J. Int. Financ. Markets Inst. Money 103 (2025) 102183

Contents lists available at ScienceDirect

Journal of International Financial Markets, Institutions & Money

journal homepage: www.elsevier.com/locate/intfin

Centralized exchanges & proof-of-solvency: The guardians of trust

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ARTICLE INFO

JEL classification:
G10
G11
G40

Keywords:
Centralized exchanges
Proof-of-solvency
Proof-of-reserves
Cryptocurrency
Stablecoins

ABSTRACT

The stability and transparency of centralized cryptocurrency exchanges have received limited attention, despite their growing role in digital asset markets. This paper analyzes their stability through proof-of-assets disclosures. Using an AR-GARCH framework and MVaR assessment, we evaluate centralized exchange resilience during the extreme events of 2022 within the impersonal trust framework of Shapiro (1987). Our findings highlight that the FTX and Celsius bankruptcies had the most detrimental impact on market stability, while stablecoins played a dual role—enhancing resilience under normal conditions but posing systemic risks in the event of failure. Additionally, exchanges should maintain extra reserves of 6% to 14% to withstand adverse events and improve resilience during periods of stress. Paradoxically, the cryptocurrency ecosystem, designed to reduce reliance on trust, now demands even more "guardians of trust" than traditional finance to create a trustworthy environment for participants.

1. Introduction

The evolution of financial markets increasingly relies on abstract and institutional mechanisms of trust (Murinde et al., 2022). In traditional finance, individuals deposit savings in banks, invest via intermediaries, and transact globally through opaque systems, often without any personal knowledge of the institutions safeguarding their assets. This transition from direct, interpersonal trust to structurally mediated "impersonal trust" (Shapiro, 1987; Williamson, 1993) is central to modern financial systems. Shapiro theorizes this shift, arguing that as complexity and scale grow, trust must be institutionally established through social-control mechanisms—referred to as "guardians of trust"—such as regulations, credentials, procedures, and reputational monitoring, which serve as substitutes for face-to-face accountability (Zucker, 1986). This insight is particularly relevant in the context of cryptocurrency markets, where the collapse of major centralized exchanges renews fundamental questions about trust, transparency, and institutional credibility (Buxton et al., 2022).

This paper explores centralized cryptocurrency exchanges through the lens of Shapiro's impersonal trust framework. In this context, centralized exchanges are not merely technical platforms but institutional trustees that require users to place faith in their solvency, operational integrity, and adherence to implicit fiduciary duties. These exchanges occupy a paradoxical space: while the cryptocurrency ecosystem is built to eliminate the need for trust via decentralized, algorithmic verification (Nakamoto, 2008), in practice, most transactions and user assets remain with centralized entities, reintroducing institutional dependency and custodial risks that blockchain was designed to eliminate—yet under even weaker regulatory oversight (Aramonte et al., 2021; Panetta, 2023).

According to Shapiro (1987), impersonal trust arises in systems where direct, interpersonal control over agents is infeasible and must be replaced by structural guarantees. But such guarantees—rules, entry barriers, certifications, and monitoring—can

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https://doi.org/10.1016/j.intfin.2025.102183
Received 29 May 2024; Accepted 2 June 2025

Available online 20 June 2025

themselves generate new vulnerabilities. In fact, these institutional safeguards may increase the complexity of monitoring and incentivize strategic behavior, as agents exploit information asymmetries (Ryan, 2008; Demyanyk and Van Hemert, 2011). The collapse of FTX (Vidal-Tomás et al., 2023; Conlon et al., 2024) exemplifies this risk, as the lack of verifiable disclosure mechanisms allows large-scale mismanagement to go undetected until it triggers a broader crisis of confidence. More importantly, it exposes how fragile centralized exchanges can be in the face of liquidity shocks and asset volatility—revealing not just governance failures but underlying solvency risks. This raises urgent questions about the capacity of such institutions to withstand systemic stress and whether additional safeguards are needed to prevent contagion (Financial Stability Board, 2023). In light of growing concerns about opacity, asset volatility, and institutional fragility, this paper investigates how exchange-level risk exposure reflects broader structural vulnerabilities within the centralized crypto ecosystem. This leads to a central research question: How resilient are centralized exchanges to severe market stress, and what level of additional reserves might be necessary to preserve solvency during adverse events? We frame this challenge not merely as a matter of financial risk but as an institutional trust issue that requires credible safeguards consistent with Shapiro's theory of impersonal trust.

Integral to this investigation are the mechanisms of proof-of-assets, proof-of-liabilities, and proof-of-reserves, which collectively support the broader concept of proof-of-solvency (Buterin, 2022; Buxton et al., 2022). These mechanisms are intended to demonstrate that exchanges maintain sufficient collateral to satisfy user withdrawals and serve as industry-driven methods to build impersonal trust. The bankruptcy cascade of various crypto entities in 2022—such as Terra-Luna, Celsius, Three Arrows Capital, Voyager Digital, BlockFi, and especially the collapse of FTX—forced centralized exchanges to adopt additional guardians of trust, in the form of procedural norms and blockchain implementations, which aim to ensure consumer protection, increase transparency, and prevent malicious behavior. Proof-of-assets provides evidence of the existence and control of digital assets, proof-of-liabilities discloses existing liabilities in the form of customers' deposits, proof-of-reserves demonstrates that on-chain assets exceed liabilities, and proof-of-solvency verifies solvency, considering off-chain factors (for a detailed explanation of these concepts, see Appendices A.1 and A.2 in the Appendix).[1] While these measures are not new (Wilcox, 2014), the majority of centralized exchanges adopted them after the collapse of FTX to maintain customer trust and prevent the loss of deposits. This paper examines these mechanisms as key components of the operational framework through which centralized exchanges establish credibility in a trust-minimizing system. Using proof-of-assets data, we empirically evaluate the financial resilience of centralized exchanges and interpret these mechanisms as indicators of institutional soundness.

The academic literature largely overlooks the institutional architecture of centralized exchanges. Existing studies in crypto-finance predominantly examine price dynamics (Kyriazis et al., 2020), blockchain innovation (Shin and Rice, 2022), or decentralized finance (Bariviera and Merediz-Solà, 2021), neglecting the critical role centralized exchanges play in asset custody and the concentration of systemic risk. These platforms—though embedded in a decentralized vision—reintroduce many of the vulnerabilities familiar from traditional finance, including custodial opacity, maturity mismatches, and excessive leverage. By focusing on solvency practices and asset risk exposure, this paper offers a necessary correction to existing literature, which tends to treat crypto infrastructure as either fully decentralized or technologically self-regulating. Therefore, this paper contributes to the emerging literature by shifting attention to the solvency architecture and systemic resilience of centralized exchanges. We advance the theoretical discourse by applying Shapiro's framework of impersonal trust to assess the role of centralized exchanges as institutional guardians of user funds.

Our analysis also contributes to ongoing debates about crypto regulation and risk management. As policymakers explore new frameworks such as the EU's Markets in Crypto-Assets (MiCA) regulation (Official Journal of the European Union, 2023), a deeper understanding of exchange-level vulnerabilities becomes critical. By investigating the extent to which asset structure and volatility expose centralized exchanges to solvency risks during periods of market stress, we offer insights into how reserve requirements and transparency standards might be calibrated to enhance institutional stability.

To explore these issues, we analyze a novel dataset of on-chain proof-of-assets disclosures from 11 major centralized exchanges, compiled by Glassnode. These disclosures allow us to construct time-varying portfolios that reflect the asset composition of each exchange. Our dataset covers approximately 66.89% of the total assets held by centralized exchanges, leaving 33.11% unobserved. Nonetheless, the sample includes 11 of the most active exchanges, which together account for 65.31% of total trading volume in the centralized finance (CeFi) system. We therefore believe that, despite this limitation, the dataset remains broadly representative of the centralized exchange landscape. We then apply an AR-GARCH framework to examine how these portfolios respond to major crypto-specific stress events in 2022—including the collapses of Terra-Luna and FTX. To quantify the downside risk associated with these portfolios, we implement a modified value-at-risk (MVaR) analysis, which enables us to estimate the scale of reserve buffers that would be necessary to absorb losses under extreme conditions.

The main contribution of this paper is an empirical analysis of the stability of centralized exchanges. We find that: (i) the bankruptcies of FTX and Celsius have the most adverse impact across the sector; (ii) stablecoins act as a double-edged sword—while they enhance the resilience of exchanges, their potential collapse could expose platforms to severe negative consequences; and (iii) exchanges should maintain additional reserves between 6% and 14% to withstand market stress, thereby enhancing their resilience. This final point is especially relevant for policymakers, as requiring such reserves could help prevent bank runs and cascading failures within the system. In addition to this main analysis, we provide complementary insights into the composition of exchange-held assets, which may inform broader discussions about the structure of the crypto ecosystem. Specifically: (i) centralized

[1] For the sake of space and readability, we have included the description and discussion of proof-of-solvency mechanisms in the Appendix. We encourage readers to consult these sections beforehand if they are unfamiliar with these practices or wish to learn more about the current landscape of the centralized finance system in this regard.

Table 1
Information on exchanges sourced from Glassnode.

Exchange	Initial date	Final date	Exchange	Initial date	Final date
Binance	28/09/2018	01/03/2023	Deribit	01/06/2017	01/03/2023
Bitfinex	27/04/2016	01/03/2023	Huobi	23/05/2017	01/03/2023
BitMEX	22/11/2014	01/03/2023	KuCoin	26/04/2020	01/03/2023
Bybit	25/02/2021	01/03/2023	OKX	17/03/2018	01/03/2023
CheckSig	01/10/2020	01/03/2023	SwissBorg	10/12/2020	01/03/2023
Crypto.com	18/03/2019	01/03/2023			

exchanges exhibit significant heterogeneity, with a key distinction between multi-asset and BTC-only platforms; (ii) since 2021, stablecoins have become increasingly prominent, with some exchanges holding over 50% of customer assets in these instruments; and (iii) Binance has emerged as the dominant platform for users trading BTC, Ethereum (ETH), and stablecoins.

These findings contribute to the growing literature on institutional risk within the cryptocurrency ecosystem. By empirically linking exchange-level asset risk to broader concerns about transparency and trust, we offer a framework for evaluating financial fragility in an environment where formal regulatory structures are still emerging. The findings suggest that policy interventions—such as minimum reserve requirements, real-time disclosure systems, and independent audits—may be crucial for reinforcing the foundations of impersonal trust. More broadly, the findings underscore that centralized intermediaries, even within decentralized systems, must establish themselves as reliable custodians of trust to ensure systemic resilience and long-term sustainability.

To conclude this study, we underline that centralized exchanges are characterized by the emergence of a complex chain of impersonal trust. When users select a specific centralized exchange, they must trust multiple layers of entities and components. This includes trust in the exchange itself and its management, but it extends far beyond that, encompassing any other crypto entity associated with the exchange. Paradoxically, the cryptocurrency ecosystem—originally designed to eliminate reliance on trusted intermediaries—now requires an even more elaborate structure of institutional trust to function. Shapiro's framework allows us to understand this evolution not as a failure of technology, but as a natural outcome of organizational complexity in systems where trust cannot be eliminated, only displaced. To sustain user confidence and systemic stability, centralized exchanges must evolve into credible, verifiable, and accountable guardians of trust. As such, the future of the crypto ecosystem may depend not only on technological innovation but on the institutionalization of transparency norms and regulatory frameworks that legitimize impersonal trust in digital finance.

2. Data

In this paper, we use proof-of-assets data reported by Glassnode (2023). Our purpose in conducting this initial descriptive analysis of proof-of-assets is to closely examine the asset composition of these exchanges and to explore the potential implications for the future of the cryptocurrency ecosystem. In Section 2.1, we provide a static representation of the asset composition within centralized exchanges as of March 1, 2023. For the sake of space, in the Appendix (Appendix A.3), we report the dynamic evolution of asset composition over time, starting from the initial data point for each exchange and tracking it until March 1, 2023. Finally, in Section 2.2, we construct portfolios for each centralized exchange based on their respective asset compositions, enabling us to assess the stability of these exchanges. In particular, to evaluate the resilience of the CeFi system, we apply the methodologies described in Section 3 to these portfolios.

2.1. Database & static representation

To analyze the composition of exchange assets held on behalf of customers, we utilize the Glassnode database. This database offers insights into the assets stored in disclosed cold wallets by exchanges, serving as proof-of-assets. In Table 1, we present the featured exchanges along with their respective sample periods. Specifically, daily data are available for Binance, Bitfinex, BitMEX, Bybit, CheckSig, Crypto.com, Deribit, Huobi, KuCoin, OKX, and SwissBorg. We retrieve data from the earliest available point up to March 1, 2023.

Although this analysis focuses on just 11 out of the 250 centralized cryptocurrency exchanges, these platforms are among the most significant, constituting a major part of the centralized exchange business (CoinMarketCap, 2023). According to CoinMarketCap's rankings, which are based on traffic, liquidity, trading volumes, and the trustworthiness of reported trading volumes, our selected exchanges rank at the top: Binance (1st), Bitfinex (11th), BitMEX (73rd), Bybit (2nd), Crypto.com (14th), Deribit (6th), Huobi (10th), KuCoin (8th), and OKX (4th).[2] Their positions in the CoinMarketCap rankings are supported by their trading volumes, with Binance, Bybit, Crypto.com, Huobi, KuCoin, and OKX ranking among the top 15 centralized exchanges in this metric (Lee, 2025). In 2022, the 11 exchanges covered in this study account for $8.11 trillion, representing 65.31% of the total trading volume in the CeFi system. This significant share continues into 2024, with a trading volume of $12.26 trillion, again representing 65.31% of the total volume (The Block, 2025). Considering the subset of exchanges that disclose proof-of-assets data, as reported by Defillama (2023), our 11 exchanges account for 95.6% of the total assets in this group.

[2] Deribit is ranked 6th among derivatives exchanges, while the rest are ranked for spot exchanges. SwissBorg and CheckSig are not included in these rankings.

Table 2
Proof-of-assets and total assets of exchanges, expressed in billions of USD. The percentage reflects the proportional amount of USD represented by proof-of-assets compared to the overall total assets, as of March 1, 2023. A 100% ratio implies that centralized exchanges have sufficient funds to cover all their users' assets on a 1:1 basis. It is also possible that exchanges maintain additional reserves, resulting in a ratio higher than 100%. It is important to note that, as previously stated in the study, a low percentage in our case may reflect limitations in the dataset.

Exchange	Proof-of-assets	Total assets	Percentage	Exchange	Proof-of-assets	Total assets	Percentage
Binance	34.6864	62.3360	55.64%	Deribit	1.6929	1.6500	102.60%
Bitfinex	7.8398	7.8430	99.96%	Huobi	1.7850	3.1830	56.08%
BitMEX	1.5209	1.4963	101.65%	KuCoin	1.6405	2.7490	59.68%
Bybit	1.9681	2.6460	74.38%	OKX	7.6816	8.0110	95.89%
CheckSig	0.0132	0.0128	103.11%	SwissBorg	0.4633	0.5054	91.67%
Crypto.com	3.5441	3.5050	101.11%	Aggregated	62.8358	93.9374	66.89%

In constructing this dataset, Glassnode prioritizes the most resilient networks and ecosystems within the space. As a result, it encompasses the BTC and ETH ecosystems, including all corresponding ETH-based tokens (Schultze-Kraft, 2022). Despite the limitation of not encompassing all existing assets, the resulting dataset represents approximately 66.89% of the total assets held by the exchanges, as reported in Table 2.[3,4] The disparity between proof-of-assets and total assets is understandable, given that most exchanges extend their services to a multitude of crypto assets beyond the BTC and ETH blockchains. In Table 2, Binance, Huobi, and KuCoin serve as examples showcasing this fact. Nevertheless, it is also relevant to underline that due to the elevated expenses associated with implementing proof-of-reserves across multiple assets, certain exchanges opt to provide proof only for the most substantial assets. For instance, Binance discloses assets for only 31 tokens. This practice is considered a vulnerability by the community, as disclosing only a portion of its assets may raise concerns about insolvency and transparency, as it may not hold enough assets to cover customer deposits (Thomas, 2023; Carter, 2023). Without full transparency, users must blindly trust the exchange, exposing them to potential mismanagement, fraud, or collapses like FTX.[5]

Glassnode provides data for the 10 largest asset positions in each exchange, with the remaining assets aggregated under the label "Other". Table 3 presents an overview of the aggregated cryptocurrencies held by all exchanges as of March 1, 2023, with the corresponding sectors according to Messari (2023). We observe that BTC (33.63%), ETH (20.08%), and stablecoins (30.36%)—comprising especially BUSD (13.12%), USDT (9.55%), and USDC (7.64%)—account for 84.03% of the assets held in the exchanges in our dataset. The asset composition on exchanges, as emphasized by Barucci et al. (2022, 2023) and Adachi et al. (2021), reflects the significance of stablecoins within the crypto space.

Table 4 also reveals notable percentages for various sectors, including exchange tokens (5.62%), memecoins (2.86%), data management (0.95%), and gaming (0.76%).[6]

In Table 5, we display the relative weights of each cryptocurrency, and in Table 6, we show the relative weights of each cryptocurrency sector on their respective exchanges. From these tables, three key observations can be highlighted. First, the disparity in available crypto-assets across exchanges is notable, particularly as BitMEX and CheckSig predominantly focus on BTC, while other platforms provide the opportunity to trade a broader range of alternative assets. Indeed, Binance and KuCoin distinguish themselves by providing an extensive list of alternative cryptocurrencies. This is exemplified by the "Other" category, representing 7.65% and 8.96% on these respective exchanges. Second, consistent with the findings in Tables 3 and 4, the dominance of BTC, ETH, and stablecoins is evident across all exchanges. Except for SwissBorg, BTC constitutes at least 20% of proof-of-assets on every exchange, and similarly, ETH represents a minimum of 9% across the board. Notably, stablecoins play a significant role in the asset composition of Binance (39.31%), Bybit (51.28%), KuCoin (43.15%), and OKX (37.30%), surpassing even BTC and ETH percentages. Third, we emphasize the inclusion of the exchange tokens LEO (27.78%), HT (56.8%), and CHSB (40.17%) in Bitfinex, Huobi, and SwissBorg, respectively. The utilization of these utility tokens within centralized exchanges is inherent for internal services and offerings. Hence, it is not rare to find a concentration of these tokens within their respective centralized exchanges. However, following the misuse of the exchange token FTT by the FTX exchange, there is a crucial need for the crypto community, policymakers, and management

3 The total assets data are sourced from Defillama (2023), with the exception of BitMEX (2023) and CheckSig (2023), which can be directly reviewed by any user.

4 The percentage in Table 2 reflects the proportional amount of USD represented by proof-of-assets compared to the total assets as of March 1, 2023. It indicates whether the exchange is disclosing all the assets it should officially control on behalf of the consumers. This percentage does not have an official name, and exchanges refer to it in various ways. For instance, Crypto.com names it "reserve ratio". A reliable exchange should ensure that customer funds are safely held 1:1 in reserve, meaning the centralized exchange has funds that cover all of their users' assets 1:1. Indeed, it is possible that the exchange might also maintain some additional reserves, resulting in a ratio that is slightly higher than 100%.

5 Considering the novelty of proof-of-reserves procedures, undisclosed wallets may still exist, potentially contributing to the disparity between proof-of-assets and total assets. However, this issue is expected to diminish over time as exchanges progressively disclose all cold wallets. It is also important to note that, in comparison to wallets containing proof-of-assets, total assets are often more dynamic as they encompass a broader set of addresses (Schultze-Kraft, 2022).

6 The presence of exchange tokens is inherent in centralized exchanges, where they function as utility tokens, providing users with benefits such as reduced fees (Briola and Aste, 2022; Conlon et al., 2023). Memecoins represent a particularly speculative aspect of cryptocurrency trading, involving tokens not necessarily associated with robust projects (Rosenberg, 2023). Blockchain projects focused on data management aim to facilitate secure connections between smart contracts and real-world data, APIs, and payment systems. The rise of gaming tokens reflects the increasing impact of metaverse and play-to-earn initiatives in the crypto ecosystem (Dowling, 2021a,b; Vidal-Tomás, 2023).

Table 3
Constituents of proof-of-assets, considering all the exchanges, as of March 1, 2023. The percentage reflects the relevance of the cryptocurrency within our dataset.

Crypto	Sector	Percentage	Crypto	Sector	Percentage	Crypto	Sector	Percentage
BTC	Currency	33.6302%	MANA	Gaming	0.2684%	DAI	Stablecoin	0.0051%
ETH	Smart contract platform	20.0771%	CRO	Exchange token	0.2408%	USDP	Stablecoin	0.0040%
BUSD	Stablecoin	13.1228%	HOT	Storage	0.1657%	OMG	Scaling	0.0039%
USDT	Stablecoin	9.5549%	STETH	Staking	0.1523%	SAN	Asset management	0.0033%
USDC	Stablecoin	7.6412%	MATIC	Scaling	0.1202%	APE	Gaming	0.0030%
Other	Other	5.1467%	TEL	Payment platform	0.0675%	UNI	Decentralized exchange	0.0023%
LEO	Exchange token	3.4659%	QNT	Interoperavility	0.0400%	AAVE	Defi	0.0021%
SHIB	Memecoin	2.8602%	ENJ	Gaming	0.0336%	FTT	Exchange token	0.0013%
HT	Exchange token	1.6136%	OCEAN	Data management	0.0335%	HUSD	Stablecoin	0.0000%
LINK	Data management	0.9190%	USDK	Stablecoin	0.0271%	RSR	Asset management	0.0000%
SAND	Gaming	0.4546%	UTK	Payment platform	0.0252%	EURS	Stablecoin	0.0000%
CHSB	Exchange token	0.2962%	WBTC	Wrapped-token	0.0180%	WETH	Wrapped-token	0.0000%

Table 4
Allocation of assets, considering all the exchanges, based on the sector classification provided by Messari, as of March 1, 2023. The percentage reflects the relevance of the cryptocurrency sector within our dataset.

Sector	Percentage	Sector	Percentage	Sector	Percentage
Currency	33.6302%	Data management	0.9524%	Interoperavility	0.0400%
Stablecoin	30.3551%	Gaming	0.7597%	Wrapped-token	0.0180%
Smart contract platform	20.0771%	Storage	0.1657%	Asset management	0.0033%
Exchange token	5.6179%	Staking	0.1523%	Decentralized exchange	0.0023%
Other	5.1467%	Scaling	0.1241%	Defi	0.0021%
Memecoin	2.8602%	Payment platform	0.0928%		

to establish a regulatory framework for centralized exchanges with significant holdings of native tokens, due to potential misuses similar to what was observed in the case of FTX.

In Table 7, we present the relative weights of individual cryptocurrencies, and Table 8 reports the relative weights of cryptocurrency sectors across the 11 exchanges. In contrast to Tables 5 and 6, our emphasis in this instance is not on the weights of cryptocurrencies within individual exchanges. Instead, we investigate the distribution of cryptocurrencies across the broader ecosystem among the 11 exchanges. As expected from Table 2, Binance is the preferred choice for users to deposit and trade cryptocurrencies. Indeed, it stands out as the primary custodian of BTC and ETH, with holdings of 40.43% and 59.73%, respectively, across the 11 exchanges in our dataset. It is also noteworthy that Binance holds 71.48% of all the stablecoins represented in our dataset.

Given the absolute dominance of Binance, controlling a significant portion of crypto capital, it is unsurprising that the SEC is scrutinizing all procedures and potential transactions associated with the exchange. This scrutiny is particularly driven by concerns regarding potential fund mismanagement (Lindrea, 2023). Under these circumstances, the prevailing dominance of Binance could ultimately pose a threat to the stability of the system, considering that the exchange serves as the primary custodian across all cryptocurrency sectors.

2.2. Portfolio construction

To assess the stability of centralized exchanges, we construct a portfolio for each platform by considering the assets held on behalf of customers, i.e., proof-of-assets. The daily portfolio returns of the centralized exchanges ($r_{CEX,t}$) are computed using the standard formula:

$$r_{CEX,t} = \sum_{i=1}^{N} w_{i,t} \cdot r_{i,t} \tag{1}$$

where N is the number of assets held by the exchange, $w_{i,t}$ denotes the proportion of assets on each day t, as depicted in Fig. 5, and $r_{i,t}$ represents each cryptocurrency log-return, which is calculated using the daily prices from the CoinMarketCap (2023) database (see Vidal-Tomás, 2022).

Table 9 provides descriptive statistics for the portfolios created from February 25, 2021, to March 1, 2023. These statistics are computed starting on February 25, 2021, as it represents the earliest date for which comprehensive data are accessible for all exchanges. Specifically, Bybit is the exchange with the most recent initial date, as indicated in Table 1. The heterogeneous composition of proof-of-assets is apparent in Table 9, where Binance, Bybit, Crypto.com, Huobi, and KuCoin exhibit positive means, while Bitfinex, BitMEX, CheckSig, Deribit, OKX, and SwissBorg report negative means. Despite the differences in means, the standard deviation is relatively consistent across exchanges.

In Table 10, we present the descriptive statistics spanning from January 1, 2022, to March 1, 2023. In contrast to Table 9, it is noteworthy that all exchanges exhibit negative means during this period. This observation may be linked to the cryptocurrency bubble crash in 2021 and the subsequent bankruptcies in the crypto sphere since January 2022, which led to a cascade of failures within the system.

Table 5
Relative weight of cryptocurrencies on respective exchanges, as of March 1, 2023.

	Binance	Bitfinex	BitMEX	Bybit	CheckSig	Crypto.com	Deribit	Huobi	KuCoin	OKX	SwissBorg
AAVE	–	–	–	–	–	–	–	–	–	–	0.2822%
APE	–	–	–	0.0963%	–	–	–	–	–	–	–
BTC	25.2405%	58.7266%	100%	32.8495%	100%	29.5007%	59.9404%	22.8490%	22.0388%	34.9398%	16.9574%
BUSD	23.7724%	–	–	–	–	–	–	–	–	–	–
CHSB	–	–	–	–	–	–	–	–	–	–	40.1737%
CRO	–	–	–	–	–	4.2700%	–	–	–	–	–
DAI	–	–	–	0.1619%	–	–	–	–	–	–	–
ENJ	–	–	–	–	–	0.4602%	–	–	–	–	1.0378%
ETH	21.7235%	9.1727%	–	13.0562%	–	24.2421%	37.8091%	9.5467%	15.4957%	27.7601%	10.4013%
EURS	–	–	–	–	–	–	–	–	–	0.0000%	–
FTT	–	0.0105%	–	–	–	–	–	0.0005%	–	–	–
HOT	0.3002%	–	–	–	–	–	–	–	–	–	–
HT	–	–	–	–	–	–	–	56.8019%	–	–	–
HUSD	–	–	–	–	–	–	–	0.0007%	–	–	–
LEO	–	27.7793%	–	–	–	–	–	–	–	–	–
LINK	1.4487%	0.1221%	–	0.3563%	–	1.0391%	–	0.3145%	0.9699%	–	–
MANA	0.4695%	0.0743%	–	–	–	–	–	–	–	–	–
MATIC	–	–	–	0.3381%	–	1.7500%	–	–	–	–	1.4763%
OCEAN	–	–	–	–	–	–	–	–	1.2823%	–	–
OMG	–	0.0316%	–	–	–	–	–	–	–	–	–
Other	7.6537%	1.2205%	–	1.3871%	–	6.0425%	–	4.7033%	8.9604%	–	2.3926%
QNT	–	–	–	–	–	–	–	–	1.5323%	–	–
RSR	–	–	–	–	–	–	–	–	–	0.0000%	–
SAN	–	0.0261%	–	–	–	–	–	–	–	–	–
SAND	0.8107%	–	–	0.2280%	–	–	–	–	–	–	–
SHIB	3.0463%	–	–	0.4015%	–	19.0825%	–	–	3.4375%	–	–
STETH	–	–	–	–	–	–	–	–	–	–	20.6584%
TEL	–	–	–	–	–	–	–	–	2.5864%	–	–
UNI	–	–	–	–	–	–	–	0.0795%	–	–	–
USDC	11.3377%	0.2241%	–	3.5835%	–	11.5944%	2.2505%	2.2608%	6.1008%	2.1947%	4.8767%
USDK	–	–	–	–	–	–	–	–	–	0.2220%	–
USDP	–	–	–	–	–	–	–	–	–	0.0326%	–
USDT	4.1967%	2.6122%	–	47.5417%	–	1.6986%	–	3.2539%	37.0537%	34.8507%	0.9686%
UTK	–	–	–	–	–	–	–	0.1893%	0.5421%	–	0.7751%
WBTC	–	–	–	–	–	0.3199%	–	–	–	–	–
WETH	–	–	–	–	–	–	–	–	–	0.0000%	–

Table 6
Relative weight of cryptocurrency sectors on respective exchanges, as of March 1, 2023.

Sector	Binance	Bitfinex	BitMEX	Bybit	CheckSig	Crypto.com	Deribit	Huobi	KuCoin	OKX	SwissBorg
Asset management	–	0.0261%	–	–	–	–	–	–	–	0.0000%	–
Currency	25.2405%	58.7266%	100%	32.8495%	100%	29.5007%	59.9404%	22.8490%	22.0388%	34.9398%	16.9574%
Data management	1.4487%	0.1221%	–	0.3563%	–	1.0391%	–	0.3145%	2.2522%	–	–
Decentralized exchange	–	–	–	–	–	–	–	0.0795%	–	–	–
Defi	–	–	–	–	–	–	–	–	–	–	0.2822%
Exchange token	–	27.7898%	–	–	–	4.2700%	–	56.8024%	–	–	40.1737%
Gaming	1.2801%	0.0743%	–	0.3243%	–	0.4602%	–	–	–	–	1.0378%
Interoperavility	–	–	–	–	–	–	–	–	1.5323%	–	–
Memecoin	3.0463%	–	–	0.4015%	–	19.0825%	–	–	3.4375%	–	–
Other	7.6537%	1.2205%	–	1.3871%	–	6.0425%	–	4.7033%	8.9604%	–	2.3926%
Payment platform	–	–	–	–	–	–	–	0.1893%	3.1285%	–	0.7751%
Scaling	–	0.0316%	–	0.3381%	–	1.7500%	–	–	–	–	1.4763%
Smart contract platform	21.7235%	9.1727%	–	13.0562%	–	24.2421%	37.8091%	9.5467%	15.4957%	27.7601%	10.4013%
Stablecoin	39.3069%	2.8363%	–	51.2871%	–	13.2929%	2.2505%	5.5154%	43.1545%	37.3001%	5.8453%
Staking	–	–	–	–	–	–	–	–	–	–	20.6584%
Storage	0.3002%	–	–	–	–	–	–	–	–	–	–
Wrapped-token	–	–	–	–	–	0.3199%	–	–	–	0.0000%	–

To evaluate the stability of centralized exchanges during extreme events, we use the portfolio returns calculated from January 1, 2022, to March 1, 2023. This specific timeframe is chosen as it corresponds to the period during which all identified bank runs and bankruptcies occur (Clarke, 2022).

3. Methodology

In this section, we outline the methodology employed for analyzing the stability of the CeFi system using the previously constructed portfolios. More specifically, in Section 3.1, we introduce the AR-GARCH framework, which we use to evaluate how

Table 7
Distribution of cryptocurrencies across the 11 exchanges, as of March 1, 2023.

	Binance	Bitfinex	BitMEX	Bybit	CheckSig	Crypto.com	Deribit	Huobi	KuCoin	OKX	SwissBorg
AAVE	–	–	–	–	–	–	–	–	–	–	100%
APE	–	–	–	100.0000%	–	–	–	–	–	–	–
BTC	41.4304%	21.7873%	7.1973%	3.0595%	0.0624%	4.9476%	4.8018%	1.9301%	1.7109%	12.7009%	0.3718%
BUSD	100%	–	–	–	–	–	–	–	–	–	–
CHSB	–	–	–	–	–	–	–	–	–	–	100%
CRO	–	–	–	–	–	100%	–	–	–	–	–
DAI	–	–	–	100%	–	–	–	–	–	–	–
ENJ	–	–	–	–	–	77.2312%	–	–	–	–	22.7688%
ETH	59.7283%	5.7003%	–	2.0369%	–	6.8102%	5.0735%	1.3508%	2.0151%	16.9030%	0.3820%
EURS	–	–	–	–	–	–	–	–	–	100%	–
FTT	–	98.9581%	–	–	–	–	–	1.0419%	–	–	–
HOT	100%	–	–	–	–	–	–	–	–	–	–
HT	–	–	–	–	–	–	–	100%	–	–	–
HUSD	–	–	–	–	–	–	–	100%	–	–	–
LEO	–	100%	–	–	–	–	–	–	–	–	–
LINK	87.0230%	1.6571%	–	1.2144%	–	6.3778%	–	0.9722%	2.7555%	–	–
MANA	96.5449%	3.4551%	–	–	–	–	–	–	–	–	–
MATIC	–	–	–	8.8125%	–	82.1303%	–	–	–	–	9.0572%
OCEAN	–	–	–	–	–	–	–	–	100%	–	–
OMG	–	100%	–	–	–	–	–	–	–	–	–
Other	82.0911%	2.9586%	–	0.8442%	–	6.6219%	–	2.5961%	4.5455%	–	0.3427%
QNT	–	–	–	–	–	–	–	–	100%	–	–
RSR	–	–	–	–	–	–	–	–	–	100%	–
SAN	–	100%	–	–	–	–	–	–	–	–	–
SAND	98.4291%	–	–	1.5709%	–	–	–	–	–	–	–
SHIB	58.7932%	–	–	0.4396%	–	37.6294%	–	–	3.1378%	–	–
STETH	–	–	–	–	–	–	–	–	–	–	100%
TEL	–	–	–	–	–	–	–	–	100%	–	–
UNI	–	–	–	–	–	–	–	100%	–	–	–
USDC	81.9067%	0.3659%	–	1.4689%	–	8.5582%	0.7935%	0.8405%	2.0845%	3.5112%	0.4706%
USDK	–	–	–	–	–	–	–	–	–	100%	–
USDP	–	–	–	–	–	–	–	–	–	100%	–
USDT	24.2458%	3.4110%	–	15.5846%	–	1.0026%	–	0.9674%	10.1247%	44.5890%	0.0747%
UTK	–	–	–	–	–	–	–	21.2989%	56.0644%	–	22.6367%
WBTC	–	–	–	–	–	100%	–	–	–	–	–
WETH	–	–	–	–	–	–	–	–	–	100%	–

Table 8
Distribution of cryptocurrency sectors across the 11 exchanges, as of March 1, 2023.

Sector	Binance	BitMEX	Bitfinex	Bybit	CheckSig	Crypto.com	Deribit	Huobi	KuCoin	OKX	SwissBorg
Asset management	–	–	99.9881%	–	–	–	–	–	–	0.0119%	–
Currency	41.4304%	7.1973%	21.7873%	3.0595%	0.0624%	4.9476%	4.8018%	1.9301%	1.7109%	12.7009%	0.3718%
Data management	83.9641%	–	1.5989%	1.1717%	–	6.1536%	–	0.9380%	6.1737%	–	–
Decentralized exchange	–	–	–	–	–	–	–	100.0000%	–	–	–
Defi	–	–	–	–	–	–	–	–	–	–	100.0000%
Exchange token	–	–	61.7175%	–	–	4.2869%	–	28.7232%	–	–	5.2724%
Gaming	93.0183%	–	1.2208%	1.3371%	–	3.4165%	–	–	–	–	1.0072%
Interoperavility	–	–	–	–	–	–	–	–	100.0000%	–	–
Memecoin	58.7932%	–	–	0.4396%	–	37.6294%	–	–	3.1378%	–	–
Other	82.0911%	–	2.9586%	0.8442%	–	6.6219%	–	2.5961%	4.5455%	–	0.3427%
Payment platform	–	–	–	–	–	–	–	5.7958%	88.0444%	–	6.1598%
Scaling	–	–	3.1769%	8.5326%	–	79.5210%	–	–	–	–	8.7695%
Smart contract platform	59.7283%	–	5.7003%	2.0369%	–	6.8102%	5.0735%	1.3508%	2.0151%	16.9030%	0.3820%
Stablecoin	71.4808%	–	1.1658%	5.2921%	–	2.4699%	0.1997%	0.5162%	3.7117%	15.0218%	0.1420%
Staking	–	–	–	–	–	–	–	–	–	–	100.0000%
Storage	100.0000%	–	–	–	–	–	–	–	–	–	–
Wrapped-token	–	–	–	–	–	100.0000%	–	–	–	0.0000%	–

exchanges respond to extreme negative events that occurred in 2022. In Section 3.2, we describe the MVaR approach, which we use to evaluate the downside risk associated with depositing users' assets in a given exchange.

3.1. Event study: AR-GARCH framework

In our pursuit of evaluating the robustness of centralized exchanges, we aim to analyze how the portfolio returns, computed between January 1, 2022, and March 1, 2023, reacted to significant adverse events (d) within the cryptocurrency market. In

Table 9
Descriptive statistics from February 25, 2021, to March 1, 2023.

Exchange	Mean	Std. Dev.	Skewness	Kurtosis	Min.	Max.
Binance	0.00007	0.02528	−0.65843	5.51846	−0.18433	0.11933
Bitfinex	−0.00048	0.03633	−0.45878	3.23527	−0.20621	0.15519
BitMEX	−0.00088	0.03564	−0.39194	2.83974	−0.17405	0.13576
Bybit	0.00033	0.03410	−0.60170	10.51725	−0.29092	0.20859
Checksig	−0.00088	0.03564	−0.39194	2.83974	−0.17405	0.13576
Crypto.com	0.00000	0.03597	−0.64387	6.10186	−0.26125	0.20057
Deribit	−0.00047	0.03845	−0.51574	3.23788	−0.20955	0.15559
Huobi	0.00037	0.02322	−0.10198	3.76991	−0.12231	0.12043
KuCoin	0.00086	0.04059	−0.33396	10.80428	−0.31524	0.23305
OKX	−0.00010	0.03080	−0.45518	3.69460	−0.18929	0.13700
Swissborg	−0.00035	0.03983	−0.74299	9.26603	−0.32543	0.22066

Table 10
Descriptive statistics from January 1, 2022, to March 1, 2023.

Exchange	Mean	Std. Dev.	Skewness	Kurtosis	Min.	Max.
Binance	−0.00088	0.01906	−0.42634	2.76838	−0.08453	0.07691
Bitfinex	−0.00183	0.03206	−0.45416	3.65671	−0.16447	0.12533
BitMEX	−0.00158	0.03260	−0.55398	4.76835	−0.17405	0.13576
Bybit	−0.00143	0.02609	−0.55293	4.47166	−0.13321	0.10257
Checksig	−0.00158	0.03260	−0.55398	4.76835	−0.17405	0.13576
Crypto.com	−0.00139	0.03004	−0.56263	3.30586	−0.14969	0.12098
Deribit	−0.00162	0.03540	−0.55781	3.97914	−0.17416	0.12901
Huobi	−0.00056	0.02372	0.11639	4.23565	−0.11874	0.12043
KuCoin	−0.00085	0.01964	−0.51040	2.50345	−0.08415	0.06770
OKX	−0.00103	0.02353	−0.38868	3.29239	−0.10448	0.09809
Swissborg	−0.00199	0.03446	−0.54164	4.87586	−0.20375	0.17092

particular, we focus on the most significant collapses within the crypto ecosystem in 2022: Terra-Luna on May 11,[7] Celsius on June 12,[8] Three Arrows Capital on June 16,[9] Voyager Digital on July 1,[10] FTX on November 8,[11] and BlockFi on November 11.[12] The Terra-Luna protocol is a blockchain system designed to produce an algorithmic stablecoin pegged to various fiat currencies. It functions on the Terra blockchain and utilizes a two-token model: Terra (the algorithmic stablecoin) and Luna (the governance and utility token). Celsius Network is a blockchain-based financial platform that offers cryptocurrency lending, borrowing, and interest-earning services. Three Arrows Capital is a Singapore-based cryptocurrency hedge fund renowned for its significant investments and diverse portfolio in the digital assets market. Voyager Digital is a cryptocurrency brokerage firm that provides a platform for trading and investing in various digital assets. FTX is a cryptocurrency exchange platform that provides a wide range of trading services, including spot trading, derivatives, and leveraged tokens. BlockFi is a financial services company in the cryptocurrency space, offering various products such as interest-bearing accounts, crypto-backed loans, and trading services.

To analyze the stability of centralized exchanges to previous events, we employ the traditional AR-GARCH framework. This methodology allows us to observe the market response according to each event, quantify the effect on each centralized exchange, and determine its significance. We model the dynamic behavior of the total assets held by the exchanges, and represented by the portfolios, with the AR-GARCH model along with the corresponding events (d) as exogenous variables, resulting in the methodological form:

$$r_{CEX,t} = c + \sum_{j=1}^{n} b_j r_{CEX,t-j} + \phi d_t + u_t, \qquad u_t = \sigma_t z_t, \quad z_t \sim t_v \tag{2}$$

[7] From May 11, 2022, UST's price sharply declined to 10 cents, and LUNA tumbled to "virtually zero", marking a substantial drop from its previous all-time high of $119.51 (Briola et al., 2023).

[8] On June 12, Celsius posted a memo informing users that it had frozen their assets, sending the price of Bitcoin and other cryptos down along with it (Napolitano, 2022).

[9] The Financial Times reported on June 16, 2022, that Three Arrows had not met its margin calls (Financial Times, 2022).

[10] The company suspended "trading, deposits, withdrawals, and loyalty rewards" on July 1, 2022 (Ge Huang, 2022).

[11] On November 8, 2022, FTX experienced a significant decrease in the price of FTT. According to Khoo et al. (2022), creditors initiated the recall of Alameda Research loans backed by FTT as collateral. As Alameda Research was unable to repay these loans, Sam Bankman-Fried was compelled to request Binance's intervention in acquiring the firm. As a result, on the same day, Binance made an announcement regarding a non-binding letter of intent to acquire FTX (Coghlan, 2022; see also Vidal-Tomás et al., 2023; Conlon et al., 2023, 2024; Yousaf and Goodell, 2023).

[12] On November 11, California's financial regulator revoked BlockFi's lending license after BlockFi paused customer withdrawals amid "the lack of clarity" about FTX (The Guardian, 2022).

Table 11
GARCH-type models used in this study. The standard GARCH model is applied in the main analysis, while the others are used for robustness checks.

Model	Volatility equation	Proposed by
GARCH	$\sigma_t^2 = \omega + \alpha u_{t-1}^2 + \beta\sigma_{t-1}^2$	Bollerslev (1986)
EGARCH	$\log\left(\sigma_t^2\right) = \omega + \alpha\epsilon_{t-1}^2 + \gamma\left(\left\|\epsilon_{t-1}\right\| - E\left(\left\|\epsilon_{t-1}\right\|\right)\right) + \beta\log\left(\sigma_{t-1}^2\right)$	Nelson (1991)
IGARCH	$\sigma_t^2 = \omega + \alpha u_{t-1}^2 + (1-\alpha)\sigma_{t-1}^2$	Engle and Bollerslev (1986)
APARCH	$\sigma_t^\delta = \omega + \alpha\left(\left\|u_{t-1}\right\| - \gamma u_{t-1}\right)^\delta + \beta\sigma_{t-1}^\delta$	Ding et al. (1993)
CGARCH	$\sigma_t^2 = q_t + \alpha\left(u_{t-1}^2 - q_{t-1}\right) + \beta\left(\sigma_{t-1}^2 - q_{t-1}\right)$	
GJR	$\sigma_t^2 = \omega + \alpha u_{t-1}^2 + \gamma I\left(r_{t-1} < 0\right)u_{t-1}^2 + \beta\sigma_{t-1}^2$	Glosten et al. (1993)

where ϕ_t denotes the impact of each event (d) on each exchange, d represents the event dummies, u_t is the error term, z_t is a white noise process, and σ_t denotes the conditional standard deviation.[13] Concerning the dummy variables, we take into account two scenarios: (i) "Period [0]", in which we examine the event's effect solely on the specific day it occurs, and (ii) "Period [−1,1]", where we assess the event's impact while also considering the potential effects on the day before and the day after it occurs.[14,15] In line with existing literature,[16] we adopt the AR(1)-GARCH(1,1) specification as our baseline model, and we present its findings in Section 4.1. Additionally, for the sake of ensuring the robustness of our analysis, we employ various GARCH-type models. Table 11 provides a comprehensive list of all the GARCH-type variants utilized in this study, which encompass GARCH, EGARCH, IGARCH, APARCH, CGARCH, and GJR. We elaborate on the robustness of our results in Section 4.2.[17]

3.2. Modified VAR

Gaussian VaR is one of the most standard methods in the literature to measure the downside risk of a portfolio, whose returns are characterized by the normal distribution. With this methodology, any practitioner can examine the maximum potential loss incurred by an investment during a time period, given a certain probability level (Boudt et al., 2008). Mathematically, it is defined as

$$\mathrm{VaR}p(1-\alpha) = \mu p - \sigma_p z(\alpha), \tag{3}$$

where μ_p and σ_p denote the mean and standard deviation of the portfolio, and $z(\alpha)$ is the α-quantile of the standard normal distribution (Wilmott, 1998). However, this VaR measure does not consider the empirical stylized facts that are already described in the literature (Cont, 2001), such as skewness, kurtosis, and fat tails, which reduces its accuracy (Giot and Laurent, 2003). Given this fact, Zangari (1996) and Favre and Galeano (2002) propose an alternative estimator for VaR, namely modified VaR, in order to correct the Gaussian VaR for skewness and kurtosis in the return series.[18] More specifically, it adjusts the Gaussian quantile function for skewness and kurtosis, by means of the Cornish–Fisher expansion (Cornish and Fisher, 1938). As a result, the modified VaR is computed as follows:

$$\hat{Z}\left(\alpha, S_p, K_p\right) = z(\alpha) + \frac{1}{6}\left(z(\alpha)^2 - 1\right)S_p + \frac{1}{24}\left(z(\alpha)^3 - 3z(\alpha)\right)K_p - \frac{1}{36}\left(2z(\alpha)^3 - 5z(\alpha)\right)S_p^2, \tag{4}$$

where S_p and K_p denote the skewness and kurtosis of a given portfolio. Therefore, the MVaR is defined substituting in Eq. (3), $z(\alpha)$ by $\hat{Z}\left(\alpha, S_p, K_p\right)$, i.e.,

$$\mathrm{MVaR}_p(1-\alpha) = \mu_p - \sigma_p\hat{Z}\left(\alpha, S_p, K_p\right). \tag{5}$$

For a more detailed explanation of the computation of the modified VaR, readers can refer to Favre and Galeano (2002).[19] Using this approach, our objective is to assess the risks involved in depositing users' assets on each exchange. A higher downside risk indicates that the exchange is less resilient to adverse events, making it potentially vulnerable to bank runs. To achieve this objective, we compute the MVaR for the portfolios associated with each exchange. In contrast to the event study previously described, this method focuses on assessing downside risk across the entire available sample rather than analyzing specific individual events.

[13] We have used the t-Student distribution for the distributional assumption in GARCH innovations, as it is more appropriate for cryptocurrency assets, which are characterized by high volatility and heavy tails. In the Appendix, Appendix A.4 (see Figs. 7 and 8), we demonstrate that the results remain robust across different distributional assumptions, including Skew Student-t, Generalized Error Distribution, Skew Generalized Error Distribution, Normal Inverse Gaussian, Generalized Hyperbolic, and Johnson's SU. The only assumptions that differ from the rest are the normal and skew-normal distributions, which is expected since they are not well-suited for assets with high volatility and periods of market stress.

[14] In Period [0], we utilize a dummy variable set to 1 for the same day of the event and 0 otherwise. In Period [−1,1], we employ dummy variables set to 1 for the same day, the day before, and the day after the event, with 0 otherwise.

[15] Results are consistent using other time ranges. Material upon request.

[16] GARCH frameworks have been widely used in the literature not only for event studies (e.g., Vidal-Tomás and Ibañez, 2018; Conlon et al., 2023) but also for volatility analysis (Katsiampa, 2017; Sensoy et al., 2021) or forecasting (Trucíos, 2019), among other financial subjects.

[17] Bollerslev (1986) argued for restrictions on the parameters for positivity, $\omega > 0$, $\alpha \geq 0$, and $\beta \geq 0$, and the wide-sense stationarity condition, $\alpha + \beta < 1$.

[18] See Conlon and McGee, 2020 for a BTC application of this methodology during the COVID-19 pandemic.

[19] The modified VaR reduces to the traditional mean-VaR when returns follow a normal distribution. Additionally, the Cornish–Fisher expansion naturally captures much of the variability in returns that more computationally intensive techniques, such as resampling or Monte Carlo simulation, would uncover. We have applied this VaR function from the R package PerformanceAnalytics (Peterson and Carl, 2025), and it can be accessed by setting method = "modified".

4. Empirical results

In this section, we present the empirical findings of our study. Section 4.1 includes (i) AR-GARCH outcomes based on the selected negative events (d) in 2022 and (ii) MVaR(5%) and MVaR(1%) for the portfolios associated with each centralized exchange. Section 4.2 provides a robustness analysis of different GARCH variants, including GARCH, EGARCH, IGARCH, APARCH, CGARCH, and GJR variants. Section 4.3 explores the impact of stablecoins on our study's results. Lastly, in the Appendix, Appendix A.5, we replicate the primary empirical exercises of this study using an alternative dataset from Glassnode—specifically, exchange balance data.

4.1. Event study & MVaR(1%–5%) for proof-of-assets

Tables 12 and 13 report the AR-GARCH estimates for the event dummies related to the most significant collapses in 2022: (d_1) Terra-Luna on May 11, (d_2) Celsius on June 12, (d_3) Three Arrows Capital on June 16, (d_4) Voyager Digital on July 1, (d_5) FTX on November 8, and (d_6) BlockFi on November 11. Tables 12 and 13 consider Period [0] and Period [−1,1], respectively.

We show in Table 12 that the most significant negative events for Period [0] occurred chronologically as follows: (d_1) Terra-Luna, (d_2) Celsius, (d_3) Three Arrows Capital, (d_5) FTX, and (d_6) BlockFi. When considering their impact on the exchanges, the most severe events are (d_5) FTX, (d_3) Three Arrows Capital, (d_1) Terra-Luna, (d_2) Celsius, and (d_6) BlockFi. As can be observed, centralized exchanges are significantly affected by four out of six events, demonstrating (i) the interconnections within the crypto industry, (ii) the vulnerability of exchanges to third-party collapses, and (iii) the need to establish further regulations to ensure their proper functioning in the face of extreme negative events. In general, it is noteworthy that the most resilient exchanges to the impact of these events are Binance and KuCoin. Additionally, the stability of Huobi and OKX is also remarkable.

Focusing on Period [−1,1], as shown in Table 13, a shift in perspective becomes evident. Remarkably, the sole significant negative events impacting all the centralized exchanges during this period are the bankruptcies of Celsius (d_2) and FTX (d_5). Whereas the collapses of Terra-Luna and Three Arrows Capital have a pronounced impact on centralized exchanges on the day of the events, this impact diminishes when also considering the day before and after. This observation is consistent with the findings of Briola et al. (2023), who observes that certain major cryptocurrencies, such as BTC, experience significant recoveries in the days following the Terra-Luna collapse. According to Table 13, the crypto community could consider the collapses of Terra-Luna and Three Arrows Capital to be less relevant than the bankruptcies of Celsius and FTX. Initially, the Terra-Luna protocol could be seen as just the isolated collapse of an algorithmic stablecoin, which was not expected to cause additional issues in the crypto system. However, the Celsius bankruptcy was the initial signal that a cascade of bankruptcies had begun following the collapse of Terra-Luna. More specifically, the implosion of Terra-Luna damaged consumer confidence in the crypto market, accelerating the onset of a "crypto winter" and an industry-wide sell-off that spurred a bank run-style series of withdrawals by Celsius users (Napolitano, 2022). Later, in its bankruptcy filings, Celsius attributed its liquidity woes to "the domino effect" of Terra-Luna's collapse. Celsius was a relevant figure in the crypto space, as a lending company providing loans to a significant number of agents. Its collapse marked the end of lending activity in the crypto industry. The consequence was the bankruptcy of companies that base their strategy on leverage, such as Three Arrows Capital. Three Arrows' strategy involved borrowing money from across the industry and then investing that capital in other, often nascent, crypto projects. Without companies to borrow from, Three Arrows Capital collapsed. An inundation of margin calls from Three Arrows Capital's creditors clamored for repayment, yet the firm was unable to satisfy these demands due to a shortage of funds (Financial Times, 2022). Cryptocurrency broker Voyager Digital was the following victim, as Three Arrows failed to repay money lent by Voyager (Ge Huang, 2022). As can be observed, compared to other events, the collapse of Celsius and other lending companies underlines the existence of the domino effect started by Terra-Luna in the summer of 2022, and the unavailability of future lines of credit in the crypto industry. This could increase the withdrawals of funds from centralized exchanges and the decrease in crypto prices, giving rise to the negative impact on centralized exchanges reported in Table 13.

After some months in which the domino effect seemed over, FTX, the third-largest exchange at the time, collapsed due to an aggressive leverage strategy based on the use of its native token (FTT) as collateral on its loans (Khoo et al., 2022). In particular, the downturn in the cryptocurrency market also decreased the value of FTT, which Alameda (FTX's sister company) had used as collateral for some loans. As the firm struggled to repay lenders, FTX resorted to using customer deposits, intended for trading convenience, to repay Alameda's lenders. CoinDesk reported on this situation, triggering a further decrease in FTT's price and leading to the bankruptcy of FTX, which did not have access to alternative lines of credit.

The decline in cryptocurrency prices following the collapse of FTX (Vidal-Tomás et al., 2023; Conlon et al., 2023, 2024) likely triggered a withdrawal of funds from the majority of centralized exchanges. This withdrawal, in turn, exacerbated the negative impact on the value of assets held by these exchanges, giving rise to the most negative impact in Table 13. Considering that FTX was the third-largest centralized exchange at the time of the events, it is rational to assume that users transfer their funds and cryptos to safer options, such as cold wallets, in order to avoid the negative effects of a cascade of bankruptcies among other centralized exchanges within the crypto ecosystem. Finally, BlockFi suffered from a liquidity crisis due to its exposure to FTX via loans (The Guardian, 2022).

In a similar line to Table 12, the most resilient centralized exchanges to the collapse of FTX and Celsius are Binance, KuCoin, and OKX. Certainly, Binance emerges as a winner in this context, since its monthly trading activity increases by 30% just after the FTX collapse (Pan, 2022).[20]

[20] In 2022, Binance's volume market share increases from 48.7% in the first quarter to 66.7% in the last quarter (CryptoCompare, 2023).

Table 12
AR-GARCH results based on the selected negative events (d) in 2022. The dummy variables are included for the exact day on which the events occurred, i.e., Period [0].

Period [0]	Binance	Bitfinex	BitMEX	Bybit	Checksig	Crypto.com	Deribit	Huobi	KuCoin	OKX	Swissborg
d_1	−0.0616***	−0.0762***	−0.0685***	−0.0656***	−0.0685***	−0.1049***	−0.0878***	−0.0549***	−0.0623***	−0.0635***	−0.1342***
d_2	−0.0295**	−0.0593***	−0.0589***	−0.0461***	−0.0589***	−0.0530***	−0.0589***	−0.0223*	−0.0365***	−0.0382***	−0.1145***
d_3	−0.0463***	−0.1021***	−0.1012***	−0.0854***	−0.1012***	−0.0777***	−0.1136***	−0.0443***	−0.0586***	−0.0672***	−0.0906***
d_4	−0.0105	−0.0214	−0.0268	−0.0180	−0.0268	−0.0203	−0.0203	−0.0038	−0.0107	−0.0106	−0.0255
d_5	−0.0586***	−0.0878***	−0.1060***	−0.0928***	−0.1060***	−0.1297***	−0.1270***	−0.1194***	−0.0599***	−0.0692***	−0.0902***
d_6	−0.0068	−0.0289*	−0.0286	−0.0142	−0.0286	−0.0193	−0.0180	−0.0535***	−0.0092	−0.0081	−0.0245

Table 13
AR-GARCH results based on the selected negative events (d) in 2022. The dummy variables are included, considering the day before, the specific day of the events, and the day after, i.e., Period [−1,1].

Period [−1,1]	Binance	Bitfinex	BitMEX	Bybit	Checksig	Crypto.com	Deribit	Huobi	KuCoin	OKX	Swissborg
d_1	−0.0162	−0.0110	−0.0018	−0.0166	−0.0018	−0.0395	−0.0209	−0.0223*	−0.0127	−0.0178	−0.0158
d_2	−0.0333***	−0.0553***	−0.0491***	−0.0439***	−0.0491***	−0.0574***	−0.0573***	−0.0334***	−0.0406***	−0.0422***	−0.0954***
d_3	−0.0034	−0.0023	−0.0021	−0.0038	−0.0021	0.0001	0.0005	−0.0027	0.0006	−0.0035	−0.0135
d_4	−0.0059	−0.0137	−0.0148	−0.0113	−0.0148	−0.0090	−0.0136	−0.0038	−0.0062	−0.0076	−0.0129
d_5	−0.0530***	−0.0858***	−0.1050***	−0.0870***	−0.1050***	−0.1118***	−0.1268***	−0.0975***	−0.0568***	−0.0657***	−0.0751***
d_6	−0.0009	−0.0068	−0.0095	0.0051	−0.0095	−0.0006	−0.0036	−0.0427***	−0.0021	−0.0008	−0.0017

Table 14
MVaR(5%) & MVaR(1%) for the portfolio corresponding to each centralized exchange. Centralized exchanges are ordered alphabetically.

	Binance	Bitfinex	BitMEX	Bybit	Checksig	Crypto.com	Deribit	Huobi	KuCoin	OKX	Swissborg
MVaR(5%)	−0.0334	−0.0561	−0.0569	−0.0459	−0.0569	−0.0534	−0.0623	−0.0367	−0.0349	−0.0406	−0.0603
MVaR(1%)	−0.0623	−0.1122	−0.1234	−0.0971	−0.1234	−0.1034	−0.1274	−0.0772	−0.0635	−0.0793	−0.1315

Table 15
MVaR(5%) & MVaR(1%) for the portfolio corresponding to each centralized exchange. Centralized exchanges are ordered according to MVaR(5%) & MVaR(1%) values.

	Binance	KuCoin	Huobi	OKX	Bybit	Crypto.com	Bitfinex	BitMEX	Checksig	Swissborg	Deribit
MVaR(5%)	−0.0334	−0.0349	−0.0367	−0.0406	−0.0459	−0.0534	−0.0561	−0.0569	−0.0569	−0.0603	−0.0623
	Binance	KuCoin	Huobi	OKX	Bybit	Crypto.com	Bitfinex	BitMEX	Checksig	Deribit	Swissborg
MVaR(1%)	−0.06229	−0.06353	−0.07716	−0.07934	−0.09711	−0.10344	−0.11217	−0.12343	−0.12343	−0.12742	−0.13152

Taking into account the findings from Tables 12 and 13, it can be affirmed that centralized exchanges are significantly affected by negative events in the crypto industry. Particularly relevant are events related to the collapses of lending companies (Celsius) and other large centralized exchanges (FTX). This underlines the need for policymakers to regulate the crypto sector as a whole, given the interconnections within the industry.

On the other hand, Tables 14 and 15 present the MVaR(5%) and MVaR(1%) values for the portfolios associated with each centralized exchange. Table 14 lists the values for the exchanges in alphabetical order, consistent with the arrangement in other tables. To enhance clarity, Table 15 displays the same values but organizes the exchanges based on the downside risk experienced during the sample period. In comparison to Tables 12 and 13, which focus on specific cryptocurrency events, MVaR(5%) and MVaR(1%) consider the entire sample period. Consequently, they complement the previous results by accounting for any potential events that may have been omitted earlier.

Consistent with our event study findings presented in Tables 14 and 15, it remains evident that Binance and KuCoin stand out as the most resilient centralized exchanges. Consequently, these exchanges exhibit a lower level of risk, indicating a reduced likelihood of encountering substantial losses compared to other participants in the CeFi system. In essence, based on these results, Binance and KuCoin can be considered stable and suitable choices for risk-averse investors, as they are less susceptible to significant value fluctuations or potential bank runs due to a loss of confidence.

The resilience of centralized crypto exchanges is a crucial factor in maintaining stability and ensuring the continuous operation of the crypto ecosystem, making this analysis particularly relevant for policymakers. Our analysis suggests that exchanges should maintain additional reserves in the range of 6% to 14% to absorb market shocks and negative returns. This finding aligns with the regulatory provisions set forth in MiCA (Official Journal of the European Union, 2023), which aims to establish financial safeguards, enhance consumer protection, and prevent systemic risks in the crypto market. The introduction of prudential requirements for crypto-asset service providers under MiCA reinforces the need for sufficient liquidity provisions, ensuring that exchanges can withstand liquidity stresses and maintain market integrity. In this context, our findings align closely with key MiCA provisions, offering a data-driven perspective on regulatory requirements. This alignment is further demonstrated through specific aspects of MiCA's framework, particularly in the areas of financial resilience, market stability, and consumer protection.

MiCA mandates exchanges to hold own funds or insurance proportional to their risk exposure. This requirement directly correlates with our findings, where negative returns can be seen as an indicator of reserve needs. By maintaining additional reserves, exchanges can better manage their financial risks and avoid insolvency during turbulent market conditions. The regulation also emphasizes the need for robust risk management frameworks, requiring exchanges to implement policies that address liquidity and market risks. This measure aligns with our empirical results, which demonstrate that reserves within the range of 6%–14% serve as effective protection against financial distress. The importance of such measures is further underscored by MiCA's provisions that grant regulators the authority to monitor and mitigate systemic risks, preventing the contagion effect that could arise from the collapse of a major exchange.

Consumer protection is a core component of MiCA, as it requires exchanges to safeguard client assets. Maintaining additional reserves could prevent issues such as withdrawal suspensions, a frequent concern during market downturns. This aspect of capital adequacy ensures that investors retain access to their funds even in times of crisis, fostering trust and stability within the crypto ecosystem. Furthermore, MiCA seeks to address regulatory arbitrage by enforcing standardized prudential requirements across EU-based exchanges. This regulatory uniformity prevents exchanges from relocating to jurisdictions with weaker oversight, thereby reducing systemic vulnerabilities. Our research supports this initiative by providing a quantitative basis for setting reserve requirements that can be applied uniformly across different regulatory landscapes.

Our findings align with MiCA's overarching goal of reinforcing financial discipline among crypto exchanges. By integrating our results with MiCA's framework, we emphasize the role of maintaining sufficient reserves in promoting responsible risk management, enhancing market stability, and supporting a regulatory structure that fosters long-term sustainability in the crypto ecosystem.

4.2. GARCH-type variants

In Section 4.1, we employ the conventional GARCH framework to examine the impact of the major collapses in 2022 on centralized exchanges. To ensure the robustness of our analysis, in Figs. 1 and 2, we present boxplots illustrating the estimated dummy variables derived from a comprehensive set of GARCH variants, which include GARCH, EGARCH, IGARCH, APARCH, CGARCH, and GJR. As can be observed, the consistency in our results is apparent due to the similarity in the estimates obtained from the various GARCH types. Consequently, the results obtained in Section 4.1 remain robust even when utilizing different GARCH variants.

4.3. The relevance of stablecoins

In the modern crypto landscape, stablecoins account for nearly 75% of total trading activity, serving as both a bridge between fiat currencies and crypto-assets and a safe haven to mitigate market volatility (Adachi et al., 2021, 2022). Interestingly, as demonstrated by Barucci et al. (2022), the trading volumes of markets involving USDT against major cryptocurrencies have consistently risen, establishing USDT as the crypto-asset with the highest trading volume since the second quarter of 2019. Additionally, Barucci et al. (2023) highlights that stablecoins, such as USDT, serve as a secure haven and/or store of value, facilitating cryptocurrency trading without the need for traditional currencies, which hold a marginal role in the crypto space.[21] In this context, it becomes evident that stablecoins could introduce risks to financial stability through various contagion channels unless a regulatory framework is established. These channels include: (i) financial sector exposures; (ii) wealth effects; (iii) confidence effects; and (iv) the extent of crypto-assets' use in payments and settlements (Adachi et al., 2022; Financial Stability Board, 2023). Beyond financial stability, stablecoins present challenges and risks in areas such as consumer protection, taxation, cybersecurity, money laundering, terrorism financing, market price manipulation, and legal certainty. The potential for certain stablecoins to achieve substantial international scale in the future raises concerns related to domains such as monetary sovereignty and monetary policy. Exemplifying these concerns, BlackRock disclosed "exposure to stablecoin risks" on its spot BTC ETF: "a large portion of the digital asset market still depends on stablecoins such as USDT and USDC, there is a risk that a disorderly de-pegging or a run on USDT or USDC could lead to dramatic market volatility in digital assets more broadly" (Barbosa, 2023).

To address the various challenges associated with the increasing prevalence of stablecoins and the dominant role of centralized exchanges, as depicted in Figs. 5 and 6, governments around the world are proposing diverse regulatory frameworks (Asmakov, 2022). An exemplary initiative is MiCA, which stands as the first major jurisdiction globally to introduce comprehensive and tailored rules for the crypto sector. Under MiCA, stablecoins—referred to as "e-money tokens" (EMTs) when linked to the value of a fiat currency or "asset-referenced tokens" (ARTs) otherwise—are mandated to maintain appropriate reserves and adhere to robust governance standards. The regulatory constraints become more stringent as the tokens gain wider usage, with stablecoins not pegged to an EU currency facing an outright ban if they exceed one million transactions per day and EUR 200 million in circulation, as authorities seek to safeguard the euro's status. One of the main consequences of MiCA has been the delisting of Tether's USDT in the EU by various exchanges, such as Crypto.com (Craig, 2025).

[21] Similarly, the growing significance of the stablecoin BUSD within Binance (see Fig. 5) drew the scrutiny of U.S. policymakers for legal reasons. Specifically, in February 2023, the United States Securities and Exchange Commission raised concerns about BUSD being an unregistered security in a Wells notice directed at Paxos—the entity responsible for issuing the stablecoin. The New York Department of Financial Services issued an order instructing Paxos to cease the issuance of BUSD.

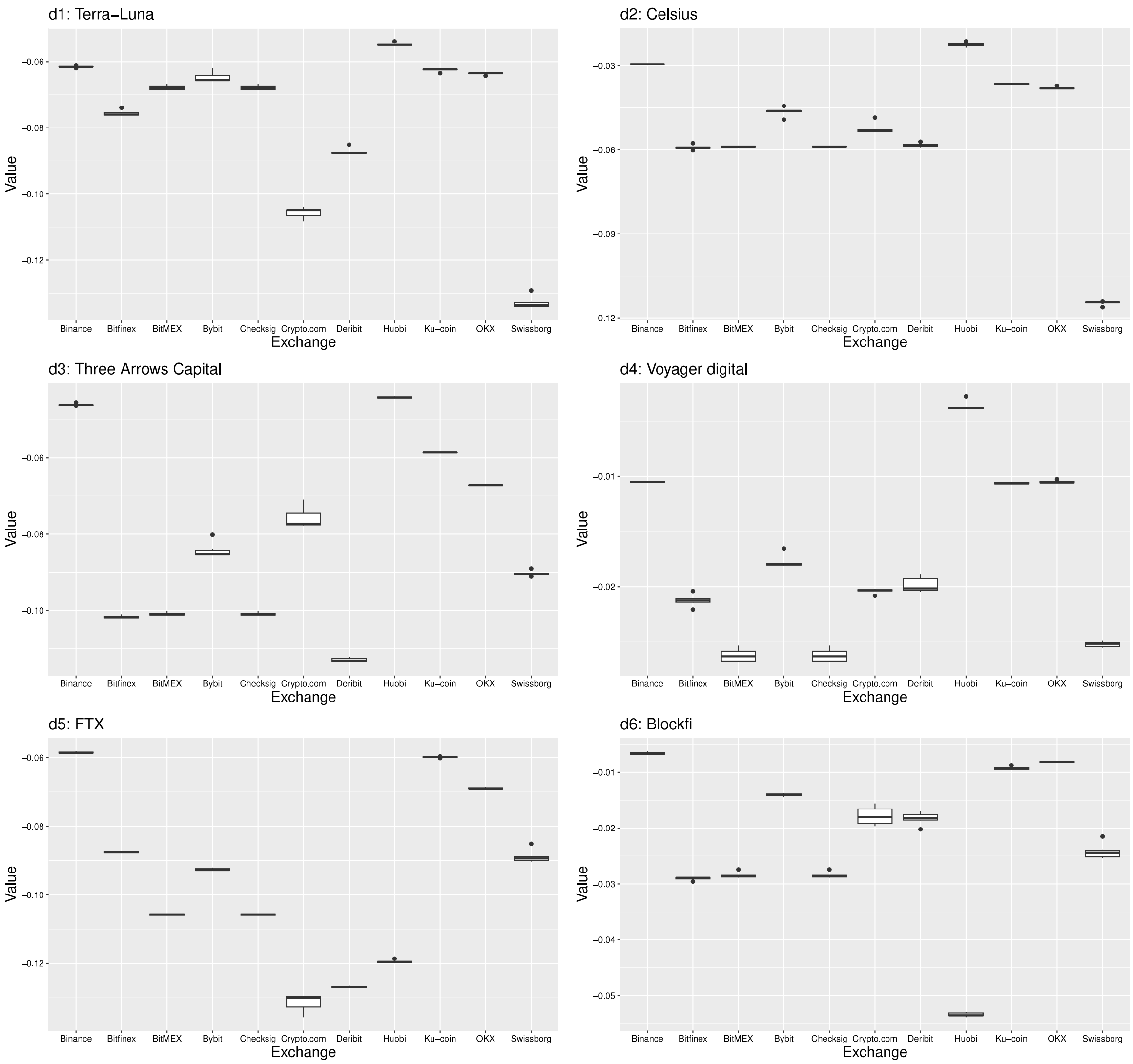

Fig. 1. GARCH-type variant results based on the selected negative events (d) in 2022. The boxplot includes the dummy estimates obtained using GARCH, EGARCH, IGARCH, APARCH, CGARCH, and GJR variants. The dummy variables are included for the exact day on which the events occurred, i.e., Period [0].

In this subsection, we empirically demonstrate the significance of stablecoins through a case study and highlight the need for global regulatory frameworks similar to MiCA. This is due to the potential negative effects that stablecoin depegging and the collapse of stablecoin issuers could have on centralized exchanges and the crypto ecosystem as a whole.

As shown in Fig. 3, the results observed for MVaR can be linked to the proportion of stablecoins held by the exchanges. Notably, Binance and KuCoin demonstrate greater resilience among the centralized exchanges, primarily due to their substantial holdings of stablecoins. Given their nature, stablecoins are stable cryptocurrencies that mainly fluctuate around 1 USD. Consequently, during the emergence of negative shocks that lead to a price decline in all cryptocurrency prices, stablecoins tend to stay near the 1 USD level. This characteristic implies that the presence of significant stablecoin deposits within a given exchange helps mitigate the overall negative impact on the centralized exchange. Nevertheless, stablecoins could also have an adverse effect on the overall value of assets held by exchanges in two scenarios: (i) when users withdraw their deposits in stablecoins, and (ii) in the event of a stablecoin depegging and collapse, as exemplified by the Terra-Luna case.

The results observed in the previous sections imply that, in the case of Binance and KuCoin, stablecoins do indeed mitigate the negative shock on the total value of the assets held without experiencing significant withdrawals in stablecoins. However, at the same time, stablecoins in these exchanges can be considered a double-edged sword. The large deposits of stablecoins could improve the resilience of the system during times of stress; however, if stablecoins were to collapse, the centralized exchange could immediately suffer a significant negative impact. In other words, paradoxically, the most resilient exchanges could become the most unstable overnight due to the large deposits in stablecoins. To support these statements, we create a hypothetical scenario

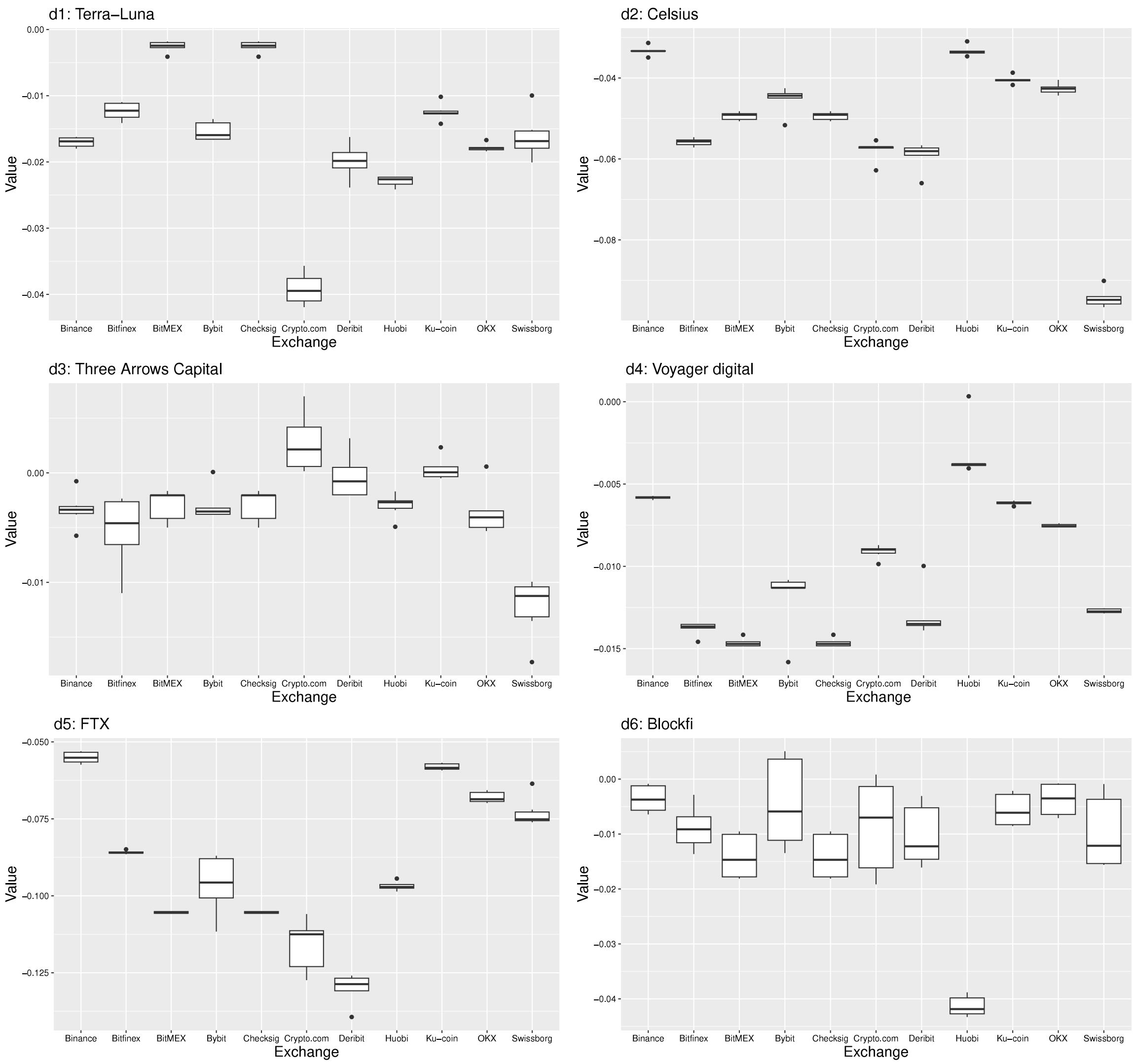

Fig. 2. GARCH-type variant results based on the selected negative events (d) in 2022. The boxplot includes the dummy estimates obtained using GARCH, EGARCH, IGARCH, APARCH, CGARCH, and GJR variants. The dummy variables are included, considering the day before, the specific day of the events, and the day after, i.e., Period [−1,1].

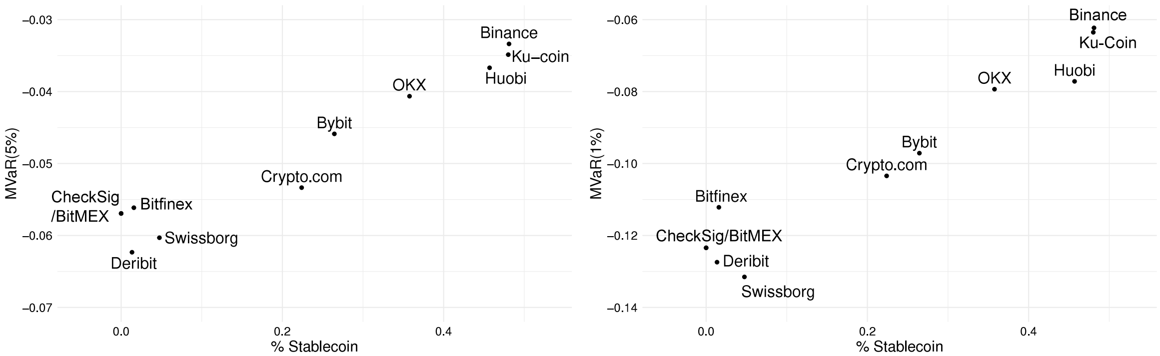

Fig. 3. Scatter plots reporting the relationship between the proportion of stablecoin on centralized exchanges since 2022 and MVaR (5%) & MVaR (1%) values.

Table 16
AR-GARCH results based on a scenario in which all stablecoins simultaneously depeg from their $1 USD peg to $0.7, $0.5, $0.3, and $0.1 at the end of our sample period.

Depeg	Binance	Bitfinex	BitMEX	Bybit	Checksig	Crypto.com	Deribit	Huobi	Ku-coin	OKX	Swissborg
$0.7	−0.1396***	−0.0093	0.0012	−0.1829***	0.0012	−0.0458***	−0.0073	−0.0185	−0.1535***	−0.1329***	−0.0176
$0.5	−0.2719***	−0.0189*	0.0012	−0.3555***	0.0012	−0.0906***	−0.0149	−0.0371***	−0.2986***	−0.2584***	−0.0372**
$0.3	−0.4727***	−0.0333***	0.0012	−0.6175***	0.0012	−0.1585***	−0.0264	−0.0652***	−0.5191***	−0.4490***	−0.0671***
$0.1	−0.9045***	−0.0645***	0.0012	−1.1809***	0.0012	−0.3045***	−0.0511***	−0.1258***	−0.9932***	−0.8587***	−0.1313***

in which all stablecoins held by the exchanges lose their parity with the US dollar on the same day. More specifically, at the end of our sample, we add a new day during which all stablecoins depeg from their $1 USD peg to $0.7, $0.5, $0.3, and $0.1. This hypothetical day/event is included as the only dummy variable in the AR-GARCH framework to analyze the effect of simultaneous stablecoin depegging on centralized exchanges. The impact on portfolio log returns is shown in Table 16. Here, we see that Bybit, KuCoin, OKX, and Binance could experience losses greater than 0.80 in the worst scenario, with a depeg from $1 USD to $0.1.[22] The other exchanges would experience a lesser impact due to their lower concentration of stablecoins at the end of our sample period.

These findings demonstrate that stablecoin depegging can have severe negative consequences on centralized exchanges, affecting their liquidity, trading stability, and overall market confidence. Given that stablecoins account for a significant share of crypto trading volume, any failure in their underlying mechanisms or mismanagement by issuers could lead to market disruptions, withdrawal suspensions, and even exchange insolvencies. These risks reinforce the necessity of global frameworks similar to MiCA to ensure stablecoin transparency, proper reserve backing, and consumer protection. By implementing standardized regulations worldwide, policymakers could mitigate systemic risks, prevent fraudulent or poorly managed stablecoin models, and enhance financial stability within the crypto ecosystem. As observed in the EU's regulatory approach, requiring full reserve backing, redemption guarantees, and strict oversight would help prevent incidents like the collapse of Terra's UST or potential liquidity crises in major centralized exchanges. Therefore, our results align with the argument that a global adoption of MiCA-like regulations is essential to safeguarding financial stability in the crypto market.

5. Limitations

In this paper, we examine the stability of centralized exchanges through an empirical analysis of proof-of-assets. However, as explained in Section 2, the dataset used in this study covers approximately 66.89% of the total assets held by the exchanges. In other words, a key limitation of our analysis is the lack of data for 33.11% of the assets held by centralized exchanges. This limitation is particularly relevant for Binance, Huobi, and KuCoin, which have a lower representation in our dataset. We would also like to clarify that our dataset includes only BTC and ETH tokens. Therefore, the limited scope of the dataset may be due to the absence of data on other tokens held by the exchanges, and should not be interpreted as a lack of transparency or unwillingness by the exchanges to disclose their holdings. Consequently, the reliability and accuracy of our results may be affected due to the incomplete data used in constructing the portfolios. However, this does not diminish the significance of our findings. In fact, the observation that Binance, Huobi, and KuCoin initially appear to be the most resilient exchanges under traditional financial methodologies is likely linked to their holdings of stablecoins, as previously demonstrated, as well as the absence of complete data. This highlights the importance of implementing frameworks that enable policymakers to identify and analyze exchange asset compositions. In cases where data is not fully disclosed, policymakers should implement precautionary measures by requiring additional safeguards.

At this point, a fundamental question arises: from a trust perspective, which exchange is more secure and stable? If a user's primary focus is investing in BTC and they place significant importance on trust, they may find BTC-only exchanges that fully disclose their assets to be more suitable than multi-asset exchanges with incomplete asset disclosure.[23]

We also believe that the recommended additional reserve requirements of 6% to 14% remain a robust result, given that our dataset provides a strong representation of assets for the remaining exchanges. This recommendation could still be applicable to exchanges for which we lack complete data. Policymakers may even consider requiring exchanges that do not fully disclose relevant information to implement the maximum reserve requirement suggested by our empirical study, i.e., 14%.

On the other hand, this paper may be subject to survivorship bias, as we are only able to analyze active exchanges while neglecting failed ones, such as FTX. The asset composition and empirical outcomes of these failed exchanges could differ significantly from those of the active exchanges represented in this study. However, it is important to highlight that the lack of asset disclosure is one of the key reasons why the scientific community was unable to identify bad practices in these exchanges at an earlier stage. In fact, a robust proof-of-solvency framework could have flagged FTX's mismanagement, given the large proportion of its native exchange token on its balance sheet. In other words, if data had been available for failed exchanges, we likely would have been able to identify clear signs of mismanagement.

[22] Given that we are using the last day of our sample, Bybit could suffer a more severe impact due to its higher concentration of stablecoins on March 1, 2023. Similarly, the lesser impact on Huobi is associated with its lower concentration of stablecoins at the end of our sample period (see Fig. 6).

[23] If the exchange is not misusing the assets that are not disclosed, we believe that a large holding in stablecoins is the main factor reducing the risk of exchanges when using traditional financial methodology. Indeed, if the undisclosed assets behave similarly to the average cryptocurrency, we should observe the same results. However, if there is mismanagement and the assets are lost, then incomplete data becomes the most relevant concern.

Despite the absence of data on failed exchanges, we believe that our findings remain relevant for future inferences, as we are still analyzing the largest exchanges in the centralized market. As mentioned in Section 2, our sample of 11 active exchanges accounts for 65.31% of the total trading volume in the CeFi system. Given that these are the most widely used exchanges by cryptocurrency traders, our results provide valuable insights into the overall stability of the market and can help shape future regulatory frameworks and risk management strategies.

Finally, we are unable to conduct an empirical analysis matching liabilities and assets. Since liabilities are generally not disclosed by centralized exchanges, such an analysis is not feasible. Indeed, as explained in Appendix A.1, validating proof-of-liabilities is far more complex than proof-of-assets, as merely disclosing liabilities is not sufficient. To ensure that liabilities do not exceed assets, the role of auditors and user self-verification is crucial.

6. Conclusion

This paper examined the stability and risk structure of centralized exchanges under stress conditions. Using an AR-GARCH event study and MVaR estimates, we found that the collapses of FTX and Celsius cause the strongest negative reactions across the ecosystem, followed by the Terra-Luna and Three Arrows Capital events. Binance and KuCoin display relatively high resilience, although this is partly linked to large stablecoin holdings. Stablecoins in these exchanges can be considered a double-edged sword, given that large deposits held in the exchange may improve the resilience of the system during times of stress; however, if stablecoins were to collapse, the centralized exchange would immediately face a significant negative impact. Based on our risk estimates, exchanges should consider holding additional reserves between 6% and 14%, depending on their exposure and balance sheet structure, to mitigate the impact of future shocks.

In parallel, our analysis of asset composition revealed significant heterogeneity across exchanges. BTC-only platforms such as BitMEX and CheckSig concentrate risk in a single asset and internal management. In contrast, multi-asset exchanges expose users to a wider set of risks, including altcoins of varying quality, stablecoins, and other third-party services. Stablecoins now represent a major component of exchange portfolios, sometimes surpassing BTC and ETH, which increases users' dependence on the reliability and governance of external issuers. These differences affect not only investment risk, but also the trust structure users must navigate when engaging with these platforms. MiCA's regulatory framework has taken initial steps to address these concerns by requiring both stablecoin issuers and exchanges to adopt transparency and risk-control measures.

A central contribution of this study is to frame these dynamics through Shapiro's theory of impersonal trust. In centralized exchanges, users are not merely transacting with a platform, but engaging with a layered structure of interdependencies that demand trust in multiple agents and mechanisms. When users deposit funds, they are required to trust not only the exchange's management, but also stablecoin issuers, third-party custodians, token governance models, and the overall solvency infrastructure. This constitutes a chain of impersonal trust—a structure in which institutional safeguards must substitute for direct control or personal accountability. The collapse of Terra-Luna and its cascading effects on Celsius and FTX illustrate how fragility in one node of this chain can generate systemic consequences. In the absence of clear, verifiable disclosures, users operate within a black-box environment that undermines trust, transparency, and accountability. Shapiro's framework suggests that these are not merely individual management failures, but symptoms of deeper weaknesses in the institutional structures designed to generate trust in complex financial systems.

While mechanisms like proof-of-assets, proof-of-reserves and proof-of-solvency are emerging responses to this challenge, they are not sufficient in isolation. These tools offer partial verification of asset holdings but do not account for off-chain liabilities, poor governance, or the risk characteristics of held assets. A key insight of this study is that the examination of asset composition is indispensable. Even an exchange that fully satisfies proof-of-reserves criteria may be vulnerable if its portfolio consists of illiquid, volatile, or low-quality tokens such as meme coins, native tokens, or unbacked stablecoins. Any meaningful assessment of solvency must therefore go beyond asset quantity to include asset quality.

To improve the structural reliability of CeFi and reduce dependence on opaque trust relationships, two key actions are necessary. First, centralized exchanges must provide regular, verifiable disclosures of both on-chain and off-chain asset holdings, and offer greater transparency regarding their governance, ownership, and risk controls. Second, regulators must adopt comprehensive frameworks that extend beyond exchanges to include stablecoin issuers, lending platforms, and other critical actors in the crypto infrastructure. MiCA provides a foundational framework for such regulation, offering a set of mandatory, sector-specific rules that directly address the vulnerabilities identified in this paper. Together, these steps would strengthen institutional credibility and help shift the crypto ecosystem toward a more accountable model of impersonal trust.

This study proposes several directions for future research. One particularly promising direction involves analyzing the correlation dynamics between the assets held by centralized exchanges as a measure of financial risk. We conjecture that (i) significant correlation jumps may signal major shocks affecting an exchange, and (ii) exchanges with persistently high asset correlations over time could be more susceptible to bank runs. A dynamic time-series analysis of these correlations could provide real-time insights into the overall state of the crypto market. Periods of stable high correlation, for instance, might indicate synchronized movements across cryptocurrencies due to broader market stress. Understanding these patterns could help policymakers and exchange managers implement risk-mitigation strategies during periods of heightened systemic risk, such as increasing reserves, reducing leverage, or implementing additional risk-mitigation strategies. This future line of research underscores the importance of proof-of-assets data disclosure by exchanges, which could provide policymakers and researchers with deeper insights into the stability of centralized exchanges.

Acknowledgments

The author acknowledges the financial support from the Margarita Salas contract MGS/2021/13 (UP2021-021) financed by the European Union-NextGenerationEU, and the financial support from Generalitat Valenciana, Spain under the project CIGE/2022/132.

Appendix

A.1. Overview of proof-of-solvency mechanisms

In recent years, exchanges have been working toward establishing solvency proofs to build trust among users. This also involves minimizing the disclosure of additional information that could compromise client data, thereby preserving the characteristics of (pseudo)-anonymity. Unavoidably, in response to the bankruptcy cascades during 2022, we now observe a noticeable increase in the demand for standardizing proof-of-solvency within the digital assets industry, which also includes proof-of-assets, proof-of-liabilities, and, therefore, proof-of-reserves (Chalkias et al., 2020, 2022; Buxton et al., 2022).

A.1.1. Proof-of-reserves: proof-of-assets & proof-of-liabilities

Acting as guardians of trust, centralized exchanges facilitate user deposits through methods such as bank transfers or other conventional means. These exchanges retain users' private keys and offer authentication through usernames and passwords to verify the customer's identity. Additionally, they provide recovery options in case customers forget or lose their authentication details. Consequently, users are relieved from the responsibility of storing private keys for their cryptocurrencies in exchange for a user-friendly interface that facilitates cryptocurrency trading. However, there is a potential risk of loss of customer assets managed by exchanges.

The platform's digital assets, which are based on blockchain technology, are relatively easy to verify in terms of quantity and ownership. To report proof-of-assets, the exchange simply has to consistently disclose the complete list of digital asset addresses under its control—mainly cold storage wallet addresses. As a result, any external party can track the balances of coins and tokens within these addresses reported by the exchange by aggregating the amounts visible at a specific block height (Pines et al., 2022). More specifically, the existence and ownership of digital assets can be verified through cryptographic signatures, send-to-self transactions, hierarchical deterministic wallets, multi-signature wallets, and/or secure multi-party computation.

However, proof-of-assets is only one aspect of the equation, as stated by Carter (2022a). Simply verifying the existence and ownership of a certain amount of assets held by exchanges is not enough on its own. In the interest of transparency and customer protection, exchanges must (i) demonstrate existence and ownership of client assets and (ii) present outstanding liabilities owed to clients, in the form of deposits (Carter, 2022b). The former refers to proof-of-assets, while the latter constitutes proof-of-liabilities. Proof-of-reserves is the outcome obtained by applying both processes.

In contrast to demonstrating proof-of-assets, validating proof-of-liabilities is more challenging, primarily due to the increasing prevalence of fraud and mismanagement. As illustrated by Buxton et al. (2022), if a digital asset platform has incurred a loss or if management is engaged in fraudulent activities, there may be an inclination to under-report liabilities. This tactic is employed to create the illusion that the digital asset platform is fully reserved. As a result, it is imperative for both the scientific community and the industry to identify a method that ensures the inclusion of customers' deposits in the exchange balance. The primary objective of proof-of-liabilities is, indeed, to demonstrate the amount of funds a centralized exchange owes to its customers, while preserving privacy.

Recently, decentralized solutions (Wilcox, 2014; Hu et al., 2019; Chalkias et al., 2019; Camacho, 2014; Dagher et al., 2015; Chalkias et al., 2020; Ji and Chalkias, 2021; Buterin, 2022; Buterin et al., 2023) have been proposed as an alternative or supplementary approach to traditional auditing in the crypto space. These solutions involve customers actively participating in the auditing process, reducing reliance on auditors. Decentralized auditing is considered more promising because it enables customers to verify their own balances, addressing a limitation of centralized auditing. Existing schemes generally follow a similar principle: a prover aggregates user balances using an accumulator, and consumers can then verify the inclusion of their balances in the reported total (Ji and Chalkias, 2021). The technical details of these schemes are presented in the Appendix, Appendix A.2. However, irrespective of the chosen scheme, the involvement of auditors remains crucial in the proof-of-reserves process, particularly in the stages of proof-of-assets and proof-of-liabilities. In essence, the audit procedure should at least encompass (i) an initial audit analysis and (ii) independent consumer verification (Bitpanda, 2022), conditional on the exchange's activities. The third-party auditor initiates the process by generating a snapshot of the crypto company's liabilities, representing the total customer deposits. Additionally, the auditor verifies the ownership of the company's crypto assets, wherein the company provides a digital signature from the private keys corresponding to all its addresses. Ultimately, the auditor ensures that the amount of assets surpasses the number of liabilities. In the subsequent stage, exchanges must consider independent customer verification to enhance transparency and assure customers that their accounts are included in the liabilities covered by the held assets.[24,25]

[24] To achieve this, the exchange constructs a Merkle tree where each customer account serves as a leaf. The auditor verifies that the Merkle tree encompasses all liabilities and provides each customer with their leaf information and a means to verify the path from their leaf to the Merkle root.

[25] The necessity for an external auditor should be contingent upon the complexity inherent in the exchange platform. In instances where the platform deals with multi-assets or intricate financial products within the crypto ecosystem (such as yield farming, staking, derivatives), the complexity could compel the exchange to engage an auditor for a more thorough analysis. This is because a proof-of-reserves procedure alone might not provide sufficient assurances to customers in such intricate financial scenarios.

As the reader can observe, aligning with Carter (2022a,b), proof-of-reserves implicitly incorporates proof-of-assets and proof-of-liabilities in the process, making it challenging to completely isolate an individual part from the whole. It is also important to note that all these processes are executed on-chain, meaning assets or liabilities outside the blockchain are not considered, as they are included in the proof-of-solvency stage.

A.1.2. Proof-of-solvency

Proof-of-solvency involves a more comprehensive concept, taking into consideration not only proof-of-reserves (on-chain assets and liabilities) but also the company's assets and liabilities beyond the distributed ledger and any other factors that might affect its proper function in the future. In other words, proof-of-solvency offers insights into the overall financial health of the centralized exchange. Conversely, the primary objective of proof-of-reserves is to demonstrate on-chain that customer liabilities are either less than or equal to the assets held by the exchanges on behalf of customers (Buxton et al., 2022). Therefore, proof-of-reserves alone does not guarantee the solvency of the exchange or address the risks tied to its assets and liabilities. Even if an exchange demonstrates that the value of its assets is equal to or greater than its liabilities, insolvency could still occur due to external shocks or spillover effects affecting its assets. For instance, a cryptocurrency entity with Terra-Luna tokens in its possession could have undergone a bank run or faced bankruptcy due to its association with this ecosystem, even if its assets were valued higher than its liabilities before the Terra-Luna collapse.

The proof-of-solvency requirements for a digital asset platform providing services across various crypto-assets should significantly differ from those applicable to a platform exclusively offering institutional investor services for specific assets, such as BTC. A proof-of-solvency approach should encompass the evaluation of assets and liabilities held by the exchange, considering their potential impact on the entity's future solvency.

A.2. Proof-of-reserves schemes

In 2013, BTC developer Greg Maxwell explored schemes for establishing proof-of-reserves, particularly discussing the "merkleized approach" to address this issue. In the same discussion, Maxwell explains how aggregating hashed user information in a Merkle tree could allow users on a digital asset platform to efficiently confirm their membership in the set without exposing themselves to the entire contents of the liability set. Maxwell acknowledges that while this process would not prevent fractional reserve or theft, it could discourage the covering of thefts, act as a preventive measure against prolonged fraudulent activities and detect platforms that were insolvent for a long period of time.

Expanding on these discussions, in February 2014, Wilcox (2014) formalized the ideas proposed by BTC developers Greg Maxwell and Peter Todd, with a specific focus on the proof-of-liabilities concept and a detailed exploration of the Merkle approach. Wilcox (2014) proposed a summation Merkle tree construction to prove total liabilities. Merkle trees serve as a data structure that allows a set owner to demonstrate the inclusion of an element in the set with efficiency. In their construction, each participant is depicted by a leaf node within the tree, aligning with the squares in the bottom row (e.g, 1, 2, 3, 4), as illustrated in Fig. 4. The branches, or internal nodes (e.g., 5, 6), are utilized to reach the root, integrating information from the leaf nodes while safeguarding privacy. In the Merkle tree, each node contains a hash field (h) and a value field (v). The v_{root} denotes the total liabilities, representing the collective deposits of consumers on the platform. Furthermore, v_5 and v_6 indicate the sums of values in their respective child nodes, specifically v_1–v_2 and v_3–v_4, which reflect the deposits of individual customers. For the hash field, Maxwell-Todd includes the value field and the hashes of child/leaf nodes at hashing, e.g. $h_5 = H(15\|h_1\|h_2)$. For each leaf node mapped to a user, the hash value is the SHA256 (a common cryptographic hashing algorithm) digest of the concatenated (i) users' deposit v, (ii) user information ui (e.g. Alice) and (iii) and a random "nonce", i.e., $h = H(v\|ui\|nonce)$.[26] Through the application of a hash summary function, the Merkle tree enables users to verify their inclusion in the complete tree. Users are unable to reconstruct the entire tree from their partial information unless they acquire more than half of the total number of users (Bybit, 2022).

Nevertheless, this scheme presents a relevant issue, as it allows the exchange to claim lower liabilities while still generating inclusion proofs and effectively responding to user queries (Chalkias et al., 2022). Furthermore, the public disclosure of the total liabilities value enables anyone to deduce both the population and individual liabilities through a series of inclusion proofs. To address the issues presented by the original Merkle tree proposal, authors have introduced supplementary schemes or modifications to offer exchanges and users more appropriate approaches. Readers can find a comprehensive description of these schemes in Ji and Chalkias (2021).

Hu et al. (2019) [Maxwell+] addresses the vulnerability of underreporting liabilities by directly modifying each node field to include both values and hashes of child nodes. This adjustment securely ties the value of each node to its parent, preventing the manipulation of the tree. However, it is crucial to highlight that this scheme does not rectify the privacy concerns. In the work presented by Chalkias et al. (2019) [Maxwell++], an extension of Maxwell+, the concealment of both population and individual liabilities is achieved. This is accomplished through the fragmentation and shuffling of values into smaller units. However, it is essential to note that despite these privacy enhancements, the total liabilities of the exchange are still observable. In Camacho (2014) [Camacho], privacy of liabilities is achieved by substituting the values in Maxwell–Todd with Pedersen commitments

[26] The nonce serves as a one-time random number employed as a privacy-preserving measure, akin to the use of salt in password encryption. Its role is to guarantee that customers cannot deduce information about other nodes along their path to the Merkle root. The nonce should only be accessible to both the digital asset platform and the respective customer.

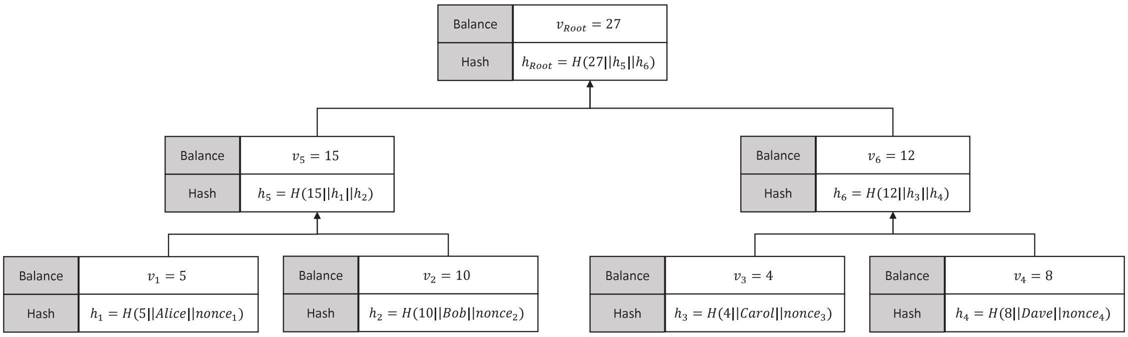

Fig. 4. Example of Merkle tree following Chalkias et al. (2022).

accompanied by zero-knowledge range proofs. The hiding and binding properties of Pedersen commitments ensure privacy while preventing manipulation of liabilities, and their homomorphic properties allow summation in commitments. Total liabilities can only be disclosed through voluntary commitment opening, or alternatively, the exchange can prove the range of total liabilities using zero-knowledge proofs. In short, Camacho (2014) ensures the privacy of individual and total liabilities but does not extend this privacy protection to the number of users. Additionally, it does not rectify the security flaw present in Maxwell–Todd's summation Merkle tree. In Chalkias et al. (2020) [DAPOL] and Ji and Chalkias (2021) [DAPOL+], enhancements to Camacho are introduced by incorporating the proposed fix from Hu et al. (2019) and implementing sparse Merkle trees (SMT) for a more efficient concealment of the number of users.

In Dagher et al. (2015) [Provisions], the protection of liability privacy is achieved through the utilization of homomorphic commitments and zero-knowledge proofs, omitting the use of a Merkle tree. The prover publishes commitments to their liabilities for each user, accompanied by a range proof on the public bulletin board. Each user autonomously verifies the validity of their commitment and associated range proofs. In this scheme, no information about customer holdings is disclosed, and the total liabilities of the digital asset platform remain concealed and secure.

In a recent proposal by Buterin (2022), the utilization of ZK-SNARK technology is suggested to significantly enhance and simplify privacy in proof-of-liabilities protocols. In this approach, all users' deposits are incorporated into a Merkle tree (or, alternatively, a KZG commitment), and a ZK-SNARK is employed to demonstrate that all balances in the tree are non-negative and collectively amount to a claimed value. Adding a layer of hashing for privacy ensures that the Merkle branch (or KZG proof) provided to each user discloses no information about the balance of any other user.

As discussed by Carter (2022b), at present, the prevailing approach used by most of the exchanges in proof-of-liabilities involves the use of the Merkle proof method, where liabilities are revealed only on a per-client basis. This method opens up more possibilities for concealing liabilities (see also Chalkias et al., 2022). However, future advancements may address this limitation through next-generation schemes that leverage zero-knowledge proofs, enabling the disclosure of the complete liability set without compromising privacy.[27]

A.3. Dynamic visualization of portfolio composition

Compared to the static representation of proof-of-assets depicted in Tables 5 and 6 for the centralized exchanges as of March 1, 2023, Figs. 5 and 6 present a dynamic perspective, illustrating the evolution of asset composition over time. Specifically, Fig. 5 displays the absolute value in USD and the weights of individual cryptocurrencies on their respective exchanges over time, while Fig. 6 outlines the progression of USD amounts and weights for each particular cryptocurrency sector on the corresponding exchange. These figures allow us to emphasize two general facts regarding the evolution of proof-of-assets over time.

First, it is noticeable that centralized exchanges experience a surge in popularity toward the conclusion of 2021, aligning with the peak of the cryptocurrency market's last bubble. Second, since 2021, there has been a noticeable increase in the prevalence of stablecoins across various exchanges. Notably, instances involving Binance, Huobi, KuCoin, Bybit, and OKX reveal periods when these platforms hold more than 50% of total customer assets in stablecoins. These two points emphasize the existing literature where policymakers, institutions, and the scientific community underline the necessity to analyze the risks associated with stablecoins and centralized exchanges in the crypto ecosystem (Bullmann et al., 2019; Arner et al., 2020; ECB, 2020; Adachi et al., 2021, 2022; Bank for International Settlements, 2022; Asmakov, 2022; European Council, 2022; Financial Stability Board, 2023; Beau, 2023).

[27] In this paper, we refrain from proposing a definitive solution, recognizing the existence of various options, each with its own set of strengths and weaknesses.

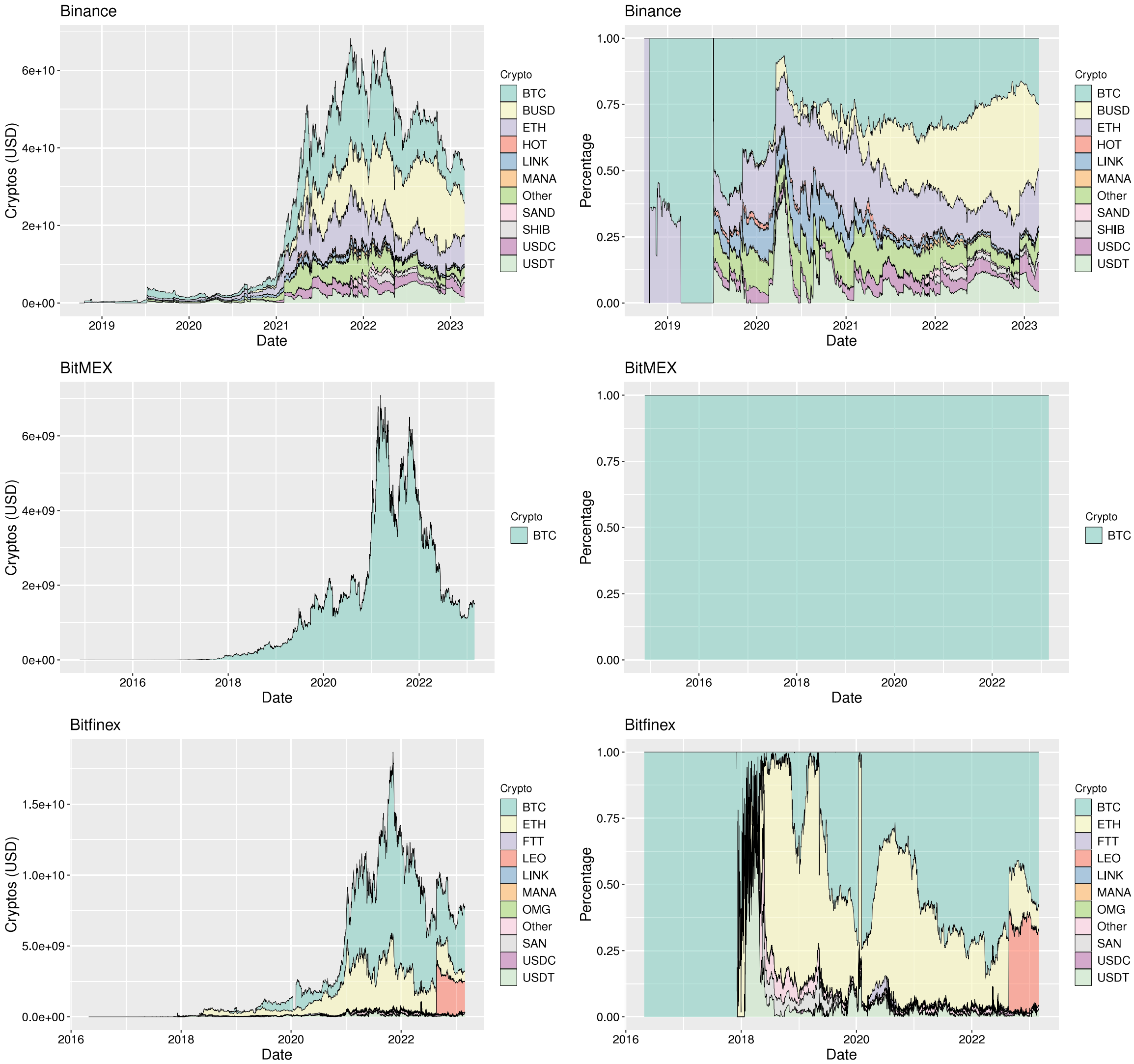

Fig. 5. Proof-of-assets on centralized exchanges, presented in both USD and percentage terms.

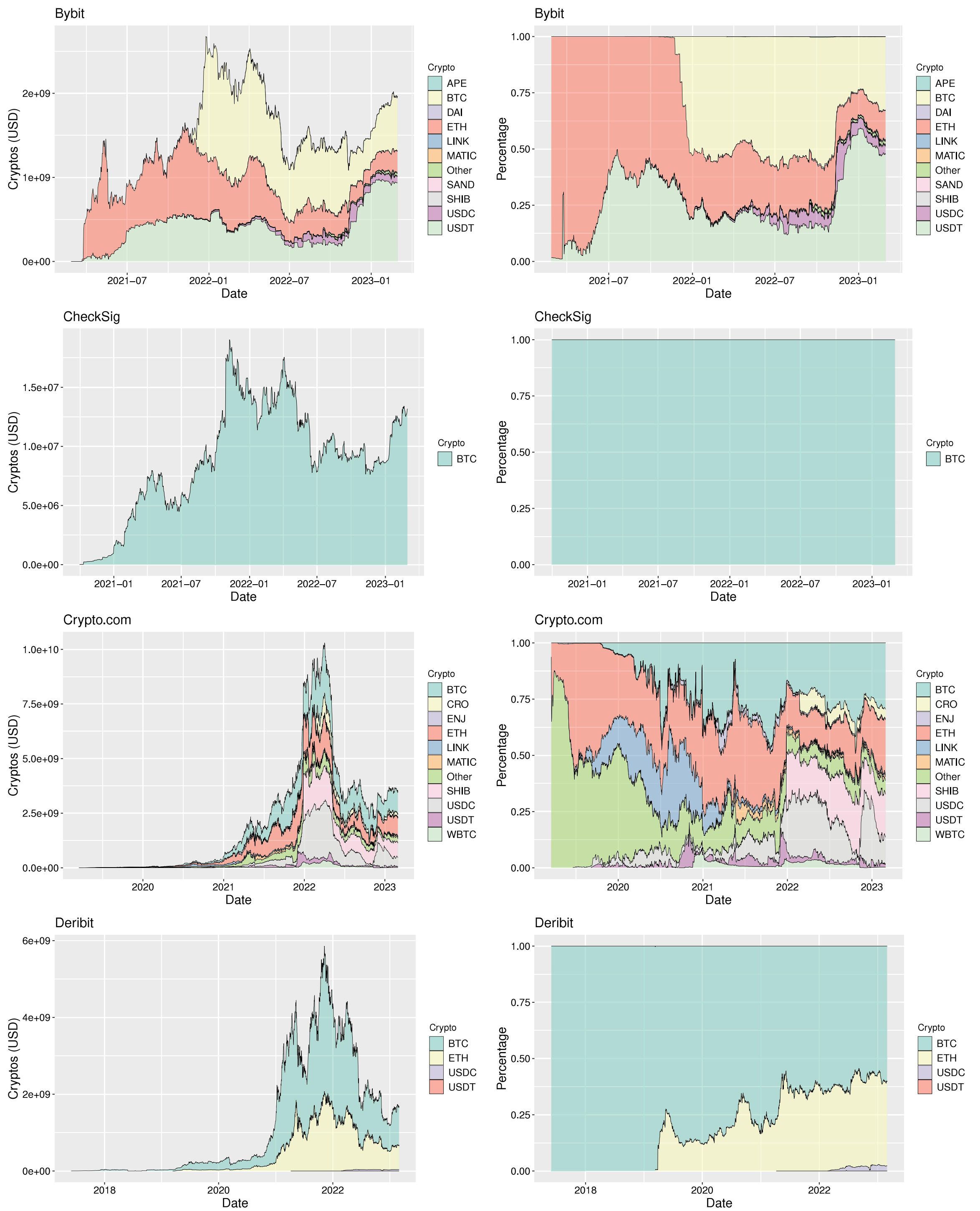

Fig. 5. (*continued*).

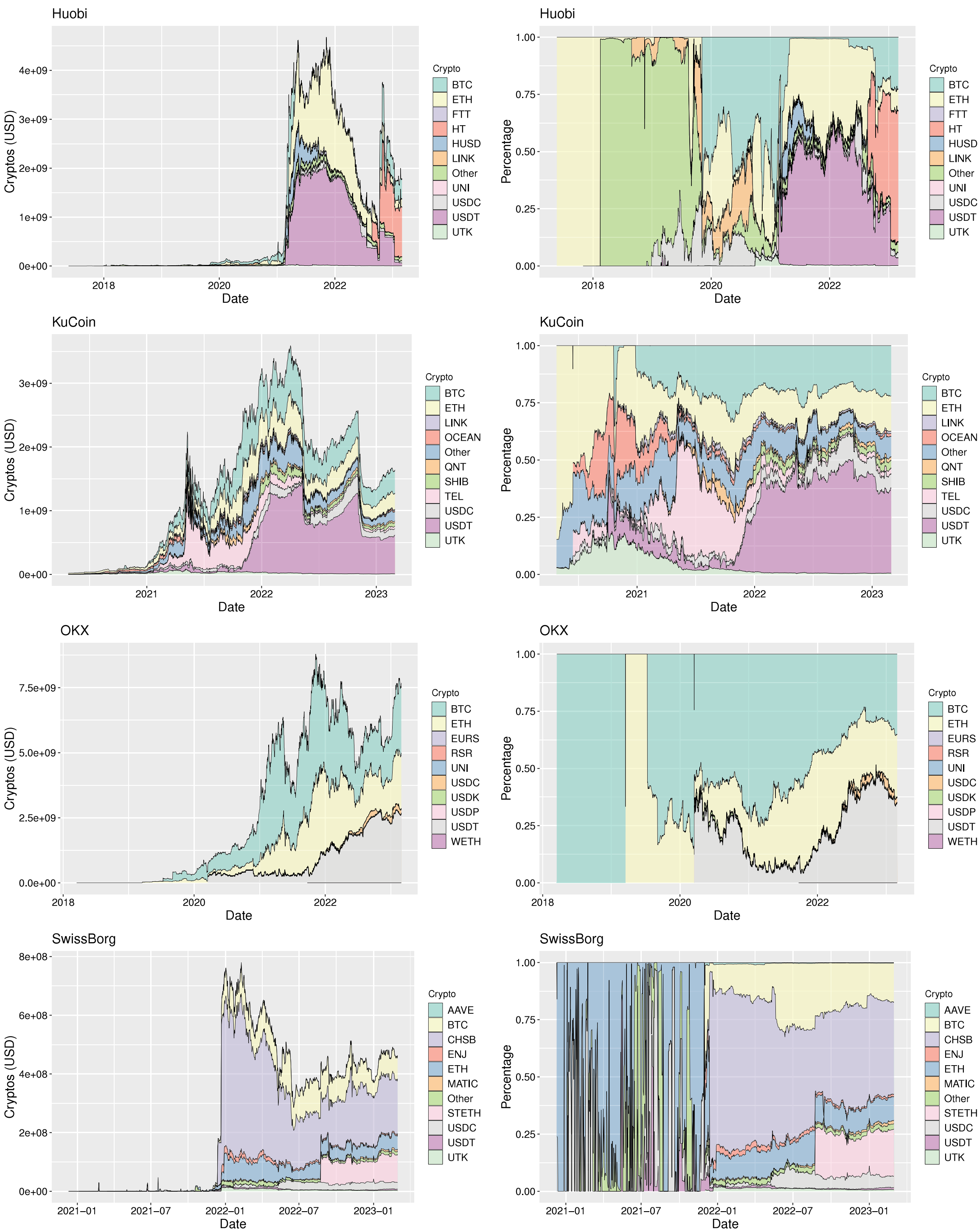

Fig. 5. (*continued*).

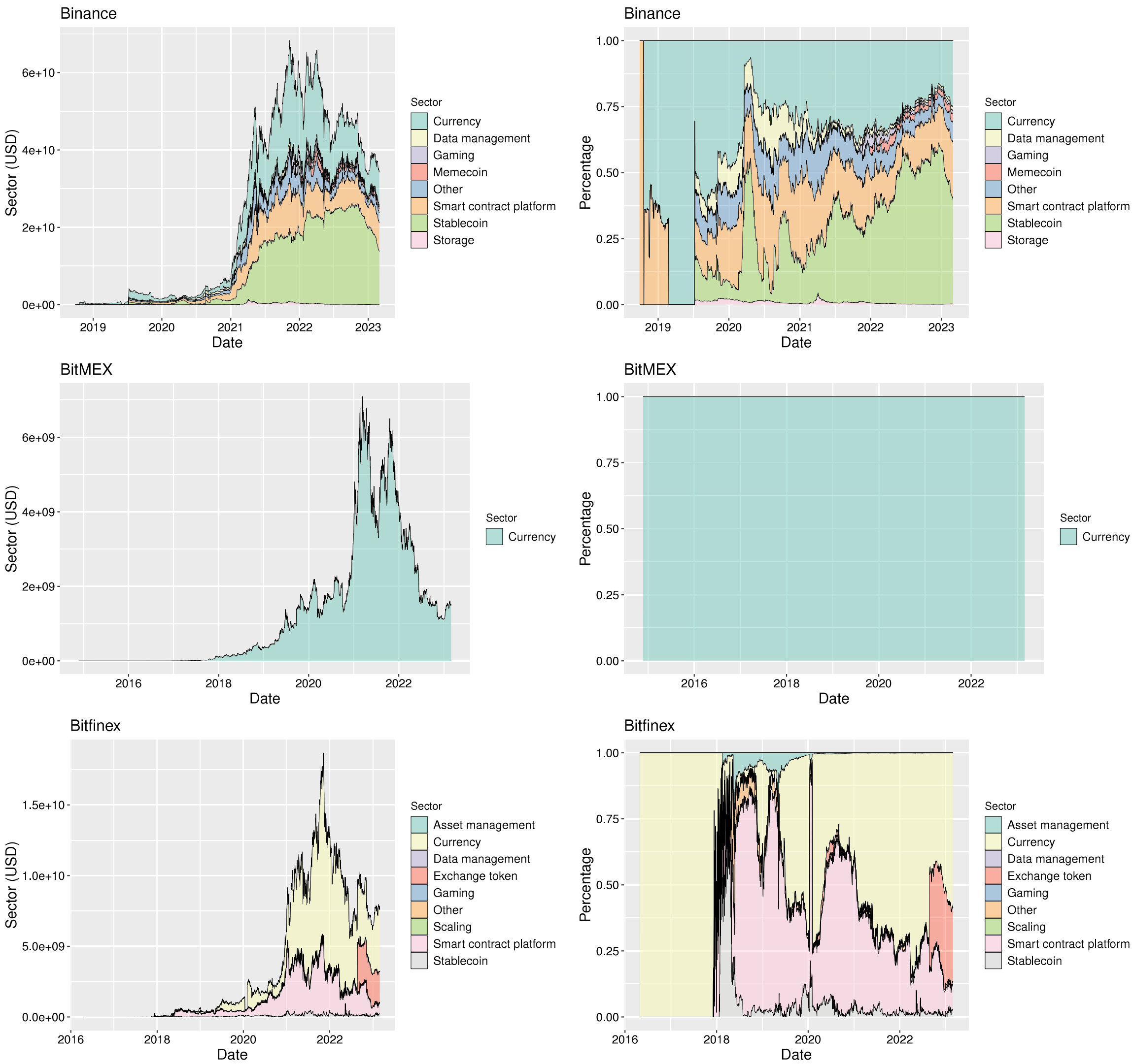

Fig. 6. Proof-of-assets on centralized exchanges, categorized by sector and presented in both USD and percentage terms.

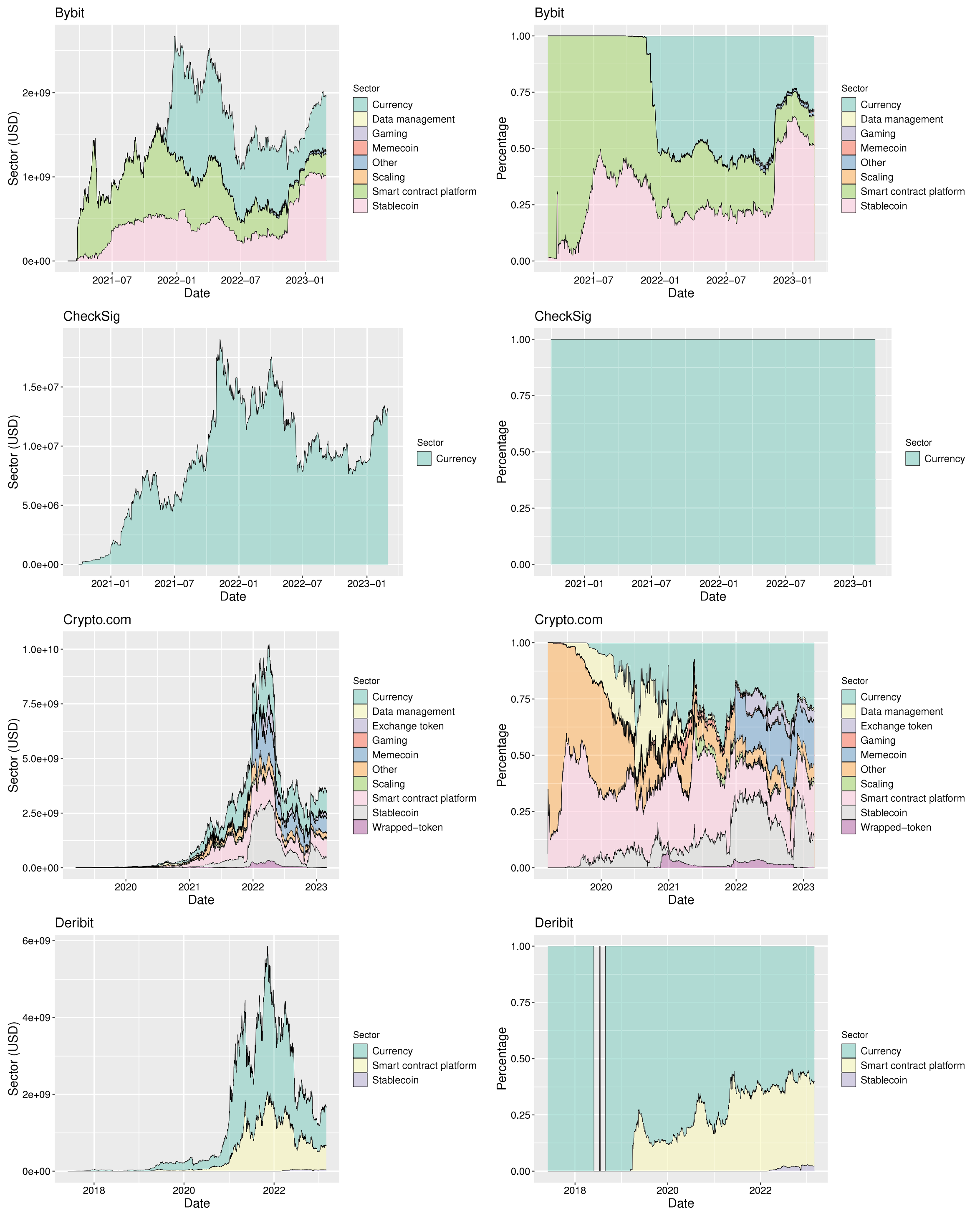

Fig. 6. (*continued*).

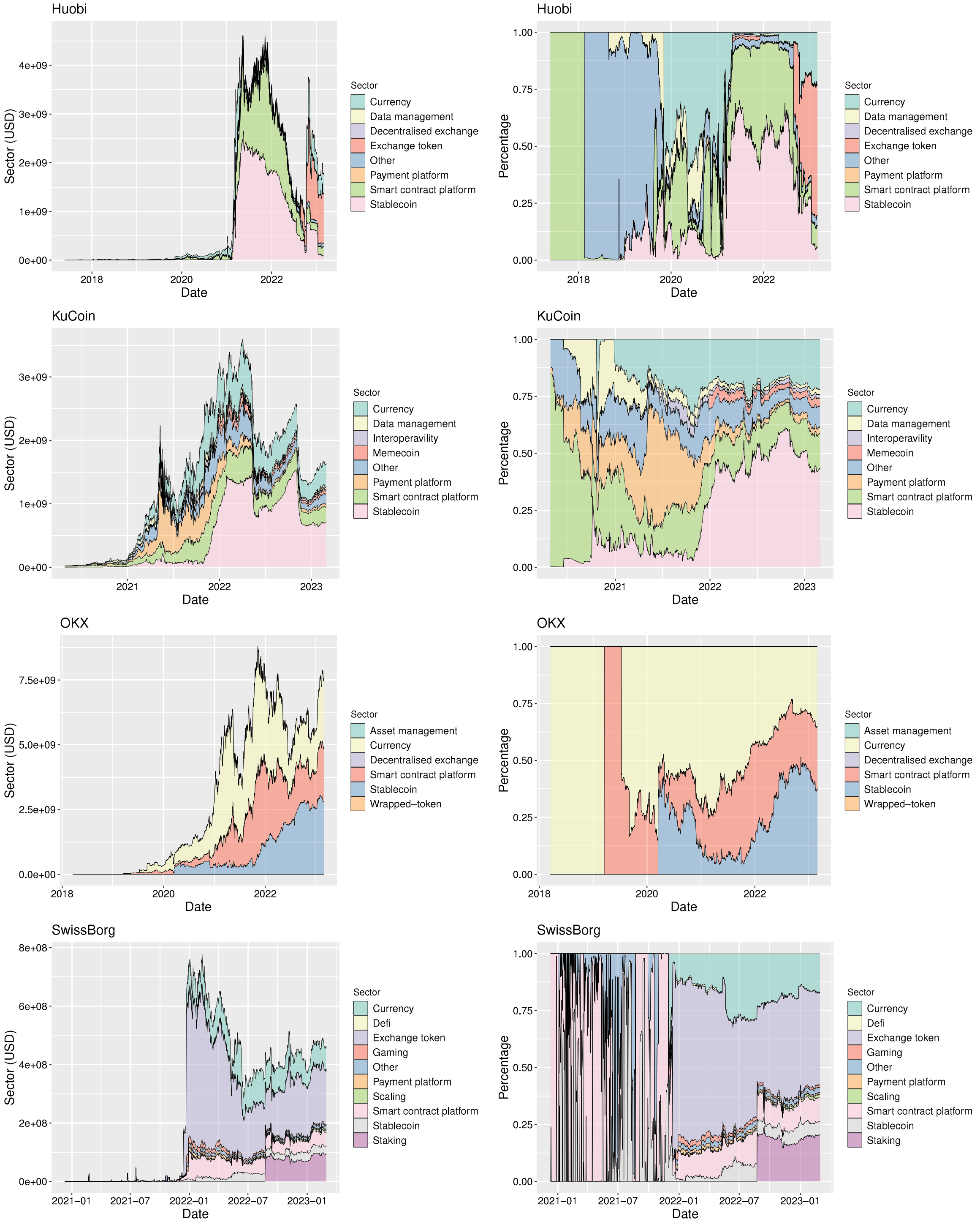

Fig. 6. (*continued*).

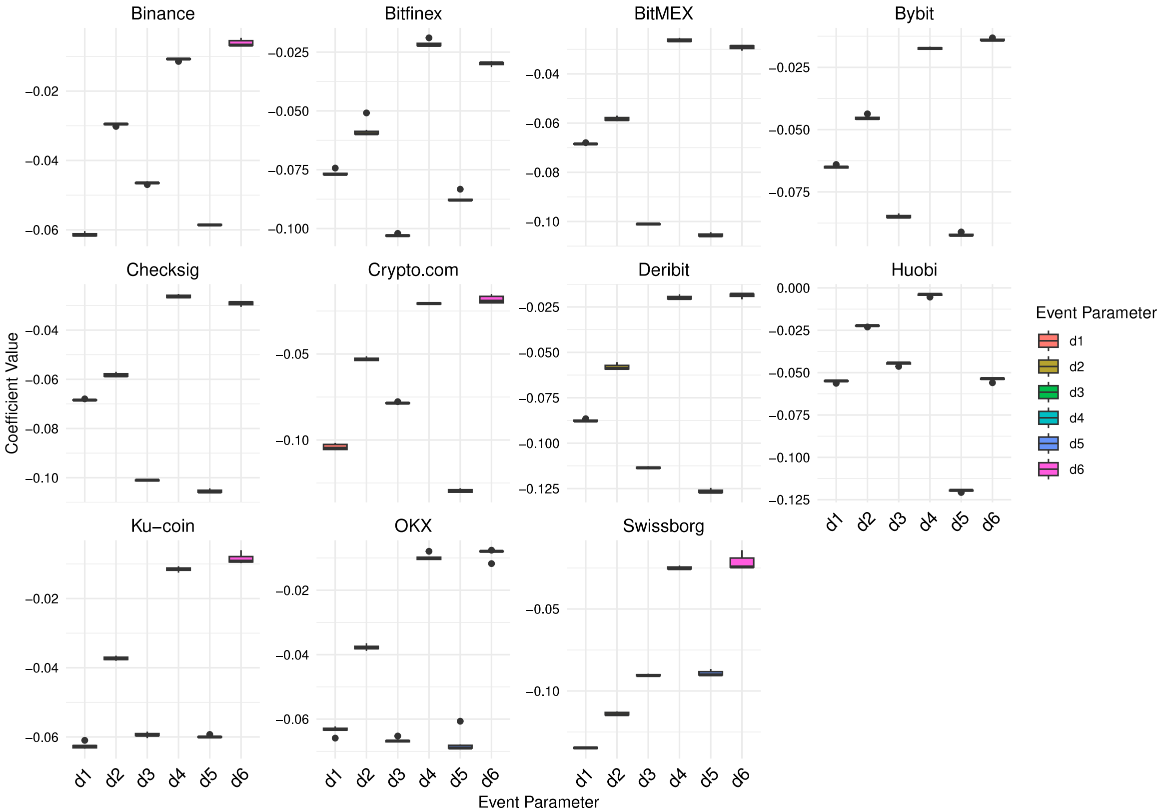

Fig. 7. Boxplot of event coefficients under different GARCH model assumptions: Student-t, Skew Student-t, Generalized Error Distribution, Skew Generalized Error Distribution, Normal Inverse Gaussian, Generalized Hyperbolic, Johnson's SU. Period [0].

A.4. Event coefficients under different GARCH model distributional assumptions

See Figs. 7 and 8.

A.5. Exchange balance data

In Sections Section 4.1, 4.2, and 4.3, we utilize proof-of-assets data, as previously described in Section 2. This metric exclusively focuses on the balances of a predefined set of addresses publicly disclosed by the respective exchange. This set of addresses remains static and only changes when an exchange publicly updates its proof-of-assets addresses.

Alternatively, Glassnode also provides a different methodology to identify the assets held by exchanges, namely, exchange balance data (Schultze-Kraft, 2022). It is relevant to consider that exchanges operate on-chain in a highly intricate manner, involving labyrinthine and dynamic transaction patterns and wallet management practices, each tailored to the specific exchange. A complex network of cold, hot, and one-time wallets constantly evolves, occasionally undergoing complete redesigns. In this context, data providers like Glassnode compute exchange balance metrics that are the result of sophisticated data acquisition systems relying on a combination of publicly available information, clustering algorithms, and exchange-specific heuristics. Exchange balance metrics do not necessarily align with the officially reported figures provided by the exchanges themselves, nor can they guarantee an accurate quantification of on-chain exchange funds. Instead, these metrics represent Glassnode's best approximation of the actual balance held by each exchange, quantified as closely and as verifiably accurate as possible, taking into account the intricate and ever-changing network of cold, hot, and one-time wallets. In contrast, proof-of-assets data simply reflect the total coins held in addresses that exchanges officially disclose.

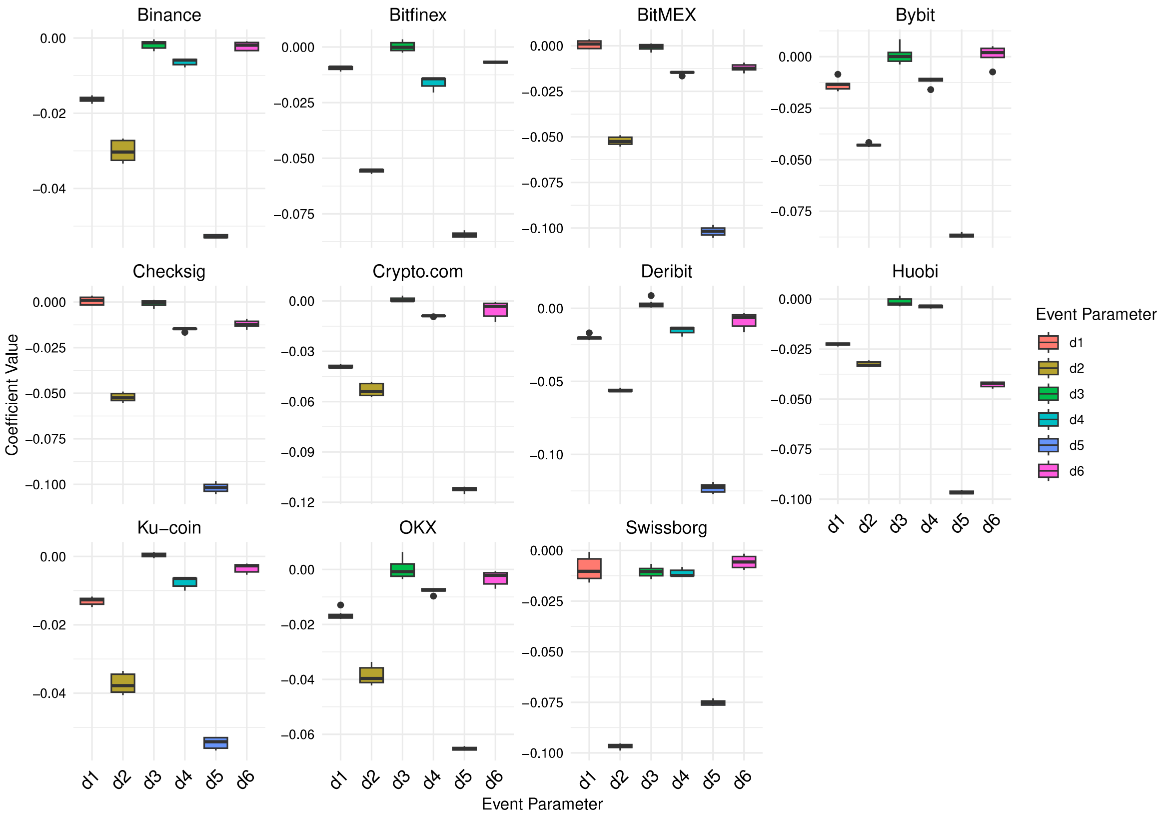

Fig. 8. Boxplot of event coefficients under different GARCH model assumptions: Student-t, Skew Student-t, Generalized Error Distribution, Skew Generalized Error Distribution, Normal Inverse Gaussian, Generalized Hyperbolic, Johnson's SU. Period [−1,1].

With both of these datasets available, this section conducts a robustness analysis by applying the same methodologies to exchange balance data as previously utilized for proof-of-assets data.

Exchange balances are frequently more dynamic, as they encompass a broader range of addresses, whereas proof-of-assets addresses typically constitute only a small portion of (cold) wallets. Depending on the comprehensiveness of the officially disclosed proof-of-assets addresses, the total balance can closely align with the exchange balance data reported by Glassnode. In Table 17, we present the ratios derived from dividing the proof-of-assets and exchange balance data for Binance, Bitfinex, BitMEX, Bybit, Crypto.com, Deribit, Huobi, KuCoin, and OKX.[28] The outcome predominantly underscores the similarity between both datasets, with a few exceptions. Indeed, as mentioned earlier, it is not uncommon to encounter differences between the two datasets. This can be attributed to two primary factors: (i) the dynamic nature of exchange balance data and (ii) the possibility that some addresses have not yet been disclosed due to the relatively novel nature of these metrics. Related to the latter point, it is important to emphasize that due to the significant costs associated with implementing a proof-of-reserves framework for all the assets held by platforms, some exchanges choose to disclose only a subset of their available addresses for a selected sample of cryptocurrencies.

Following the same approach as in Section 4.1, Tables 18 and 19 report the AR-GARCH estimates for the event dummies related to the most significant collapses in 2022. Tables 18 and 19 consider the Period [0] and Period [−1,1], respectively. We generally observe consistent results: (i) for the Period [0], (d_5) FTX, (d_3) Three Arrows Capital, (d_1) Terra-Luna, (d_2) Celsius, and (d_6) Blockfi negatively affect centralized exchanges; (ii) for the Period [−1,1], the collapses of (d_5) FTX and (d_2) Celsius are the most significant; (iii) Binance and KuCoin display considerable resilience in the face of negative events.

Tables 20 and 21 continue to exhibit consistent results when compared to Section 4.1. While some minor changes may be noticeable, Binance and KuCoin remain the most resilient exchanges, as indicated by the MVaR values. They are followed by Huobi, Bitfinex, and OKX.[29]

[28] Exchange balance data were not available for CheckSig and SwissBorg.

[29] Bitfinex's higher resilience when using exchange balance data can be attributed to the presence of substantial stablecoin deposits in exchange balance information, as opposed to the proof-of-assets dataset.

Table 17
Ratios computed by dividing proof-of-assets and exchange balance values.

	Binance	Bitfinex	BitMEX	Bybit	Crypto.com	Deribit	Huobi	KuCoin	OKX
APE	–	–	–	100.6196%	–	–	–	–	–
BTC	59.8560%	64.6663%	100.0578%	99.2261%	97.9110%	100.1497%	37.6670%	100.1266%	83.8662%
BUSD	89.0674%	–	–	–	–	–	–	–	–
CRO	–	–	–	–	100.1735%	–	–	–	–
DAI	–	–	–	100.1102%	–	–	–	–	–
ENJ	–	–	–	–	100.8207%	–	–	–	–
ETH	97.5803%	24.2144%	–	101.0294%	99.6957%	101.0294%	95.9603%	100.9480%	100.3616%
EURS	–	–	–	–	–	–	–	–	0.2030%
FTT	–	100.3361%	–	–	–	–	1.1252%	–	–
HOT	97.2581%	–	–	–	–	–	–	–	–
HT	–	–	–	–	–	–	100.1753%	–	–
HUSD	–	–	–	–	–	–	0.1773%	–	–
LEO	–	100.0437%	–	–	–	–	–	–	–
LINK	95.5967%	100.4543%	–	100.4543%	100.1267%	–	68.0065%	100.4509%	–
MANA	88.5609%	100.5305%	–	–	–	–	–	–	–
MATIC	–	–	–	101.0500%	100.3270%	–	–	–	–
OCEAN	–	–	–	–	–	–	–	507.3492%	–
OMG	–	98.3720%	–	–	–	–	–	–	–
QNT	–	–	–	–	–	–	–	99.9669%	–
RSR	–	–	–	–	–	–	–	–	0.0075%
SAN	–	100.5445%	–	–	–	–	–	–	–
SAND	97.2636%	–	–	100.6510%	–	–	–	–	–
SHIB	90.8924%	–	–	100.5801%	100.4863%	–	–	100.5786%	–
TEL	–	–	–	–	–	–	–	101.4644%	–
UNI	–	–	–	–	–	–	23.3748%	–	–
USDC	97.5492%	100.0976%	–	100.0976%	95.9986%	100.0976%	100.0949%	99.8058%	93.6034%
USDK	–	–	–	–	–	–	–	–	71.0101%
USDP	–	–	–	–	–	–	–	–	99.4648%
USDT	97.8875%	2.0116%	–	100.0837%	78.6462%	–	41.7746%	100.0716%	98.2400%
UTK	–	–	–	–	–	–	609.6168%	381.9803%	–
WBTC	–	–	–	–	97.2292%	–	–	–	–
WETH	–	–	–	–	–	–	–	–	0.2949%

(*continued on next page*)

Table 18
AR-GARCH results based on the selected negative events (d) in 2022. The dummy variables are included for the exact day on which the events occurred, i.e., Period [0].

Period [0]	Binance	Bitfinex	BitMEX	Bybit	Crypto.com	Deribit	Huobi	KuCoin	OKX
d_1	−0.0644***	−0.0680***	−0.0685***	−0.0670***	−0.1023***	−0.0883***	−0.0662***	−0.0557***	−0.0661***
d_2	−0.0325**	−0.0348**	−0.0589***	−0.0467***	−0.0525***	−0.0589***	−0.0347**	−0.0342***	−0.0413***
d_3	−0.0521***	−0.0548***	−0.1012***	−0.0871***	−0.0766***	−0.1138***	−0.0674***	−0.0531***	−0.0737***
d_4	−0.0105	−0.0087	−0.0268	−0.0183	−0.0200	−0.0203	−0.0283*	−0.0092	−0.0131
d_5	−0.0609***	−0.0613***	−0.1060***	−0.0941***	−0.1285***	−0.1276***	−0.1205***	−0.0566***	−0.0753***
d_6	−0.0077	−0.0122	−0.0286	−0.0143	−0.0188	−0.0182	−0.0507***	−0.0087	−0.0088

Table 19
AR-GARCH results based on the selected negative events (d) in 2022. The dummy variables are included, considering the day before, the specific day of the events, and the day after, i.e., Period [−1,1].

Period [−1,1]	Binance	Bitfinex	BitMEX	Bybit	Crypto.com	Deribit	Huobi	KuCoin	OKX
d_1	−0.0164	−0.0202	−0.0018	−0.0164	−0.0368	−0.0210	−0.0169	−0.0085	−0.0165
d_2	−0.0354***	−0.0380***	−0.0491***	−0.0441***	−0.0540***	−0.0574***	−0.0347***	−0.0364***	−0.0420***
d_3	−0.0038	−0.0117	−0.0021	−0.0043	−0.0021	0.0006	−0.0016	−0.0025	−0.0029
d_4	−0.0062	−0.0076	−0.0148	−0.0114	−0.0090	−0.0135	−0.0145	−0.0054	−0.0086
d_5	−0.0564***	−0.0581***	−0.1050***	−0.0885***	−0.1107***	−0.1274***	−0.1017***	−0.0546***	−0.0703***
d_6	−0.0011	−0.0026	−0.0095	0.0049	−0.0004	−0.0038	−0.0388***	−0.0026	0.0006

Data availability

The authors do not have permission to share data.

Table 20
MVaR(5%) & MVaR(1%) for the portfolio corresponding to each centralized exchange. Centralized exchanges are ordered alphabetically.

Balance	Binance	Bitfinex	BitMEX	Bybit	Crypto.com	Deribit	Huobi	KuCoin	OKX
MVaR(5%)	−0.0357	−0.0387	−0.0569	−0.0468	−0.0535	−0.0625	−0.0445	−0.0329	−0.0436
MVaR(1%)	−0.0680	−0.0846	−0.1234	−0.0995	−0.1035	−0.1277	−0.0846	−0.0620	−0.0851

Table 21
MVaR(5%) & MVaR(1%) for the portfolio corresponding to each centralized exchange. Centralized exchanges are ordered according to MVaR(5%) & MVaR(1%) values.

	KuCoin	Binance	Bitfinex	OKX	Huobi	Bybit	Crypto.com	BitMEX	Deribit
MVaR(5%)	−0.0329	−0.0357	−0.0387	−0.0436	−0.0445	−0.0468	−0.0535	−0.0569	−0.0625
	KuCoin	Binance	Huobi	Bitfinex	OKX	Bybit	Crypto.com	BitMEX	Deribit
MVaR(1%)	−0.0620	−0.0680	−0.0846	−0.0846	−0.0851	−0.0995	−0.1035	−0.1234	−0.1277

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