, Goswami and Uddin (2025) reevaluate the importance of predictors for stock returns using XAI. The results show that ensemble and deep learning models produce more generalizable forecasts, and that characteristics related to momentum and trading have strong predictive power, as validated by long-short portfolio tests. XAI techniques such as SHAP emerge as intuitive and practical tools for interpreting complex nonlinear models.

Karatepe et al. (2025) introduce an original simulation framework for assessing financial risks, profitability, and investment efficiency in large-scale projects. The approach relies on Bayesian Networks (BN), which have the distinct advantage of incorporating expert knowledge into the modelling process, thereby enhancing their effectiveness when data are scarce. The novel framework is applied to large-scale commercial aquaponics—an example of a complex investment context characterized by numerous variables, uncertainty, and risks. The aim is to estimate return on investment and other key financial indicators, such as payback period, debt service coverage ratio, and return on equity. Thanks to the specification of the conditional independence relationships among the network's variables, BN offers some interpretability and provides a flexible support in a complex environment.

Considered altogether, these selected studies underscore the rapid progress of AI and ML with BD in finance—not only for improving the accuracy of forecasting and valuation, but also in bringing much-needed transparency and insights into rational and efficient financial decision-making processes.

3 Dynamics, microstructure, and interconnectedness of financial markets

Market dynamics, microstructure, and interconnectedness constitute core pillars of contemporary financial research, particularly in the era of ultra-high-frequency data and rapid technological innovations. Recent studies seek to develop robust models to characterize the complex features of intraday prices, assess the performance and risk of emerging assets such as cryptocurrencies, understand the transmission of shocks across technology sectors, and optimize investment strategies amid the increasing complexity of futures markets.

This ongoing field of research provides a deeper understanding of the mechanisms that govern financial markets and the challenges posed by discrete, irregular observations, microstructural noise, extreme volatility, and dynamic interdependencies among assets. This section presents several results related to the adoption of advanced methodologies, such as Score-based Generalized AutoRegressive Heteroskedastic-type (SGARCH) models, axiomatic risk indices, and deep learning techniques.

Holý (2024) proposes an intraday GARCH framework to account for discrete price changes with irregularly spaced observations, which is an essential issue for the analysis of ultra-high-frequency data. More specifically, this model addresses important issues, including simultaneous transactions, price discretion, and market microstructure noise. It uses a zero-inflation Skellam distribution and incorporates smoothing splines to capture intraday patterns in transaction duration and price volatility. An application to IBM stock data is provided. The results show that conditioning on current trade duration is essential, substantially improving model fit and resolving problems associated with zero-trade durations. It further illustrates that aggregating simultaneous trades, which represent a large share of observations (47% for IBM stock for instance), is not an adequate remedy and may obscure valuable information.

Yamawake et al. (2024) examine the relative performance of cryptocurrencies (Bitcoin, Ethereum, Binance Coin) and the SPDR S&P 500 ETF Trust (SPY ticker) exchange-traded fund using the Aumann and Serrano Economic Index of Riskiness (EIR). Unlike the Sharpe ratio, the EIR measures indicate that Bitcoin is considerably riskier than other cryptocurrencies, and that SPY is the less risky, with the differences largely attributable to underlying volatilities. This study uses normal mixture models with GARCH-type models for conditional volatility to reflect the pronounced variability of cryptocurrencies returns and the need for modelling volatility clustering. Notably, dynamic specifications accentuate SPY's outperformance relative to cryptocurrencies, suggesting that risk compounds over time. By focusing on daily returns, the analysis finally provides a bridge to tail risk assessment and cross-asset interconnectedness.

Interconnectedness and extreme risks are the object of study in Ali et al. (2024). The authors use the Asymmetric-Slope Conditional Autoregressive Value-at-Risk (AS-CAViaR) model approach to quantify tail risk and a Time-Varying Parameter–Vector AutoRegressive

(TVP–VAR) model to examine the dynamic transmission of risks. The authors document a significant increase in aggregate tail risk spillovers during the initial phase of the COVID-19 pandemic, particularly at the 5% quantile. AI related equities persistently act as net transmitters of shocks, whereas FinTech equities are net receivers, which is consistent with AI's foundational role as an enabling technology for FinTech firms. Macro financial and geopolitical factors also shape connectivity: gold volatility and geopolitical risk reduce it, whereas U.S. equity market volatility and economic policy uncertainty push it up. These findings underscore the importance of diversification strategies and prudential policies when they are specifically designed and tailored for crisis periods.

Liu et al. (2024) study the complexity of Chinese futures markets, which are marked by substantial noise and high volatility, using Deep Learning (DP) techniques, notably Long Short-Term Memory (LSTM) networks. The findings suggest that for time-series momentum strategies in the way of return and risk control, LSTM is superior to some other ML algorithms. Moreover, adding the learning objective of the Sharpe ratio yields higher returns with lower risk. Such a method can pinpoint momentum turning points, and the combination of forecasting horizons is more profitable than using a single horizon, with Sharpe ratios higher than 2.5 for multi-period strategies. The study highlights DP ability to capture nonlinear relations and dynamic correlations more effectively than traditional models. Changes in market microstructure, such as regulatory adjustments, are also shown to affect strategy efficacy. Although currently focused on Chinese futures, these advances are poised to extend to cryptocurrency markets, which indeed align with the cryptocurrency risk assessment of Yamawake et al. (2024), as presented above.

Using data spanning major stress episodes, which include the COVID-19 pandemic and the early phase of the Ukraine/Russia conflict, Palumbo (2025) show substantial heterogeneity across both currencies and trading frequency measurements. Indeed, most daily-frequency correlations appear rather stable, with limited diversification benefits, whereas hourly-frequency correlations predominantly exhibit significant dynamic patterns. On an intraday basis, precious metals provide effective hedges against the depreciation of the US dollar. For instance, they confirm in their study that gold is a capital-efficient hedge for emerging markets during periods of daily stress. At higher frequencies, however, silver seems to offer the better result achievements, even though it requires higher hedge weighting variabilities. Ultimately, their findings highlight the importance of formally testing dynamic correlations before any modelling, since incorrect assumptions can significantly undermine the effectiveness of the hedge.

Overall, these studies point out the necessity of sophisticated analytical tools to decipher the complex volatility, interdependencies, and risks inherent in nowadays actual financial markets. Whether through granular microstructure modelling, the assessment of emerging asset risk, the mapping of shock propagation, and the optimization of trading strategies using AI, each article contributes to a more nuanced understanding of market dynamics and financial interconnectedness.

4 Regarding rational portfolio constructions and risk optimizations of efficient portfolios

Contemporary challenges in financial markets, marked by successive crises and a proliferation of risk episodes, call for increasingly sophisticated approaches to portfolio construction, risk modelling, and optimization. The articles considered in this section enable the evaluation of dynamic asset allocation strategies by relying on the integration of complex dependency structures, the identification of dominant sources of risk, and improved accuracy in risk assessments. All studies converge toward a common goal: developing more robust and effective frameworks for asset allocation.

This body of literature makes substantive contributions by proposing complementary solutions. di Tollo and Filograsso (2025) revisit standard investment rules by incorporating systemic risk and joint co-movements across asset classes such as equities, commodities, and bonds through the estimation of financial networks with community structures. This approach identifies clusters of assets with distinct exposure profiles to systemic risk and tests their defensive capacity during periods of acute stress, including the COVID-19 crisis. In addition to studies on interdependencies, Xu et al. (2025) address the issue of the so-called “zoo of factors”. The results show that a stochastic discount factor based on a Principal Component Analysis (PCA) and regularization can aggregate characteristics into dominant sources of risk and strike a balance between parsimony and robustness. This approach is shown to outperform traditional models, even in emerging markets such as China, where idiosyncratic risks are heightened. To address high dimensionality, L_2-norm regularization mitigates overfitting to anomalies, while L_1-norm parsimony constraint in the principal component space isolates the main risk factors.

Bertrand and Prigent (2025) rigorously assess the appeal of factor investing relative to traditional market-index strategies. Employing long-short exposures to the five Fama–French factors, they examine two portfolio constructions: a constrained 130/30 strategy and a hybrid “Long-Short Market + Long-Only Factors” (LSMLOF) approach. Efficient frontiers are then derived from a universe comprising the market and ten factors, with allocations spanning both the risk-free asset and the tangency portfolio. To accommodate dynamic rebalancing, the analysis contrasts Buy-and-Hold (BH) and Constant-Mix (CM) classical strategies across a full spectrum of risk exposures. Performances are evaluated using a gamut of higher-order return moments as well as Sharpe ratios, complemented by a Hicksian compensating variation to quantify welfare losses from suboptimal portfolios. Drawing on nearly six decades of monthly data, including major crises, the study finds that the "130/30 strategy" consistently yields superior Sharpe ratios across both BH and CM frameworks. Accordingly, it appears that LSMLOF portfolios outperform the market over medium-term horizons, particularly under CM allocation. In welfare terms, the “130/30” dominates, except, however, for high risk aversion individuals. Nevertheless, it is shown that LSMLOF excels for moderate preferences. These results substantiate the efficacy of factor-based approaches, offering compelling evidence for their appealing integration into modern portfolio design.

Ferrari et al. (2024) propose to use a Smoothed Semi-Variance (SSV) estimator, an approach that reorients portfolio risk assessment toward downside exposure rather than aggregate volatility. The SSV estimator converges to the empirical semi-variance while remaining robust to non-analytic data structures and scalable to large problem instances. Its smoothing parameter offers a continuum between minimum semi-variance and minimum-variance objectives, affording practitioners nuanced control over risk preferences. When integrated with shrinkage techniques, SSV-based portfolios exhibit strong empirical performance, both in and out-of-sample.

In the same vein, Bernard et al. (2025) introduce an enhanced Block Rearrangement Algorithm, termed BRA Beta, to refine the estimation of portfolio risk bounds. BRA Beta features dynamic selection of block sizes via a Beta distribution, adapting from larger blocks early in the procedure to smaller blocks later. It outperforms other BRA variants in both variance reduction and convergence speed, particularly for large, heterogeneous portfolios, and is substantially faster than simulated annealing for these optimization problems.

Together, these last contributions furnish a sophisticated toolkit for constructing portfolios that are resilient to uncertainty and tailored to diverse investor risk profiles. They reflect a broader evolution in quantitative finance, one that privileges precision, adaptability, and relevance in the face of complex market dynamics.

5 On sustainable finance, green spreads, and policy communications

Contemporary sustainability challenges require a fair and high-level understanding of interconnections among technology, financial markets, the resilience of global systems, and the communication of public policies. This section explores the impact of digital technologies on green growth, the influence of the Environmental, Governance, and Social (ESG) factors has no significant effect yet. ESG performance on potential systemic risk impacting companies, the evaluation of green investments via dedicated bonds, the susceptibility of global food systems to import shocks, and the informational value of U.S. Federal Reserve communications regarding monetary uncertainty. Together, these studies emphasize the pivotal role of sustainable finance, the yield spreads associated with green assets ("green spreads"), and the efficacy of policy communication in aligning economic prosperity with environmental protection and social Pareto well-being within a framework targeting financial stability and regulatory clarity.

Recent ESG contributions underscore financial stability as a principal objective, with particular emphasis on the communicative role of the Federal Reserve. Arismendi-Zambrano et al. (2024) demonstrate that the rhetorical tone adopted by the Chair in official statements serves to diminish uncertainty surrounding monetary policy, thereby exerting a discernible influence on market responses to policy announcements. These pronouncements encapsulate critical insights into prospective policy trajectories, which are instrumental in fostering market stability. The clarity and efficacy of central bank communication enhance both transparency and predictability—attributes that are pivotal in cultivating investor confidence. This, in turn, bears upon the appetite for secure financial instruments, notably green bonds. In this context, Sojoudi et al. (2025) identify a pronounced so-called "greenium" effect within the U.S. municipal bond market, characterised by a yield differential between conventional and green-labelled bonds. It appears that both magnitude and sign of this premium are contingent upon factors such as coupon structure, callability, and issuance year. Another conclusion of their studies is that green bonds offering elevated coupon payments tend to be more appealing to investors and are associated with a positive "greenium". Furthermore, fiscal incentives and non-callable features augment their attractiveness, whereas mere green-washing self-designation as “green” yields negligible advantage. Enhanced anchoring of market expectations—potentially facilitated by coherent and strategic Federal Reserve communication, may contribute to the stabilisation of bond yields, including those pertaining to green financial instruments.

Li et al. (2025) show that digital technology in China plays a positive role in fostering inclusive green growth, especially along its economic dimension. At the same time, digitalization may not directly reduce carbon emissions and is associated with higher energy consumption. As policy recommendations, the paper emphasizes reducing regional disparities and leveraging digital technologies to improve access to basic public services. Wang et al. (2024) find that firms' ESG performance has a significant adverse effect on systemic risk, both in terms of vulnerability and contribution to systemwide risk. Sectors such as energy, industry, and finance are identified as central within the risk network. At the ESG Pillar level, the results show that the Environmental (E) pillar has a significant negative impact on systemic risk, Governance (G) has a considerable positive impact, but the Social (S) pillar has no significant effect yet.

Finally, Zhang et al. (2024) examine a very important basic incompressible need: the global food import shocks. They find a higher frequency of them during the 2007–2008 food crisis and notable regional variations, with North America, Africa, and Asia experiencing a higher rate of occurrence. As the wisdom may have command, it appears that import diversification and a low import dependence protect economies against exogenous shocks, leading to a low shock rate and a high recovery rate. Collectively, these results indicate that effective policy communication, the design features of financial instruments, and resilient supply chain strategies are essential for sound risk management and sustainable development.

6 Conclusion

Collectively, the contributions presented herein within this special issue aim to demonstrate that the integration of advances in AI and ML modelling with BD—attentive to microstructure, interconnectedness, and dynamic volatilities, leads to more rigorous portfolio risk optimisation within the framework of sustainable finance. In some sense, credible policy communication remains indispensable for the construction of financial systems that are stable, transparent, and resilient. It is our hope that this collection will further stimulate cross-pollination among fields, notably operations research, econometrics, and AI/ML/BD in finance and economics.

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Authors and Affiliations

Hachmi Ben Ameur[1] · Roberto Casarin[2] · Massimiliano Caporin[3,4] · Zied Ftiti[5] · Bertrand B. Maillet[2,6,7]

✉ Zied Ftiti
zftiti@edcparis.edu

Hachmi Ben Ameur
hbenameur@inseec.com

Roberto Casarin
roberto.casarin@unive.it

Massimiliano Caporin
massimiliano.caporin@unipd.it

Bertrand B. Maillet
bertrand.maillet@univ-reunion.fr

1 INSEEC Grande Ecole, OMNES Education, Paris, France

2 Ca' Foscari University of Venice, Venice, Italy

3 University of Padova, Padua, Italy

4 Rimini Center for Economic Analysis, Rimini, Italy

5 EDC Paris Business School, OCRE Research Lab, 74/80 Rue Roque de Fillol, 92807 Paris, Puteaux Cedex, France

6 University of La Reunion, Saint Denis, France

7 Variances, Paris, France