How Algorithmic Stablecoins Fail

Gleb Kurovskiy[1] Natalia Rostova[2]

April 2023

Abstract

In May 2022, the \$18.7-billion algorithmic stablecoin USD Terra (UST) and its \$20-billion backing token Luna experienced a sudden and rapid collapse from \$1 and \$80, respectively, to nearly 0 in a matter of days. Using transaction-level data from the Terra blockchain and cryptocurrency exchanges, this paper investigates the collapse and argues that several flaws in the design of UST impeded its price stabilization. Using a simple model, we demonstrate that a combination of these design features helps explain data patterns observed during the crash.

Keywords: Arbitrage, Cryptocurrency, DeFi, Stablecoin
JEL Classification: G23, G29

[2] PhD Candidate at EPFL and Swiss Finance Institute. Email: natalia.rostova@epfl.ch
[1] PhD Candidate at EPFL. Email: gleb.kurovskiy@epfl.ch
We thank our PhD supervisors Luisa Lambertini and Erwan Morellec for helpful discussions. We also thank Ilja Kantorovitch, Stylianos Tsiaras, Simon Tieche for useful comments.

1 Introduction

In May 2022, cryptocurrency markets witnessed one of the largest collapses of digital tokens in their decade-long history: the largest algorithmic stablecoin USD Terra (UST), with a circulating supply of $18.7bln, crashed from $1 to 10 cents in a matter of days (Figure 1). Its backing cryptocurrency Luna went from $80 to nearly zero, erasing almost $40bln of market capitalization and hurting hundreds of thousands of cryptocurrency investors. These events caught the attention of regulators and were discussed by the largest news outlets[1].

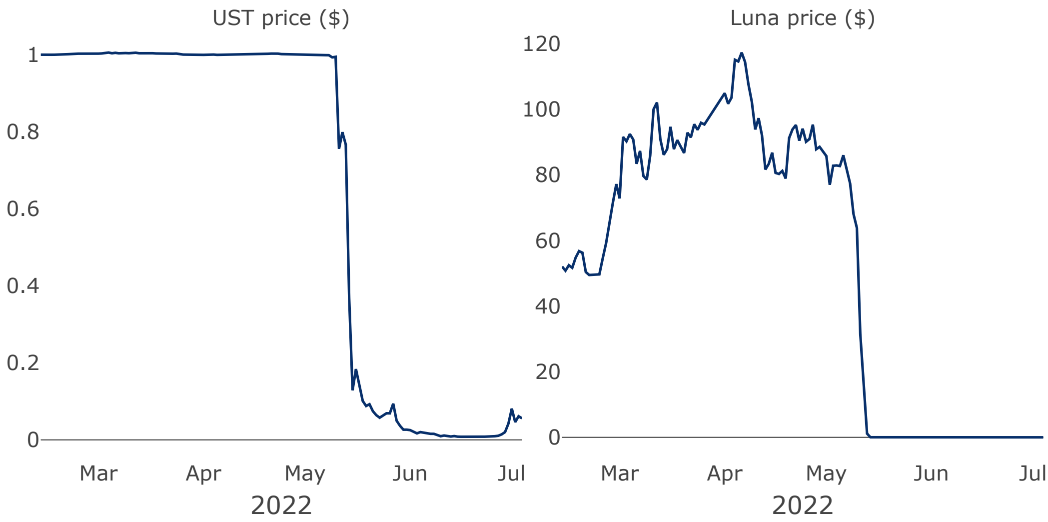


Figure 1: The figure shows prices of the stablecoin Terra USD (UST) and its backing token Luna from February 2022 to July 2022. Data Source: Messari.io.

The objective of this paper is to shed light on these events. To do so, we collect transaction-level data from the Terra blockchain and cryptocurrency exchanges and investigate the price stabilization mechanism of UST during the collapse. Our findings suggest that *the restriction on UST redemptions at par value of $1* was the main factor that impeded the price stabilization of UST in the first days of the collapse. After the limit was removed, *growing volatility of the backing token Luna*, *the accuracy of the Price Oracle* (the mechanism that translated prices from centralized exchanges to the Terra Blockchain), and *the absence of direct conversion of the UST stablecoin into dollars or any cryptocurrency that is exogenous to the Terra system* played a major role in breaking the arbitrage mechanism and led to the eventual inability of the UST stablecoin to restore the peg. Using a simple model, we show that a combination of these design features helps explain several empirical facts and data patterns such as UST trading volumes on exchanges, the price dynamics of UST, and magnitudes of arbitrage profits.

[1]Examples include The Wall Street Journal, Financial Times, and Bloomberg.

Studying the collapse of the UST stablecoin is important for several reasons. First, regulators are increasingly concerned about the transparency of the stablecoin market[2] whose market capitalization reached \$170bln on its peak in May 2022. Several authorities issued notes on the regulation of digital assets, including the US President's Working Group Report on Stablecoins (2021) and the EU Council Proposal (2022). Understanding the vulnerabilities of stablecoins' design is essential for shaping the regulatory framework and enhancing investors' protection.

Second, the crash of Luna and UST together erased almost \$60bln in a matter of days. In comparison, the valuation of the infamous health technology company Theranos which was charged with fraud was \$10bln at its peak. The UST-Luna collapse hit thousands of holders, including small retail investors: some users of social media platforms such as Reddit and Twitter complained that they held money in Luna or UST and lost a significant part of their savings[3]. Understanding flaws in token design can help investors make more sophisticated decisions and prevent future collapses.

Finally, the "run" of investors on the UST stablecoin differs from traditional bank runs in one central aspect: the information about UST holdings is recorded on the blockchain and, thus, is publicly available. This data provides a new framework for researchers to study investors' behavior during market panics. In our paper, we demonstrate how seemingly unstructured blockchain data can be used to understand, for instance, the limitations of the arbitrage mechanism of stablecoins.

A stablecoin is a cryptocurrency whose value is pegged to the value of an asset or another currency. UST was an algorithmic stablecoin on the Terra Blockchain. To maintain its price at \$1, UST relied on arbitrage incentives[4] and a dual-token system. The second token was called Luna. To issue 1 UST, one needs to buy Luna worth \$1 on an exchange and send Luna to the official Terra App called Terra Station[5]. In exchange for \$1 of Luna, the protocol issues 1 UST. Thus, issuing 1 UST reduces the circulating supply of Luna and vice-versa.

Luna was supposed to absorb the price volatility of UST: When the price of UST deviates from \$1, an arbitrageur buys UST on an exchange at a price of less than \$1, redeems it through the Terra Station, receives \$1 of Luna, and subsequently sells Luna on an exchange for \$1, pocketing the price difference. These actions cause buying pressure on UST on exchanges and reduce UST supply, driving the price back to \$1.

The arbitrage mechanism had been working until May 7, 2022. On that day, several

[2]See, for instance, the Wall Street Journal articles Why Regulators Are Worried About Stablecoins or Crypto Firm Paxos Faces SEC Lawsuit Over Binance USD Token.

[3]See one of those examples.

[4]In 2022, Terra started accumulating reserves consisting of Bitcoin and other assets to help maintain the peg but these reserves were insufficient relative to the size of UST and were quickly depleted.

[5]Interacting with Terra Station was the only way to issue or redeem UST.

wallets made a series of large withdrawals of UST from decentralized exchanges. These withdrawals created panic among other investors. In the next days, trading volumes on exchanges increased to $2-4bln per day. On May 9th, the price of UST de-peged significantly from $1 and never returned to the peg. On May 13, 2022 the Terra validators halted the blockchain.

To understand these events, we analyse data from the Terra Blockchain and two cryptocurrency exchanges Binance and Curve. We document several features of the UST-Luna collapse: i) the price of the UST stablecoin did not gradually fall to 0 and experienced several local recoveries; ii) even though UST holders could presumably redeem the stablecoin through the Terra Station at par value, there was significant trading activity on exchanges; iii) UST redemptions were gradual and distributed over several days; iv) arbitrage profits were significant and reached 200-400% on the last days of the collapse.

We argue that these empirical facts can be explained by the design of the UST stablecoin. The first important design feature is a redemption fee. A common perception about Terra USD is that the stablecoin was always redeemable at $1 with a small fee of 0.5%. In fact, that was true only in normal market conditions when redemption volumes were low. We show that, due to a built-in limit on UST redemptions, redemption fees during the collapse significantly exceeded the base fee of 0.5% reaching up to 60%. The fee of 60% implies that for every UST redeemed, a trader received 40 cents, which is significantly less than the par value of $1.

We also show that, at any point in time, the price of UST was capped from above by *1 - redemption fee*. This is because at a price of UST higher than *1 - redemption fee* holders of UST are better off by selling UST on exchanges but buying UST is not profitable for arbitrageurs. As a result, the price of UST would decline until it falls below *1 - redemption fee*.

Next, we document that the price of UST strongly correlates with the magnitudes of redemption fees before May 12 but significantly diverges afterward. On May 12 2022, Terra lowered redemption fees by removing the limit on UST redemptions. However, the price of UST did not recover to $1. We argue that after the redemption limit was removed, other factors played an important role in explaining the pattern of the UST price, namely: 1) growing volatility of the backing token Luna, 2) deteriorating accuracy of the Terra Price Oracle (the mechanism that translated prices from centralized exchanges to the Terra Blockchain), and 3) the absence of direct conversion of the UST stablecoin into dollars or any cryptocurrency that is exogenous to the Terra system.

The redemption mechanism worked in the following way: when market participants redeem UST in Terra Station, the protocol issues the Luna token that they could subsequently sell on exchanges. In other words, every redemption of UST increases the circulating supply of Luna and dilutes the holders of Luna. After a series of UST withdrawals in the first days of the collapse, the circulating supply of Luna increased many-fold. As arbitrageurs were selling the newly minted Luna on exchanges, its price was quickly falling to 0.

Another important design feature of UST is the Price Oracle. As the dollar price of Luna did not exist on-chain (as fiat currencies are off-chain assets), the price of Luna had to be translated to the blockchain from exchanges. This price was called the Luna Oracle Price and was determined by the Terra validators. More precisely, every validator submitted the price of Luna and the Luna Oracle Price was defined as the median among submitted prices. The Oracle Price of Luna was important as it determined the quantity of Luna that a trader received for redeemed UST stablecoins. We collect the time series of the Luna Oracle Price and compare it to the price of Luna on centralized exchanges. We find that discrepancies between these two prices were significant and increased up to 70% on the last days of the collapse. Large differences in the prices of Luna in the Price Oracle and on exchanges imply that market participants could incur significant losses if withdraw UST through the Market Module.

The growing volatility of the backing token Luna and deteriorated accuracy of the Price Oracle was coupled with the fact that the process of UST redemption was non-instant. By this, we mean that there was no way to directly redeem UST for dollars or any cryptocurrency whose value was exogenous to the Terra system (such as Ether or USDC). In other words, there was a time lag between the redemption of UST for Luna and the subsequent selling of Luna for any other cryptocurrency on an exchange. These design features together made the redemption mechanism significantly uncertain for market participants. As a result, arbitrageurs abstained from buying UST on exchanges and the price of UST continued to fall, despite the return of redemption fees to lower values. Classifying wallets that redeemed UST through the Terra Station into arbitrageurs and UST holders, we confirm that the fraction of UST redeemed through the Terra Station by the largest arbitrageurs declined in the last days of the collapse.

The intuition behind the explanation of why UST redemptions were gradual is straightforward. By the design of the Terra smart contract, an abnormal increase in UST redemptions leads to a rise in redemption fees. As redemption flows slow down and drop below the redemption limit, the redemption fee gradually returns to the base value of 0.5%. Therefore, to minimize fees paid in the Market Module, market participants are better off waiting and redeeming the stablecoin gradually.

Finally, why did we observe significant UST trading volumes on exchanges during the collapse period? We compared two strategies: withdraw UST in the Market Module and sell UST on an exchange. We find that redeeming UST through the Market Module would consistently result in lower losses for UST holders than selling UST on an exchange. Therefore, observing trading on exchanges is puzzling because holders of UST who wish to exit their UST positions could have redeemed the stablecoin in the Market Module. Our proposed explanation of this empirical fact is the following. Executing transactions on a blockchain and, in particular, the process of UST redemption requires experience with crypto markets (for instance, cross-blockchain transactions). While arbitrageurs are sophisticated agents and often use bots, inexperienced UST holders need more time and effort to execute transactions. As a result, selling the stablecoin on exchanges could have been an easier and quicker way for the holders to exit UST positions.

We formalize this intuition in a simple model that incorporates a combination of the outlined design features. In this model, we consider two agents: the arbitrageur, who is a sophisticated agent, and the holder of UST, an inexperienced investor. The holder is willing to exit his UST position by redeeming the stablecoin and/or selling it on an exchange to the arbitrageur. The arbitrageur decides the amount of UST she wants to arbitrage through the Terra Station. We reflect the difference between the arbitrageur and the holder by assuming that the holder needs more time to redeem UST and sell Luna on an exchange and faces higher uncertainty regarding the selling price of Luna. This leads the holder to sell the stablecoin to the arbitrageur, thus creating trading in exchanges. The volatility of Luna, accuracy of the Price Oracle, and presence of redemption fees affect the arbitrageur's willingness to buy and redeem UST. We show that in this setting, changes in the volatility of Luna and redemption fees could produce a pattern for the UST price that is closely correlated with the price observed in the data.

Our results have several implications. First, our findings suggest that in times of market stress the arbitrage mechanism might not work as expected if there is a risk that collateral becomes illiquid. The price stabilization mechanism of any stablecoin relies on arbitrage incentives, and the main difference between stablecoins is the type of collateral that backs the stablecoin. Thus, for regulators, our findings suggest that it is important to access the potential effects of the stablecoin on its collateral if the stablecoin reaches a large scale. This problem is pronounced for algorithmic stablecoins and stablecoins backed by on-chain assets such as FRAX, FEI, USDN, MIM. etc.

Second, our findings highlight the role of redemption fees in the price stabilization of stablecoins. We showed that in the case of Terra USD, the restriction on UST redemptions and floating redemption fees impeded its price stabilization in the first days of the collapse. When deciding which stablecoin to hold, market participants should audit and understand the redemption mechanism of the stablecoin, especially in times of market panic.

Related literature

This paper contributes to the growing literature on stablecoins[6]. In this literature, the most closely related paper is Uhlig (2022) which also focuses on the collapse of Terra USD. While Uhlig (2022) explains data patterns with a belief-equilibrium model, we center our paper around the role of institutional details (i.e. stablecoin design features) in the course of the UST-Luna collapse. The model of Uhlig (2022) assumes that holders of UST could redeem UST at $1. Using data from the Terra Blockchain, we show that during the collapse, redemption fees were significant and reached 60%. We argue that redemption fees and a number of other design features are important in explaining data patterns. In addition, although the UST price stabilization mechanism relied on arbitrage incentives, arbitrageurs are not considered in the model of Uhlig (2022). We, instead, investigate the arbitrage mechanism.

Our paper also relates to Griffin and Shams (2020) in that we use seemingly unstructured transaction-level blockchain data to understand the behaviour of market participants in the cryptocurrency market. While Griffin and Shams (2020) shed light on the role of Tether on Bitcoin prices, we focus on the $60bln crash of Luna and UST. Our paper increases the transparency about these events for regulators and cryptocurrency investors.

We also contribute to the literature studying arbitrage in cryptocurrency markets (Park (2021), Makarov and Schoar (2020), Borri and Shakhnov (2018, 2022)). The price stabilization mechanism of USD Terra, like any other stablecoin, relied on arbitrage incentives. Our paper investigates the limitations of this mechanism and suggests that the risk of collateral becoming illiquid when uncertainty spikes plays an important role in the recovery of the stablecoin price. This is particularly relevant for stablecoins that are backed by other cryptocurrencies.

Our study also relates to the literature that provides a general overview of decentralized finance (DeFi) such as Schär (2021), Harvey et al. (2021) and Aramonte et al. (2021). Our paper shows that price oracles remain an important limitation for DeFi protocols in times of market panic. In particular, we demonstrate that the divergence of the price of Luna translated by the Price Oracle from its price on centralized exchanges was significant and complicated the price stabilization mechanism of UST.

The remainder of this paper is organized as follows. Section 2 of the paper provides background information about stablecoins and the design of Terra USD before the col-

[6] See Lyons and Viswanath-Natraj (2021), Ante et al. (2020), Baumöhl and Vyrost (2020), Li and Mayer (2022), Bellia and Schich (2020), Catalini et al. (2021), Baur and Hoang (2021), Gorton and Zhang (2021), Griffin and Shams (2020), Wang et al. (2020), Kwon et al. (2021), Jarno and Kolodziejczyk (2021), d'Avernas et al. (2021), Cao et al. (2021), Mizrach (2022), Wei (2018), Kozhan and Viswanath-Natraj (2021), Kristoufek (2021), Gorton et al. (2022), Uhlig (2022).

lapse. Section 3 describes the data. In Sections 4 and 5 we analyze blockchain and exchange data and document empirical facts about the collapse. In Section 6 we suggest a model that explains empirical evidence, Section 7 concludes.

2 Background

2.1 Types of stablecoins

A stablecoin is a cryptocurrency whose value is tied to another currency or asset, mainly to the USD dollar. The price stability mechanism depends on the design of a stablecoin. Stablecoins can be broadly divided into three categories: 1) collateralized by off-chain assets (USDT, USDC, BUSD, etc.), 2) (over)-collateralized by on-chain assets (DAI, MIM, etc.), and 3) algorithmic (UST, USDN, USDD, FEI, etc.).

Stablecoins collateralized by off-chain assets (USDT, USDC, BUSD, etc.) such as cash and short-term debt are issued by centralized entities (Tether, Circle, etc.) that control the issuance of stablecoins. When the price of a stablecoin on an exchange exceeds $1, a trader can send $1 to the stablecoin Treasury and sell it for > $1 in the market. That increases the circulating supply of the stablecoin and drives the price back to $1.

DAI and MIM are examples of stablecoins collateralized by on-chain assets (for example, Ether). Since the price of collateral is volatile, issuance of such stablecoins requires over-collateralization. For instance, to issue 1 DAI, a user is required to deposit $1.5 worth of Ether. Over-collateralization requirement leads to capital inefficiency as users need to lock up more funds than they are able to use after minting. As a result, the scalability of such stablecoins is limited.

Algorithmic stablecoins (UST, USDN, FEI, USDD) are not backed by exogenous collateral. To maintain the peg, protocols rely on a dual-token system: a stablecoin and a governance token. To issue 1 algorithmic stablecoin, a user buys a governance token worth $1 and the protocol burns it to issue 1 stablecoin. These stablecoins are decentralized and capital efficient but carry a higher risk of price destabilization.

2.2 How are stablecoins used?

First, market participants use stablecoins to enter the crypto markets. As noted by the Wall Street Journal, ”stablecoins ... serve as a bridge between crypto and government-issued money”[7]. On the largest centralized exchanges, many tokens are quoted in stablecoins. For example, according to CoinMarketCap[8], the three most traded pairs on

[7]See, for example, the WSJ article Tether Cedes Territory to Rival Stablecoins as Crypto Investors Diversify.

[8]https://coinmarketcap.com/exchanges/binance/, accessed on Februry 3, 2023.

Binance are *Bitcoin/USD Tether*, *Binance USD/USD Tether* and *Bitcoin/Binance USD*. Though some exchanges offer trading pairs directly with the US dollar, traders often need to buy a stablecoin first and then trade it for the cryptocurrency of interest. In June 2022, more than 75% of all trading in crypto markets involved stablecoins[9].

Second, holders of stablecoins can earn interest in various DeFi (decentralized finance) protocols. Examples of interest-bearing activities include liquidity provision on decentralized exchanges (Curve, Uniswap, PancakeSwap, etc) and lending stablecoins to other market participants. Stablecoins can be also used as collateral in lending protocols such as Maker or Compound. In addition, many platforms such as Crypto.com offer interest on stablecoin deposits.

Finally, several studies (for ex., Wang et al. (2020)) find that due to relatively low volatility, stablecoins act as safe assets in times of increased volatility in cryptocurrency markets. For example, Lyons and Viswanath-Natraj (2021) find that Tether trades at premium when Bitcoin volatility increases, indicating that investors sell volatile cryptocurrencies for stablecoins.

2.3 How did Terra work before the death spiral?

Luna and UST are the native tokens of the blockchain-based project created by Terra Labs. UST is an algorithmic stablecoin, while Luna is a governance token. Like on any blockchain, transactions on the Terra network are recorded and verified by validators who, in exchange, are rewarded with transaction fees. In other words, users holding Luna can obtain transaction fees if they stake their Luna to validators.

The only way to issue new UST or redeem UST in circulation is through the Market Module of Terra Station, the official Terra wallet. To create 1 UST, a trader needs to buy Luna worth $1 on an exchange like Binance and send it to the Terra wallet. The protocol will destroy the amount of Luna worth $1 and issue 1 UST. To maintain the value of UST, Terra relies on arbitrage incentives. Figure 2 illustrates the arbitrage mechanism when the price of UST on an exchange drops to $0.8. In that case, a trader buys UST for $0.8, sends it to the Terra Wallet and redeems it in the Market Module. The protocol destroys 1 UST and, in exchange, the trader receives the amount of Luna worth $1. For instance, if the current price of Luna is $10, then the trader receives 0.1 Luna minus the fee charged by the Market Module (0.5% in normal times). The last step to make arbitrage profits is to sell Luna on an exchange. In Figure 2, the trader receives $1 for 0.1 Luna (minus fees), making an arbitrage profit of $0.2 (minus fees). Since the protocol destroys 1 UST, the circulating supply of UST decreases. The arbitrageur's actions cause an upward pressure on the UST price on exchanges, thus driving the price back to $1.

[9] https://www.theblockcrypto.com/data/crypto-markets/spot

Illustration of the UST-Luna arbitrage mechanism

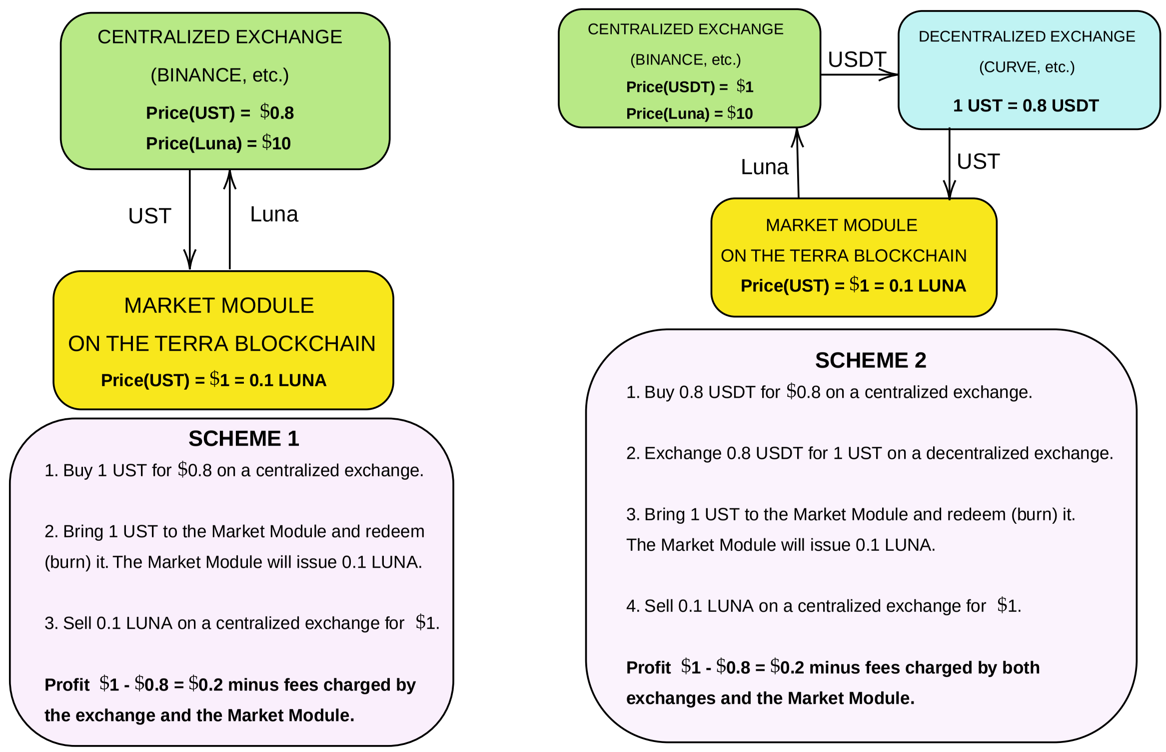


Figure 2: The figure provides an illustration of how traders could profit from a UST price deviation. The first example assumes the price of UST and Luna on the centralized exchange equal \$0.8 and \$10, respectively. The second example assumes the prices of USDT and Luna on the centralized exchange equal \$1 and \$10, respectively, and the price of UST on the decentralized exchange equals 0.8 USDT. In the Market Module, the price of UST always equals to \$1 of Luna. For illustration purposes, we assume that the exchange fees, the Market Module fees and fees for cross-blockchain transactions are zero.

2.4 Success of Terra before the Death Spiral

Before the invention of Terra USD, there were several attempts to create algorithmic stablecoins. For example, in 2020 Iron Finance launched TITAN token (similar to Luna) and algorithmic stablecoin IRON (similar to UST). In 2021, it fell into the death spiral despite the fact that IRON was partially collateralized by USDC. Before the failure, the market cap of TITAN was $2bln. Other algorithmic stablecoins such as Basis Cash, Empty Dollar Set and BEAN also failed far before reaching the valuations of Luna and UST. Before the crash in May 2022, the market capitalization of Luna reached $40bln, while USD Terra with a circulating supply of $18.7bln was the only algorithmic stablecoin that became bigger than DAI. What were the features of the design UST and Luna that help this system survive and thrive for so long compared to other algorithmic stablecoins?

First, Luna was the native token of the Terra blockchain. It played a similar role to the one of Ether on the Ethereum blockchain: all transaction fees on the Terra blockchain were paid in Luna and were distributed to validators of transactions. In comparison, other algorithmic stablecoins are (or were) built on existing blockchains such as the Ethereum blockchain and, thus, did not represent a claim on blockchain transaction fees.

Second, the team behind Terra created a range of use cases for both Luna and UST: The largest projects on the Terra blockchain such as Mirror or Anchor protocols were offering lending, borrowing, and trading of synthetic assets. All these protocols used Luna and UST tokens. Terra also launched an NFT marketplace and was planning to launch gaming protocols to support the demand for UST and Luna. In addition, Terra was listed on major centralized exchanges such as Binance and supported integration with cross-chain DeFi protocols.

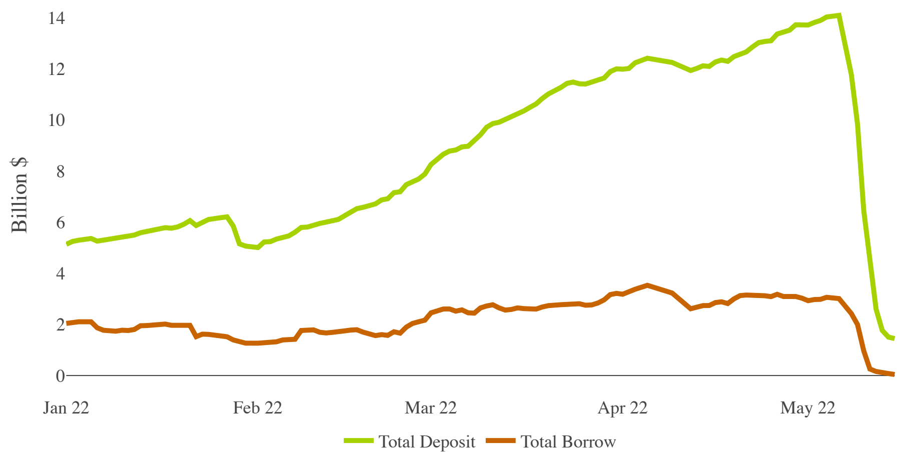


Figure 3: Total deposits and lending (in bln $) in the Anchor Protocol on the Terra Blockchain from January to June 2022.

Finally, high yields offered by Anchor protocol were the third reason driving the demand for UST. Holders of UST could deposit the stablecoin into the protocol and earn a fixed annual yield of 19-20%. This yield was coming from three sources: 1) interest paid on borrowed UST, 2) staking rewards from major proof-of-stake blockchains, and 3) Anchor Yield reserve - a treasury designed to subsidize the interest rate during bear markets. The first source relied on the assumption that there was enough demand for borrowing UST. Figure 3 shows that the supply of borrowing exceeded the demand. As the gap continued growing, Terra had to use the Anchor Treasury and replenish it once it was exhausted. By May 2022, around 80% of the total UST supply was staked in the Anchor Protocol. Clearly, such yields and the demand for UST were unsustainable in the long run and the stability of the Terra system was exposed to the risk of large UST redemption in case of a decrease in the Anchor interest rates.

3 Data Sources

The data used in this study are collected from multiple sources. Our main source is *Flipsidecrypto.xyz*, a platform that enables access to blockchain data. We use their API to obtain transactions from the Terra blockchain. This data include all issues and redeems of UST through the Market Module and the price of Luna from the Oracle Module (see Section 2.3). We also collect data from the Anchor Protocol, the platform on the Terra Blockchain that held around 80% of the UST supply before the UST collapse. This data include all deposits and withdrawals made by UST holders during the collapse period.

Next, we collect data on UST trades from Binance, the cryptocurrency exchange with the highest exchange score according to the Coinmarketcap[10]. We select the most liquid trading pair with UST which, according to *Cryptocompare.com*, was BUSD-UST. We use this data to understand trading activity during the collapse period and determine selling and buying pressure on UST.

Finally, we use Etherscan.io to parse transaction-level data from decentralized exchange *Curve.fi*. In particular, we obtain transactions from the UST-3Crv (UST-DAI/USDC/USDT) liquidity pool. The data consist of transactions made by traders between May 5th and May 13th such as selling/buying UST for another stablecoin and liquidity provision/withdrawals by liquidity providers. For each transaction, we have the block number, timestamp, transaction hash, sender's wallet address, receiver's wallet address, and the number of tokens sent/received.

Our main focus is on the period between May 5th and May 13th, 2022, from right before the UST collapse and until the Terra blockchain halt.

[10] Access date: February 3, 2023.

4 The Collapse of Terra USD

In this section, we analyze data from the Terra Blockchain and cryptocurrency exchanges and present new empirical evidence about the course of the UST-Luna collapse.

4.1 Anchor Protocol

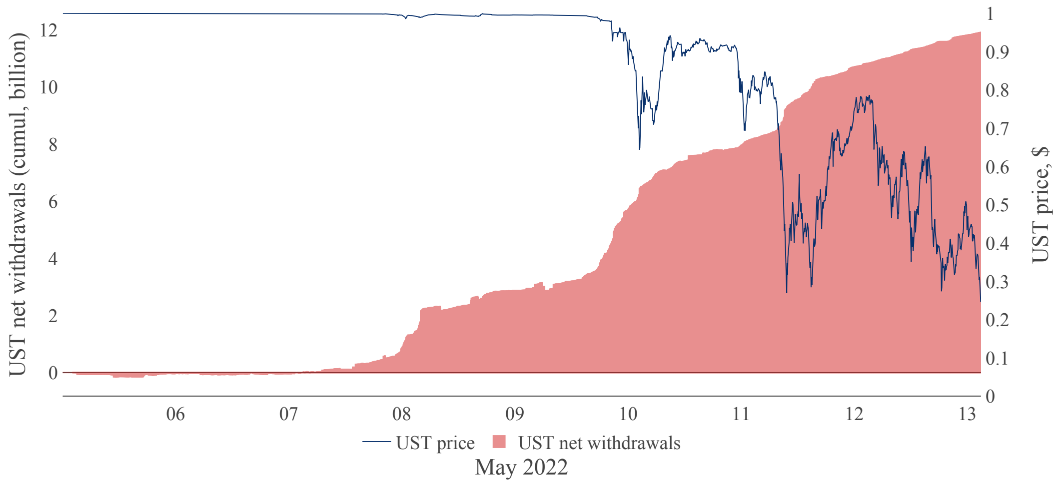
We start by examining the transactions in the Anchor Protocol, the platform that held 80% of the circulating supply of UST before the collapse. As explained in Section 2.3, the 20% yield offered by the Anchor Protocol was the primary incentive for holding UST.

Figure 4.a shows the price of UST along with net withdrawals (the difference between UST withdrawals and deposits) from the Anchor Protocol. Due to the importance of the Anchor Protocol, net withdrawals from the Anchor protocol can be viewed as a proxy for demand for UST. Net withdrawals had been gradually accumulating since May 7, 2022, while the price of UST remained close to $1 until May 9, 2022. By that time, cumulated net withdrawals had reached 6 billion UST. By May 10 2022, the price of UST significantly depegged to $0.65. In the next three days, the price of UST fluctuated between $0.9 and $0.3 until May 13 2022, when Terra validators halted the blockchain. In total, between May 7 and May 13, the Anchor Protocol experienced net withdrawals of 11.9bln UST.

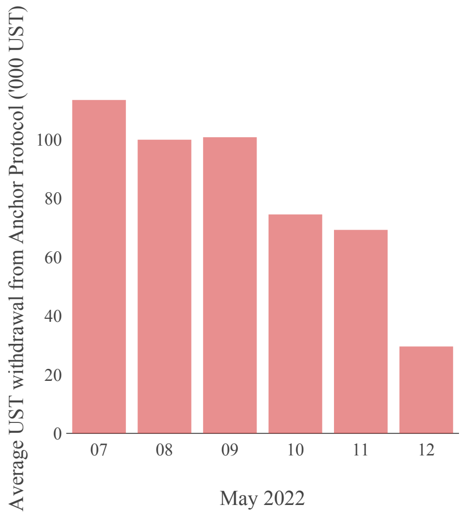
Panel b of Figure 4 reports that the average size of UST withdrawals from the Anchor Protocol had been declining from 113k UST between May 7 to 29k on May 12, 2022. This suggests that larger, presumably more sophisticated, market participants withdrew UST in the first days of the collapse while smaller investors followed later. Figure 4.c splits withdrawals and deposits into the Anchor Protocol by transaction size. Strikingly, even large market participants continued depositing UST in the Anchor Protocol despite the continuing de-peg of the UST stablecoin.

Despite the accumulating net withdrawals of UST, the UST price did not gradually decline to 0 and experienced several local recoveries. For instance, after the first de-peg to $0.6, the price recovered to $0.9. This is interesting because to exit a UST position, an investor could either sell UST on an exchange or redeem it through the Market Module. Both actions are not anticipated to lead to a recovery of the UST price. Thus, we arrive at the first empirical fact:

Empirical fact 1. *Despite a gradual decline in the demand for UST, the price of the stablecoin did not gradually go to 0 but rather experienced several local recoveries.*



(a) UST net withdrawals from the Anchor Protocol and the price of UST



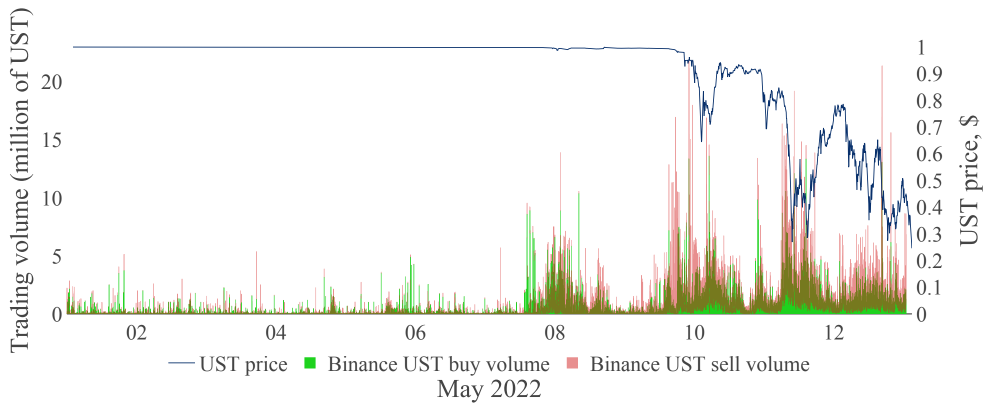
(b) Average size of UST withdrawals from the Anchor protocol by day

(c) Count of UST withdrawal and deposit transactions by transaction size

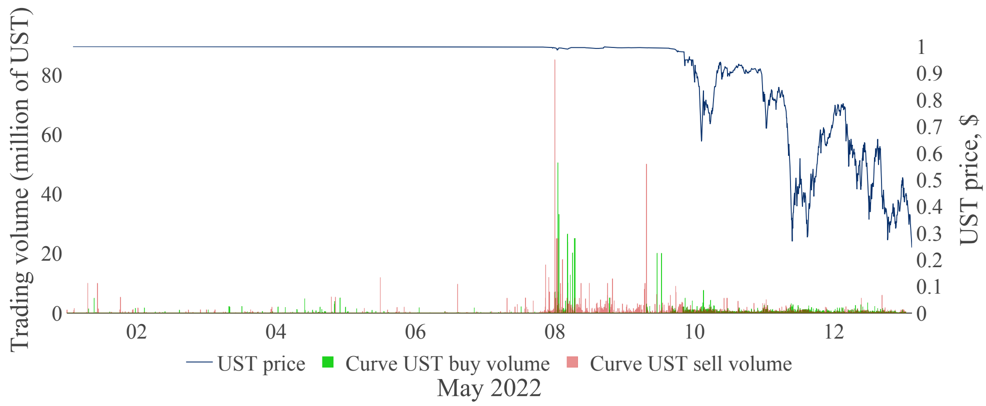
Figure 4: The Figure reports: (a) cumulative UST net withdrawals from the Anchor Protocol (red color) and the price of UST from Binance (blue color); (b) the daily average size of UST withdrawals from the Anchor protocol between May 7 and May 12, 2022; (c) the number of UST withdrawal and deposit transactions into the Anchor Protocol by transaction size from May 5, 2022 to May 13, 2022.

4.2 Cryptocurrency exchanges: Binance and Curve

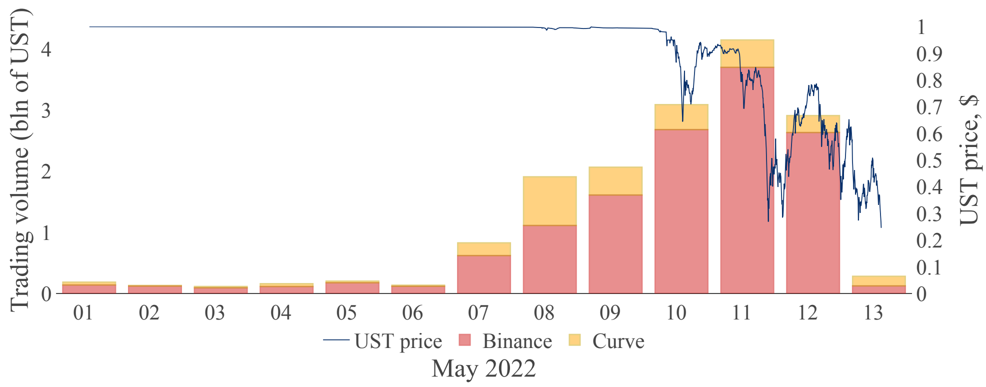
Next, we analyze UST trading volumes on two exchanges: Binance, the largest centralized exchange, and Curve, a decentralized exchange that had the highest UST liquidity on-chain. In particular, we look at transactions in the UST-BUSD trading pair (the most liquid pair with UST on Binance) in Panel a of Figure 5, and transactions in the UST-DAI/USDT/USDC liquidity pool on Curve in Panel b.



(a) Trading volume on *Binance.com* (in million of UST)



(b) Trading volume on *Curve.fi* (in million of UST)



(c) UST trading volumes on Binance.com and Curve.fi

Figure 5: The Figure reports UST trading volumes on Binance (UST-BUSD trading pair) and Curve.fi (UST-DAI/USDT/USDC liquidity pool) from May 1, 2022 to May 13, 2022. The red color corresponds to trades classified as "sell UST" trades, green color reports "buy UST" trades. The blue color indicates the price of UST. Data source: Ethereum Blockchain, Binance.com.

On both exchanges, we are able to classify transactions as either ”buy UST” or ”sell UST”. Binance provided an identifier for seller/buyer-initiated transactions, while interactions with liquidity pools on Curve are recorded on the blockchain. We classify a transaction as a ”sell UST” transaction when a trader transferred UST to the Curve liquidity pool address and received DAI/USDT/USDC in return. Conversely, a ”buy” trade is a transaction in which a trader transferred DAI/USDT/USDC to the Curve liquidity pool address and received UST in return.

On both exchanges, abnormal trading volume can be seen from the evening of May 7, 2022. Most notably, the Curve pool experienced a series of abnormal UST withdrawals: a trader sold 80mln UST in one transaction but the price did not de-peg from $1. On Binance, despite the higher overall trading volume, transaction sizes rarely exceeded 20 million UST. Overall, Figure 5 indicates that there was significant trading activity on exchanges during the collapse.

Panel c of Figure 5 shows that the UST-DAI/USDT/USDC pool experienced its peak trading volumes on May 8, 2022. Afterwards, trading volume declined as liquidity was withdrawn from the pool. In contrast, Binance's trading volumes continued to increase, reaching 3.7bln UST on May 2022.

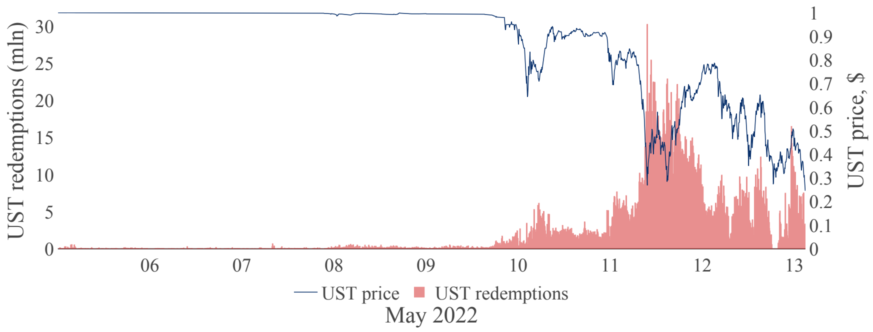
4.3 Market Module of Terra Station

As explained in Section 2.3, interacting with the Market Module was the only way to issue or redeem the UST stablecoin (i.e. increase or decrease the supply of UST). In Figures 6.a, we report the dynamics of UST redemption during the collapse period. Despite withdrawals from the Anchor Protocol had been accumulating since May 7, 2022 (Figure 4), notable withdrawals through the Terra Market Module lagged and initiated only on May 10 when the price of UST lost the peg. Redemption volume peaked on May 11, when the price of UST dropped to 30 cents.

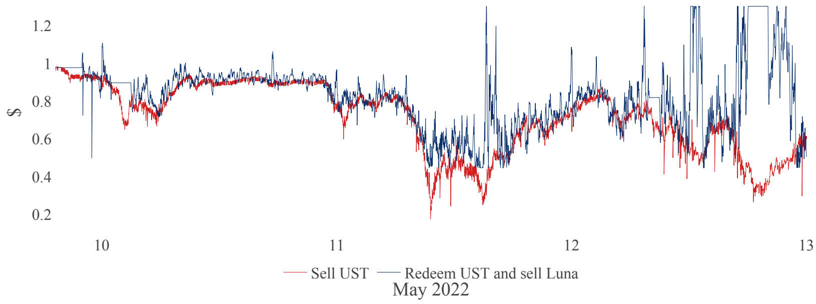
Empirical fact 2. *UST redemptions were gradual and distributed over several days.*

By May 13, 2022, the total volume of UST redemption through the Terra Station reached 4.9bln UST. In contrast, as shown in Figure 4, the total net withdrawals from the Anchor protocol amounted to 11.9bln UST. Together with the evidence of significant trading activity (Figure 5), this suggests that at least 7bln UST withdrawn by UST holders from the Anchor Protocol were not redeemed in the Market Module but rather sold on exchanges. This observation is puzzling because UST holders who intended to exit their positions could presumably redeem the stablecoin at $1 through the Market Module.

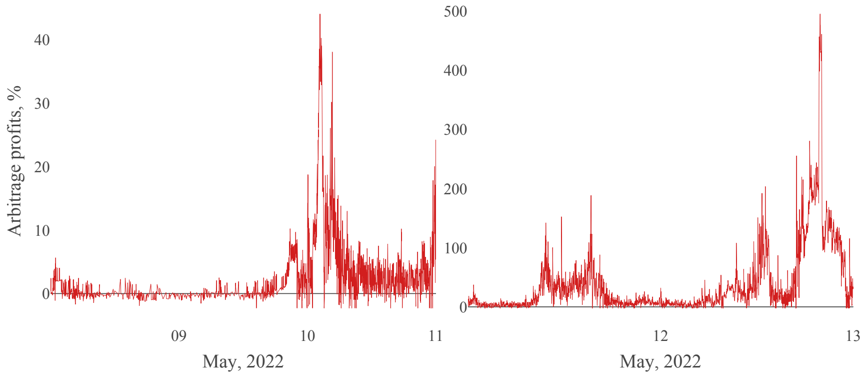
In Figure 6.b, assuming that the UST holders bought UST at $1 in the past, we compare



(a) UST redemption volume in the Market Module of Terra Station



(b) Comparison of payoffs to UST holders: selling UST on an exchange *vs* redeeming UST in the Market Module



(c) Arbitrage profits (in %)

Figure 6: This figure shows: (a) UST redemption transactions through the Market Module of the Terra Station from May 5 to May 13, 2022; (b) the comparison of pay-offs to UST holders from two different exit strategies: sell UST on Binance versus redeem UST in the Market Module with subsequent selling of Luna on Binance (excl. transaction fees); (c) arbitrage profits (in %) from May 7 to May 13, 2022.

Notes: We consider the arbitrage strategy that involves the following steps: 1) buy UST on Binance.com, 2) redeem UST through the Terra Market Module, 3) sell Luna on Binance.com. We exclude transaction fees as they are <1% on the Terra blockchain and Binance. The left figure reports profits on May 7-10, the right one - on May 11-13 2022. Due to non-instant arbitrage, we assumed a 10-minute gap between UST redemption and Luna selling. The figure is split into two subfigures as the magnitudes of arbitrage profits differ significantly in these two periods.

the payoffs from two exit strategies: 1) withdraw UST in the Market Module in exchange for Luna and sell Luna on Binance and 2) directly sell UST on an exchange. The results in Figure 6.b suggest that redeeming UST through the Market Module would consistently result in lower losses for UST holders than selling UST on exchanges.

Empirical fact 3. *Even though the UST holders could redeem the stablecoin through the Terra Station at $1, at least 60% of UST withdrawn from the Anchor Protocol were sold on exchanges.*

Finally, as the price stabilization mechanism of UST relied on arbitrage incentives, we investigate the profitability from arbitrage during the collapse. An arbitrage strategy through the Market Module requires several steps, namely: 1) buy UST on a cryptocurrency exchange, 2) redeem UST in the Market Module in exchange for Luna, and 3) sell Luna on a cryptocurrency exchange. We construct arbitrage profits at a 5-minute frequency using the following formula:

$$100\% * \frac{P_{sell}^{Luna} \times Q_m^{Luna} - P_{UST}}{P_{UST}},$$

where P_{UST} is the purchasing price of UST, Q_m^{Luna} - the amount of Luna received at redemption in the Terra Market Module per 1 UST, P_{sell}^{Luna} - the selling price of Luna. As executing transactions on a blockchain requires time, we allow for a 10-minute gap between the purchase of UST and selling Luna on the exchange[11].

As shown in Figure 6.c, arbitrage profits were highly volatile over the seven-day period: in the first days of the collapse (May 7-9, 2022), they were below 10% but increased to 40% on May 10. After declining on May 12, they again rose to 200-400% in the last hours of the collapse.

Empirical fact 4. *During the collapse period, arbitrage profits were significant and reached 200-400% in the last days of the collapse.*

[11]The results are similar with alternative time lags of 1, 3, 5, 15 min.

5 Design Flaws of Terra USD

In this section, we uncover several flaws in the design of UST and link them to the empirical facts documented in the previous section.

5.1 Redemption Fee

We start by computing the fee paid by traders in the Market Module of the Terra Blockchain. A wide perception about the redemption mechanism of UST is that an investor who redeems the stablecoin in the Market Module receives \$1 per 1 UST minus a small fee of 0.5%. As we show below, that was true only in normal market conditions. In effect, the Market Module had a daily limit on UST redemptions, meaning that only a limited amount of UST could be redeemed at a 0.5% fee. Once the limit was reached, further redemption occurred at a higher fee. We denote the redemption fee (or "redemption spread" as called by Terra) by s. By the design of the Terra protocol, the fee gradually reverts to the base value of 0.5% if redemption flows fall below the limit. The exact functional relationship between the redemption volumes and fees and the number of blocks needed to restore the redemption capacity was determined by the protocol.

Using redemption transactions in the Market Module, we compute the implied redemption fee s. For every transaction i, we have the information on the amount of UST redeemed Q_i^{UST}, the price of Luna in the Market Module at the time of redemption P_i^{Luna}, and the number of Luna tokens received Q_i^{Luna}. The redemption fee is then obtained from the following equation:

$$Q_i^{Luna} = (1-s) Q_i^{UST} \frac{1}{P_i^{Luna}}. \tag{1}$$

Table 1 presents the summary statistics on redemption fees. Strikingly, the table suggests that during the collapse, the fees were significantly higher than the base fee of 0.5%, with the mean fee amounting to 19.97% and the maximum fee equal to 59.23%. A fee of 60% implies that instead of receiving \$1 per 1 UST redeemed, an investor would only receive 40 cents.

Summary Statistics on Redemption Fee, %						
Min	q1	Median	q3	Mean	Max	# transactions
0.50	9.81	18.84	26.84	19.97	59.23	131,377

Table 1: This table reports summary statistics on redemption fees paid by traders in the Market Module of the Terra Blockchain between May 5 and May 13, 2022.

Figure 7 reports $1 - s$ (i.e. one minus the redemption fee) and compares it to the UST price. $1 - s$ indicates how much market participants received per 1 UST at redemption (in \$). The first observation from Figure 7 is that the price of UST was capped by $1 - s$. The intuition of why the price of UST does not exceed $1 - s$ is that at a price of UST higher than *1 - s*, holders of UST who exit their UST positions are better off by selling UST on exchanges but buying UST is not profitable for arbitrageurs. As a result, the price of UST would decline until it falls below *1 - redemption fee*.

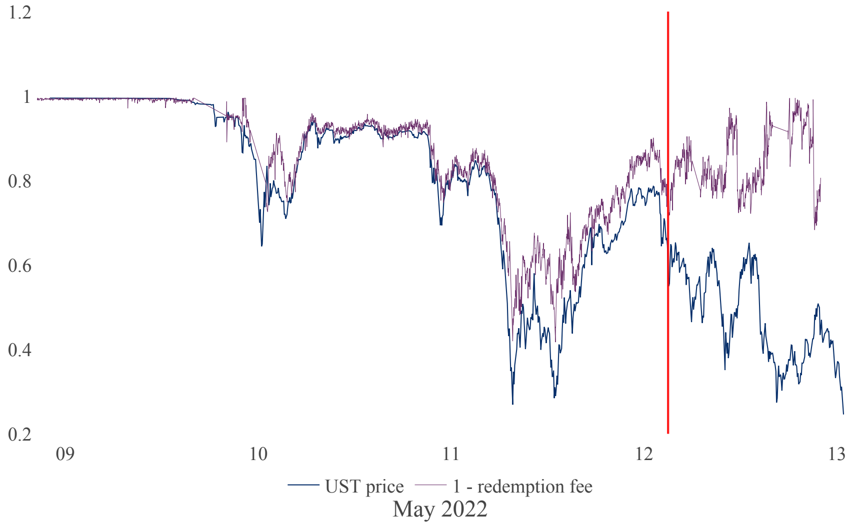


Figure 7: The Figure reports the dynamics of the UST price and $1-s$, where s denotes the redemption fee. The interpretation of s is as follows. Suppose the current price of Luna is \$10. If $s = 0$, then for one UST ($Q^{UST} = 1$) redeemed, a trader receives $Q^{Luna} = 0.1$ and sells it for \$1 on an exchange. If $s = 50\%$, the trader receives only $Q^{Luna} = 0.05$. Selling Luna at the price of \$10, he gets \$0.5 per 1 UST. The red line indicates the moment when Terra eased the restriction on UST redemptions.

Second, during the first days of the collapse (May 9 - May 10), the price of UST closely matched $1 - s$. However, on May 11, the price began to diverge from $1 - s$, and the gap increased in the final days of the collapse. According to the Terra website, on May 12, Terra passed a proposal to ease the restrictions on UST redemption (indicated by the red line in Figure 7). As a result, the redemption fee significantly decreased. However, the price of UST did not recover to \$1.

The findings in Figure 7 suggest that redemption fees are important in explaining the pattern of the UST price before May 12. However, after several days of UST de-pegging, other factors became important.

We argue that several design features played a crucial role in breaking the arbitrage mechanism of Terra USD. Namely, 1) high volatility of the backing token Luna, 2) deteriorated accuracy of the Price Oracle, and 3) the absence of direct conversion of the

UST stablecoin into dollars or any cryptocurrency that is exogenous to the Terra system (i.e. there was a time lag between UST redemption and subsequent selling of Luna on an exchange).

5.2 Luna Token

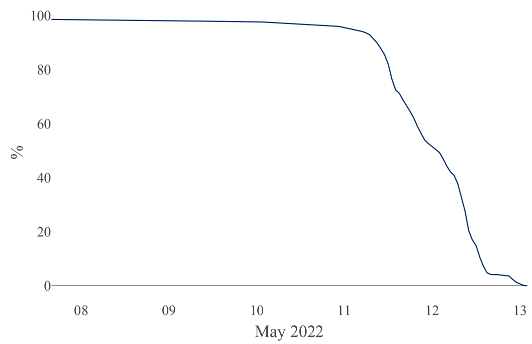
As the Market Module mints new Luna tokens every time a trader redeems UST, the prolonged price de-peg with gradual redemptions (caused by high redemption fees) causes a significant increase in the circulating supply of Luna and, thus, the dilution of Luna holders. In Figure 8.a, we report the share of the pre-collapse Luna supply in the total Luna supply from May 8 to May 13. The figure shows that by the end of May 12, the pre-collapse Luna tokens accounted for only 5% of the total number of tokens in circulation. implying that the holders of Luna were diluted by 95% if held Luna tokens until May 12.

As a result of the tremendous supply growth, the price of Luna rapidly fell and became highly volatile: Figure 8.b and Figure 8.c report the hourly standard deviation of Luna returns and the hourly growth of the Luna price, respectively. Figure 8.d illustrates that an increase in the supply of Luna is a leading indicator of the Luna price changes. In total, over the collapse period, the supply of Luna had increased from 1 billion tokens to over 1 trillion tokens.

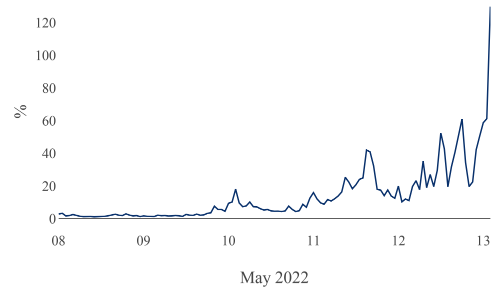
5.3 Price Oracle

Another flaw in the design of the UST stablecoin is the Price Oracle. As the dollar price of Luna did not exist on-chain (as fiat currencies are off-chain assets), they had to be translated to the blockchain from centralized exchanges and were determined in the following way. Every block, the Terra validators submitted the price of Luna on the blockchain, and the Luna Oracle Price was defined as the median among submitted prices. The Oracle Price of Luna was important because it determined the quantity of Luna that a trader received for redeemed UST stablecoins. In other words, every conversion of UST into Luna used the price of Luna from the Oracle Module.

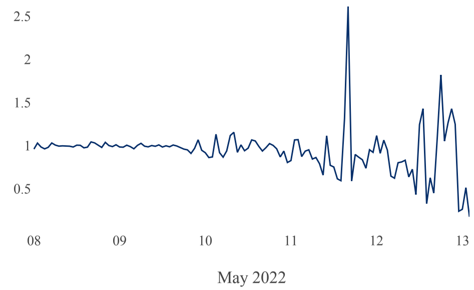
We hypothesize that since the price of Luna was highly volatile and prices could vary across exchanges, the mechanism of determining the Oracle Price might have become imprecise. To verify this, we collect the time series of the Luna Oracle Price and match it with the price of Luna on centralized exchanges. In particular, Figure 8.e reports the deviations of the Luna Oracle Price from the price of Luna on Binance. The figure reveals that the price deviations were substantial, and the accuracy of the Price Oracle deteriorated in the last days of the collapse. On May 11-12, the discrepancies between the Luna Oracle Price and the Luna price on Binance were highly volatile and increased



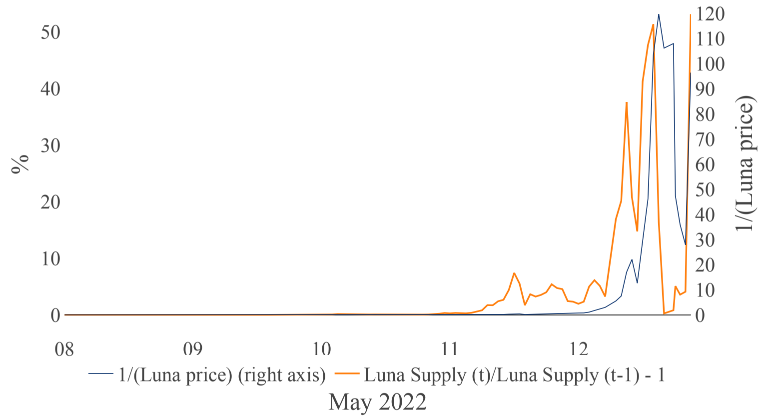
(a) Percentage of the pre-collapse Luna supply (taken on May 1 2022) in the total Luna supply



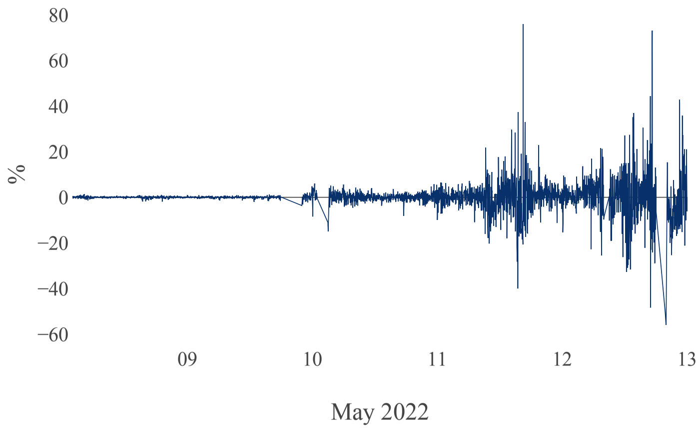
(b) Hourly st. deviation of Luna price returns (Binance)



(c) Luna price growth (Binance)



(d) Growth of the Luna supply and the inverse of the Luna price



(e) Deviations of the Luna Oracle price from the Luna price on Binance, %

Figure 8: The figure reports: (a) the fraction that the pre-collapse Luna supply (taken on May 1 2022) constitutes in the total Luna supply; (b) the hourly st. deviation of the Luna price returns (Binance); (c) the hourly Luna price growth on Binance; (d) the dynamics of the hourly growth of the Luna supply and the inverse of the Luna price (Binance); (e) deviations of the Luna Oracle price from the price of Luna on Binance from May 8, 2022 to May 13, 2022.

up to 70%.

Significant discrepancies between the Luna Price Oracle and the price of Luna on exchanges imply that market participants, independent of their sophistication and experience, could incur significant losses if they withdraw UST through the Market Module.

In addition to the deteriorated accuracy of the Price Oracle, there was no way to directly redeem the UST stablecoin for dollars or any cryptocurrency except for Luna. As a result, there was a time gap between the conversion of UST into Luna in the Market Module and selling Luna on exchanges.

As the price stabilization mechanism of UST relied on arbitrage incentives, we hypothesize that a combination of several design flaws - non-instant conversion of UST into dollars, deteriorated accuracy of the Price Oracle, and high volatility of the backing token Luna - created significant uncertainty for arbitrageurs regarding the execution price of Luna on exchanges and made redemption through the Market Module unattractive. This, in the end, led to the inability of UST to restore the peg.

In the next section, we identify arbitrageurs among the wallets that made UST withdrawals in the Market Module and investigate the demand for UST from these wallets over the collapse period.

5.4 Arbitrageurs Demand for UST

The Market Module of Terra Station and Anchor are both protocols on the Terra Blockchain. Therefore, an investor who deposited UST in the Anchor Protocol could redeem the stablecoin in the Market Module using the same wallet address. We use this fact to match wallet addresses from both protocols and classify wallets that made redemption transactions in the Market Module into three categories: 1) arbitrageurs, 2) UST holders, and 3) UST holders who also acted as arbitrageurs.

We classify a wallet as an "arbitrageur" if, between May 5 and May 13, 2022, the wallet meets the following criteria: 1) made a total of more than 20 redemption transactions in the Market Module, AND 2) redeemed more than \$10,000, AND 3) did not hold UST in the Anchor Protocol.

A wallet is defined as "a UST holder" if one of the following three conditions are met: 1) the ratio of UST redeemed in the Market Module to UST withdrawn from Anchor Protocol is ≤ 1, OR 2) the wallet did not hold UST in Anchor and the number of redemption transactions in the Market Module is less than 20, OR 3) the wallet did not hold UST in Anchor and the total amount of UST redeemed in the Market Module is less than \$10,000.

All other wallets are classified as "holders-arbitrageurs" as these wallets redeemed more UST in the Market Module than they held in the Anchor Protocol.

Table 2 presents summary statistics on wallet classification. The number of wallets classified as ”arbitrageurs” is 470. Out of 4.9bln UST redeemed in the Market Module, these wallets withdrew 3.08bln UST, i.e. 62.85% of all UST redeemed. Another 1.13bln (23.06%) was redeemed by wallets, classified as ”holders-arbitrageurs”, i.e. 1,725 wallets that held deposits in the Anchor Protocol but also actively redeemed UST in the Market Module. The total amount of UST withdrawn by this group of wallets from the Anchor Protocol is only 350mln UST. Finally, this table suggests that out of 11.9bln net withdrawals from the Anchor Protocol, only 2.75bln UST were directly withdrawn through the Market Module of Terra Station. These findings suggest that most of the depositors in the Anchor Protocol either 1) preferred direct selling UST on exchanges instead of redeeming in the Market Module or 2) were not familiar with the redemption procedure of the UST stablecoin.

Summary statistics on wallets that interacted with the Market Module

Classification	Holders	Holder-Arb.	Arbitrageurs	Top-100 Arb.
n. of unique wallets	27,586	1,725	470	100
UST Volume Redeemed in the Market Module, $	406,923,816	696,000,881	1,853,950,661	1,271,485,195
Avg Redemption Size in the Market Module, $	6,934	39,191	33,749	33,210
UST Volume Redeemed in the Market Module, UST	647,669,752	1,130,929,954	3,082,418,432	2,077,206,580
Avg Redemption Size in the Market Module, UST	11,036	63,682	56,112	54,255
UST Volume Withdrawn from the Anchor Protocol, UST	2,402,916,978	350,408,316	0	0
Avg Withdrawal Size from the Anchor Protocol, UST	87,106	203,135	0	0

Table 2: This table reports summary statistics on wallets that made redemption transactions (i.e. withdrawals of UST) in the Market Module of the Terra Station between May 5 and May 13, 2022. We classify wallets into three categories: 1) arbitrageurs, 2) UST holders, and 3) UST holders who also acted as arbitrageurs. A wallet is an ”arbitrageur” if the wallet meets the following criteria: 1) made a total of more than 20 redemption transactions in the Market Module, and 2) redeemed more than $10,000, and 3) did not hold UST in the Anchor Protocol. A wallet is defined as ”a UST holder” if: 1) the ratio of UST redeemed in the Market Module to UST withdrawn from Anchor Protocol is <= 1, or 2) the wallet did not hold UST in Anchor and the number of redemption transactions in the Market Module is less than 20, or 3) the wallet did not hold UST in Anchor and the total amount of UST redeemed in the Market Module is less than $10,000. All other wallets are classified as ”holders-arbitrageurs”.

In Figure 9, for each wallet classified as "holder" or "holder-arbitrageur" we compute the amount of time elapsed between the withdrawal from the Anchor protocol and the first redemption transaction in the Market Module. Surprisingly, around 60% of the wallets that withdrew UST from the Anchor Protocol spent more than 1 hour before redeeming UST in the Market Module.

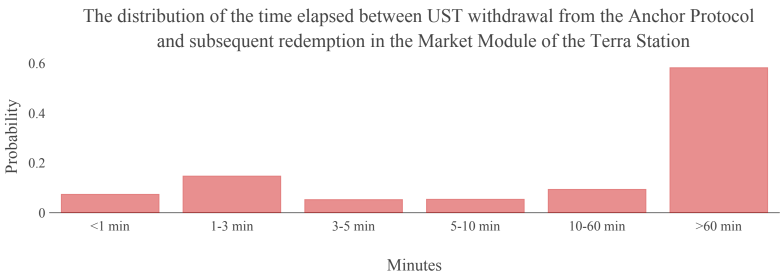


Figure 9: This figure shows the distribution of the time elapsed between UST withdrawal from the Anchor Protocol and subsequent redemption in the Market Module of the Terra Station. The time lag is measured in minutes, with a time lag of 1 minute indicating that a UST holder spent 1 minute after withdrawing the stablecoin from the Anchor Protocol before redeeming it in the Market Module.

Next, in Table 3, we provide an overview of the transactions made by top-5 wallets classified as "arbitrageurs". In the upper panel, we select top wallets by the number of redemption transactions, in the bottom panel - by the dollar volume redeemed in the Market Module. The top-1 wallets in the upper and bottom panels made 3681 and 144 redemption transactions and redeemed \$41,0 mln and \$171,6 mln, respectively. All wallets made transactions in which redemption fees exceed 50%.

As a next step, we study the dynamics of redemption transactions made by wallets classified as "arbitrageurs". For each hour during the collapse period, we compute the total dollar volume redeemed in the Market Module by each group of wallets.

Figure 10 reports the results. First, the figure suggests that the fraction of UST volume redeemed in the Market Module by wallets classified as "UST holders" (green color) rarely exceeded 20% on the first days of the collapse (May 7-9, 2022) but increased significantly since May 10. Second, on May 9-10, 2022 wallets classified as "holders-arbitrageurs" account for the largest fraction of UST redemption volume. This evidence suggests that large (presumably more sophisticated) depositors withdrew UST on the first days of the collapse when the price of UST was still close to \$1. Finally, redemption transactions by arbitrageurs account for a significant fraction of redemption activity on May 11 - 12, 2022; on some hours they redeemed more than 80% of hourly UST volume. These results suggest that arbitrageurs were indeed active in the first days of the collapse. However, their participation visibly decreased on the last day of the collapse.

In Figure 11 we provide a robustness check and report the fraction of hourly UST volume

Summary Statistics on Top-5 Arbitrageurs (top-5 by # of transactions)					
Top-arbitrageur	1	2	3	4	5
# Transactions	3681	2650	2516	2457	2159
UST Price Range, $	0.23 - 1.00	0.26 - 1.00	0.23 - 0.93	0.23 - 0.92	0.24 - 0.94
Redemption Fee Range, %	0.5 - 57.9	0.5 - 56.1	5.2 - 56.2	0.5 - 56.9	5.4 - 56.7
UST Volume Redeemed, $	41,065,225	63,901,788	1,334,107	4,749,561	57,463,813
Avg Transaction Size, $	11,156.0	24,113.8	530.25	1,933.0	26615.9

Summary Statistics on Top-5 Arbitrageurs (top-5 by UST volume redeemed)					
Top-arbitrageur	1	2	3	4	5
# Transactions	144	263	178	2650	127
UST Price Range, $	0.28 - 0.92	0.29 - 0.92	0.33 - 0.85	0.26 - 1.00	0.28 - 0.79
Redemption Fee Range, %	4.5 - 58.8	6.1 - 50.1	6.5 - 58.4	0.5 - 56.1	7.1 - 55.4
UST Volume Redeemed, $	171,600,830	88,334,836	70,494,265	63,901,788	60,265,306
Avg Transaction Size, $	1,191,672.0	335,873.9	396,035.0	24,113.8	474,530.0

Table 3: This table reports summary statistics on the top-5 arbitrageurs that redeemed the UST stablecoin in the Market Module of the Terra Station between May 5 and May 13, 2022. In the upper panel, the top-5 arbitrageurs are the wallets that made the largest number of redemption transactions. In the bottom panel, the top-5 arbitrageurs are the wallets that redeemed the largest volume of UST stablecoin (in $).

redeemed in the Market Module by top-100 arbitrageurs (by the number of transactions). The figure indicates a significant decline in the activity of these wallets: on May 11, these wallets account for 40-60% of total redemption volume while this number dropped below 20% by May 13. In the Appendix, we also report transactions made by top-1 arbitrageur (by the number of transactions and total dollar volume redeemed in the Market Module) as additional evidence of decreased activity of these wallets in the last days of the collapse.

Overall, the evidence presented in Table 2 and Figures 10 and 11 suggests that the demand for UST from large arbitrageurs played a crucial role in stabilizing its price. As the demand from these market participants decreased, the price of the stablecoin continued to decline. The results presented in Figures 10 and 11 are also consistent with our story developed in the previous sections that the demand from arbitrageurs fell once the price of Luna became highly volatile, the accuracy of the Price Oracle deteriorated and the circulating supply of Luna increased many-fold.

The empirical evidence that we presented throughout the section indicates that only a small number of depositors in the Anchor Protocol withdrew the stablecoin in the Market Module, indicating low sophistication of market participants and unfamiliarity with the complex redemption process of the stablecoin. Executing transactions on a blockchain and, in particular, the process of UST redemption requires experience with crypto markets (for instance, cross-blockchain transactions). While arbitrageurs are sophisticated agents and often use bots, inexperienced UST holders need more time and effort to ex-

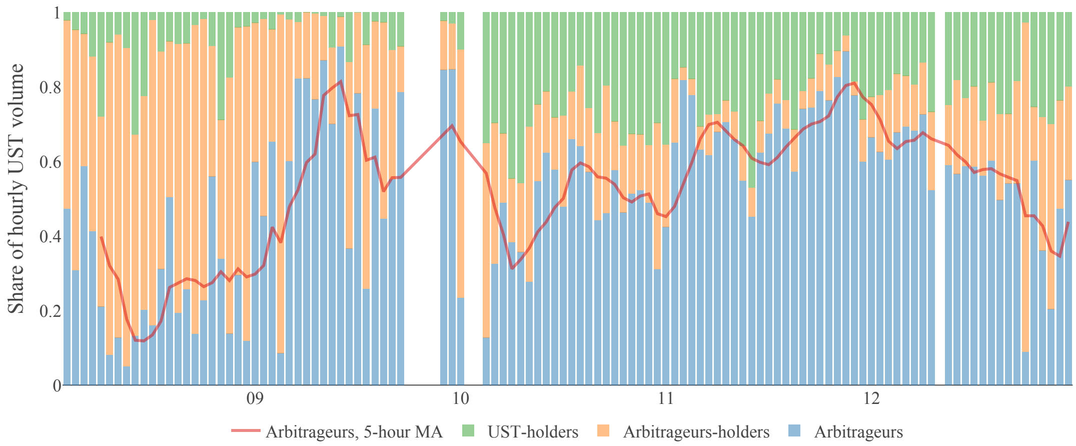


Figure 10: This figure reports the fraction of UST volume (in $) redeemed through the Market Module of Terra Station by each group of wallets that we classified as 1) arbitrageurs (blue color), 2) holders (green color), and 3) holders-arbitrageurs (orange color). The red color shows the 5-hour moving average of the fraction of UST redeemed by wallets classified as arbitrageurs. A blue bar equal, for instance, "0.5" indicates that arbitrageurs account for 50% of total dollar UST volume redeemed in the Market Module in that hour. The time period is from May 7 to May 13, 2022. White gaps correspond to time periods in which data is missing (transactions on the Terra Blockchain were paused or blocks are missing in the data).

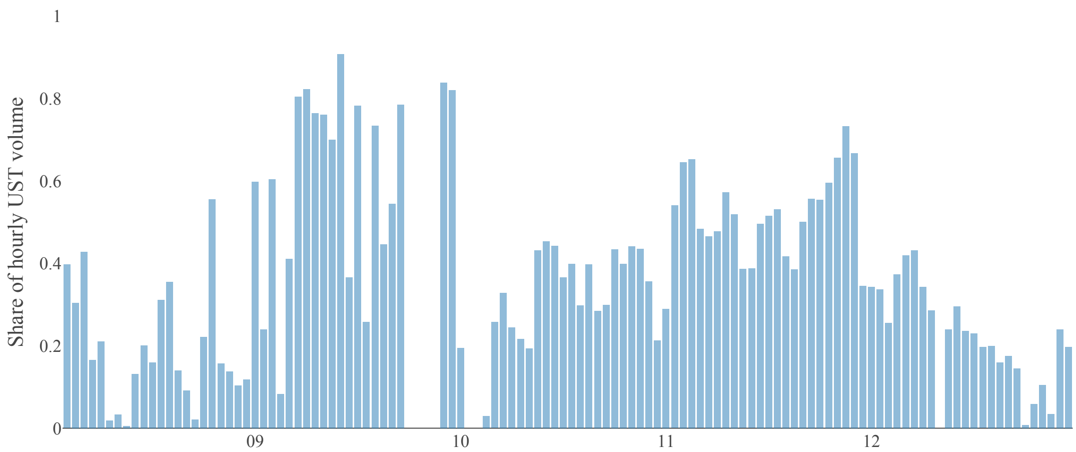


Figure 11: This figure reports the fraction of UST volume (in $) redeemed through the Market Module of Terra Station by top-100 wallets that are classified as "arbitrageurs". A blue bar equal, for instance, "0.5" indicates that arbitrageurs account for 50% of total dollar UST volume redeemed in the Market Module in that hour. The time period is from May 7 to May 13, 2022. White gaps correspond to time periods in which data is missing (transactions on the Terra Blockchain were paused or blocks are missing in the data).

ecute transactions. As a result, selling the stablecoin on exchanges could have been an easier and quicker way for the holders to exit UST positions. We formalize the intuition developed in this section in a simple model in Section 6.

6 Illustrative Model

In this section, we provide an illustrative model to support our empirical analysis.

We start by assuming that there are two market participants: the holder of the UST stablecoin and the arbitrageur, both have CARA utility function with the same risk aversion parameter γ:

$$U_i(w_i) = -\exp(-\gamma w_i),$$

where $i = A, H$, with A and H denoting the arbitrageur (she) and the holder (he), respectively, and w_i is the wealth of each agent.

The holder owns β_W of UST stablecoins, where β_W is exogenously specified and lies in $[0, 1]$. The holder seeks to exit the position by redeeming β_H of the holdings through the Terra Station and selling the rest $(\beta_W - \beta_H)$ to the arbitrageur at UST price P_{UST} on the exchange. The expected wealth of the holder is:

$$w_H = E\left[\underbrace{(1-s)P_{sell}^{Luna}\frac{\beta^H}{P_{Oracle}^{Luna}}}_{redeemUST} + \underbrace{(\beta_W - \beta_H)P_{UST}}_{sellUST}\right]$$

where s denotes the redemption fee, P_{Oracle}^{Luna} - the price of 1 Luna on the Terra Blockchain at the time of redemption, $\frac{\beta_H}{P_{Oracle}^{Luna}}$ - the quantity of Luna that the holder receives in exchange for β_H stablecoins, and P_{sell}^{Luna} - the price of 1 Luna on the exchange at the time of selling. To exit the UST position and receive \$ in exchange for the stablecoin through redemption, the holder: 1) redeems UST through the Terra Station and receives Luna, 2) transfers Luna to a wallet on a crypto exchange, and 3) sells Luna for dollars on the exchange.

The arbitrageur acquires β_A of the UST stablecoins at price P_{UST} and redeems it through the Terra Station. His wealth is:

$$w_A = E\left[\beta_A((1-s)\frac{P_{sell}^{Luna}}{P_{Oracle}^{Luna}} - P_{UST})\right]$$

where $((1-s)\frac{P_{sell}^{Luna}}{P_{Oracle}^{Luna}} - P_{UST})$ is the arbitrage profit per 1 unit of UST.

We assume that redemption fee s is defined as:

$$s = s_0 + \phi(\beta_A + \beta_H)$$

where s_0 reflects the minimum fee (base fee) and ϕ is the sensitivity of the redemption fee to redemption volumes. This definition of the redemption fee reflects two features of the design of the Terra redemption mechanism: that the redemption fee increases with redemption volume and that in the absence of redemption flows, the fee is set at the base value of 0.5%.

The only uncertainty faced by the agents is regarding the discrepancy between the price of Luna on the Terra Blockhain at redemption (i.e., the Luna Oracle Price) and the execution price of Luna on the exchange. As explained in Section 5, this discrepancy arises due to several factors such as high volatility of Luna itself and deviations of the Luna Oracle Price from its price on exchanges. We reflect this uncertainty by assuming that the ratio $\frac{P^{Luna}_{sell}}{P^{Luna}_{Oracle}}$ is a normally distributed random variable with mean μ and volatility σ^2, i.e. $\frac{P^{Luna}_{sell}}{P^{Luna}_{Oracle}} \sim N(\mu, \sigma^2)$.

As shown in Figure 8.b., the price of Luna was rapidly falling over the collapse. For instance, the average 10-minute return on Luna on May 12 and May 13 equals -3%. Thus, we assume $\mu < 1$. σ reflects not only the volatility of Luna but also uncertainty regarding the accuracy of the Price Oracle and the time needed to sell the newly minted Luna.

We assume that the arbitrageur is a sophisticated investor. She correctly estimates μ and σ^2 and maximizes her objective utility function using correct expectations (i.e. $\mu_A = \mu$ and $\sigma_A = \sigma$). In contrast, the UST holder is a less sophisticated and experienced investor, which we reflect by assuming $\mu_H < \mu_A$ and $\sigma_H > \sigma_A$. As arbitrageurs are usually agents with high knowledge of financial markets, it is reasonable to expect that they need significantly less time to complete multiple transactions on the blockchain. In addition, the price of Luna differed across exchanges during the collapse period. Experienced agents - arbitrageurs - often use bots and, thus, are more likely to choose the exchange with the best price and fees to sell Luna.

In the equilibrium, the holder solves:

$$Max_{\beta^H} \left[\beta_H(1-s)\mu_H + (\beta_W - \beta_H)P_{UST} - \frac{1}{2}\gamma\beta_H^2(1-s)^2\sigma_H^2 \right] \tag{2}$$

$$\text{s.t. } \beta_H \in [0, \beta_W].$$

The arbitrageur maximizes:

$$Max_{\beta^A} \left[\beta_A((1-s)\mu - P_{UST}) - \frac{1}{2}\gamma\beta_A^2(1-s)^2\sigma^2 \right] \tag{3}$$

Finally, the price of UST is determined such that:

$$\beta_A^* = \beta_W - \beta_H^*. \tag{4}$$

Parameters

We divide the collapse period into two sub-periods: before May 12th (sub-period I) and after May 12th (sub-period II). This choice is explained by the fact that Terra eased the redemption restriction on May 12th, 2022. Each period is characterized by different parameters μ_A, μ_H, σ_A, σ_H, and ϕ. The purpose is to demonstrate how a combination of changes in those parameters affects the price of UST, trading volume, and expected arbitrage profits.

Table 4 summarizes parameters selected for each period. μ_A and σ_A are chosen to reflect changes in the distribution of Luna price and deteriorated accuracy of the Price Oracle. In particular, we set $\mu_A^I = 0.99$ and $\mu_A^{II} = 0.97$. This means that, on average, the value of Luna tokens received by the arbitrageur drops by 1% and 3%, respectively, before they are sold on the exchange. Further, we set $\phi^I = 0.8$ and $\phi^{II} = 0.7$ to reflect the decreased sensitivity of the redemption fee to redemption volume. With those parameters, the redemption fees are 32.5% and 28.5% in periods I and II, respectively; these values are close to the average redemption fees in the data. As shown in the previous section, the volatility of Luna increased manyfold on the last days of the collapse and the Price Oracle discrepancies went up to 70%. We set $\sigma_A^{2,I} = 0.05$ and $\sigma_A^{2,II} = 0.4$ to reflect these findings. We assume that the holder is an inexperienced investor and set $\mu_H = 0.96$ and $\sigma_H = 0.5$ in both periods. Finally, β_W is taken at 0.40 in both cases.

Parameters	Period I	Period II
μ_A	0.99	0.97
μ_H	0.96	0.96
σ_A^2	0.05	0.40
σ_H^2	0.50	0.50
ϕ	0.80	0.70
γ	5.00	5.00
β_W	0.40	0.40
$1-s$	0.675	0.715
P_{UST}^*	0.44	0.37
β_A^*	0.26	0.21
β_H^*	0.14	0.19
$\frac{(1-s)\mu_A - P_{UST}^*}{P_{UST}^*}$	0.51	0.83

Table 4: The table reports parameters, the equilibrium UST price P_{UST}^*, trading volume on the exchange β_A^*, the amount of UST redeemed by the UST holder (β_H^*), and the expected arbitrage profits $\frac{(1-s)\mu_A - P_{UST}^*}{P_{UST}^*}$. The collapse period is divided into Period I (May 9 - May 11, 2022) and Period II (May 12 - 13, 2022). On May 12 2022, Terra eased the restriction on UST redemptions.

Results

In Period I, as the price of Luna is relatively stable and the accuracy of the Price Oracle is high, the arbitrageur faces lower uncertainty regarding profitability from arbitrage. As a result, the arbitrageur is willing to buy $\beta_A^* = 0.26$ UST from the holder, which is 65% of the total amount of UST stablecoins redeemed in the Terra Station. The holder redeems the rest of his holdings ($\beta_H^* = 0.14$). Despite the strong demand for UST from the arbitrageur, the price of UST holds at $0.44 due to high redemption fees.

In Period II, the sensitivity of the redemption fee to redemption volume decreases. At the same time, the price of Luna becomes more volatile and the Price Oracle deviations increase. This leads to the lower demand for UST from the arbitrageur and, hence, the lower price of UST ($P_{UST}^* = 0.37$) and trading volume ($\beta_A^* = 0.21$). The UST holder redeems 47.5% of his holdings, in contrast to 35.0% in the previous case. Lower UST price increases expected profits from arbitrage (measured as $\frac{(1-s)\mu_A - P_{UST}^*}{P_{UST}^*}$) from 51% to 83%.

This example illustrates that when uncertainty faced by arbitrageurs decreases, the price of UST and trading volume go up (*Empirical Fact 1* and *Empirical Fact 3*, respectively), and arbitrage profits decrease (*Empirical Fact 4*). Table 4 also shows that the divergence between the UST price and $1 - s$ becomes more pronounced with parameters in Period II as the effects from higher σ_A^2 and lower μ_A outweigh those from a reduction in spread s, consistent with the empirical pattern in Figure 7.

In Figure 12, we simulate UST price P_{UST}^* at a 5-minute frequency between May 9 and May 13 and compare it with the actual UST price. For each data point t, we estimate parameters μ_{A_t}, μ_{H_t}, σ_{A_t}, σ_{H_t} and s_t in the data (for the detailed description, see the caption in Figure 12).

The simulated path closely correlates with the dynamics of the actual UST price and matches local price recoveries. In addition, on the last two days of the collapse (May 12-13, 2022), the price significantly diverges from $1 - s$, despite a decrease in redemption fees. For instance, at the end of May 12, the simulated price drops to 40 cents, in line with the actual price of UST, though the redemption fee decreases to below 5%.

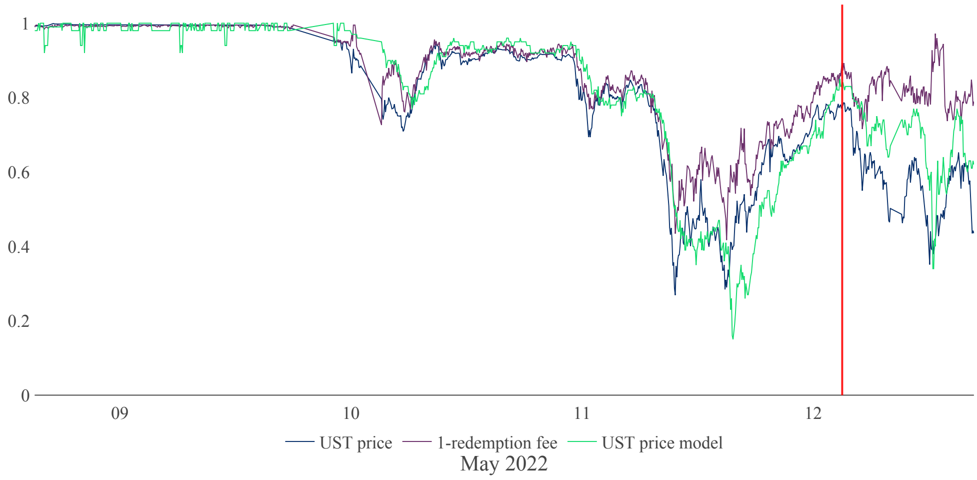


Figure 12: The figure reports the dynamics of the UST price (in blue color), the simulated path of P^*_{UST} (green color), and $1-s$ (purple color), where s is the UST redemption fee, between May 9 and May 13, 2022. Data points are simulated at a 5-minute frequency (denoted by subscript t) using the model in Section 6 and data at a 1-minute frequency (denoted by subscript τ). For each 5-minute data point, we estimate μ_{A_t}, μ_{H_t}, σ_{A_t}, σ_{H_t}, and s_t in the data. μ_{A_t} is defined as the average value of $\frac{P^{Luna}_{sell_\tau}}{P^{Luna}_{Oracle_{\tau-1}}}$ in the last 30 minutes ($\tau = 1, ..., 30$); μ_{H_t} is the minimum value of $\frac{P^{Luna}_{sell_\tau}}{P^{Luna}_{Oracle_{\tau-1}}}$ in the last 30 minutes; $\sigma^2_{A_t}$ is the variance of $\frac{P^{Luna}_{sell_\tau}}{P^{Luna}_{Oracle_{\tau-1}}}$ in the last 30 minutes; $\sigma^2_{H_t}$ is the maximum value of $\sigma^2_{A_\tau}$ in the last 30 minutes; s_t is the average redemption fee in the last 30 minutes; γ is the risk aversion coefficient equal to 3. The red vertical line indicates the moment when Terra eased the restriction on UST redemptions.

7 Conclusions

After the collapse of UST, market participants and social media users made a series of investigations and guesses (see, for instance, articles by Nansen.ai[12] or Jumpcrypto.com[13]) about how and why the crash was initiated, including market manipulation by large investors. These events could have been triggered on purpose or not, but the ultimate lesson is that the design of Terra USD was extremely fragile to sell-off events, even without prior negative news about the stablecoin. In this paper, we collect data from the Terra blockchain and cryptocurrency exchanges and attempt to explain why the arbitrage mechanism did not stabilize the price of UST as expected.

One of our main findings is that the UST stablecoin had floating redemption fees, meaning that when redemption volumes increase, redemption fees also rise. In our calculations, we found that market participants paid redemption fees as high as 60%. High redemption fees, in turn, not only made redemption through the Market Module less

[12] https://www.nansen.ai/research/on-chain-forensics-demystifying-terrausd-de-peg
[13] https://jumpcrypto.com/the-depegging-of-ust

attractive for UST holders but also discouraged arbitrageurs from buying the stablecoin on exchanges. As a result, the price of UST struggled to stabilize in the first days of the collapse.

Once redemption fees were reduced, other flaws in the design of UST appeared to be crucial. Namely, as any UST redemption resulted in the issuance of new Luna tokens, the prolonged price de-peg caused a significant increase in the circulating supply of Luna and dilution of Luna holders. As a result, the price of Luna was falling and became highly volatile. As market participants received Luna in exchange for the stablecoin at redemption, they had to sell their Luna tokens on exchanges afterwards and faced significant uncertainty regarding the execution price of Luna. This uncertainty was also fueled by the deteriorating accuracy of the Price Oracle, the system that provided the off-chain price of Luna to the Terra blockchain. We find that discrepancies between the Luna Oracle Price and its price on Binance reached up to 70% during the collapse. The combination of these design flaws made redemption through the Terra Station unattractive for market participants and eventually broke the price stabilization mechanism of the UST stablecoin.

Our analysis provides several lessons for investors and regulators. First, as floating redemption fees could lead to episodes of prolonged price destabilization, stablecoin issuers should make stablecoins always redeemable at par value. Redemption fees that increase with redemption volume hinder the recovery of the stablecoin price precisely because in times of market panic redemption flows are high. This causes the redemption fee to surge, which, in turn, discourages market participants from buying the stablecoin on exchanges and the price of the stablecoin continues to deviate from the peg.

Second, the choice of the token that backs the stablecoin is crucial. The collapse of Terra USD demonstrates the risk of relying on a backing token whose price volatility and circulating supply are affected by the stablecoin itself. This problem is clearly pronounced for algorithmic stablecoins that rely on a dual-token price stabilization mechanism. However, this problem may also arise for stablecoins backed by Ether or other large cryptocurrencies (e.g., DAI or MIM) if the supply of these stablecoins scales to a significant size.

Finally, price oracles, which act as bridges between centralized exchanges and blockchains, remain a vulnerability for decentralized applications. The collapse of Terra shows that when a stablecoin is backed by a volatile cryptocurrency that is traded on multiple exchanges, it is very dangerous to make the redemption mechanism of the stablecoin rely on some aggregated price measure from those exchanges. In times of market stress, the volatility of the backing token increases, and this leads to discrepancies between the prices of the backing token used at redemption and at the subsequent selling on an exchange.

Another feature of the UST and Luna design that we have not covered in this paper is decentralized decision-making. Any changes to the Terra protocol could only be made through the decentralized governance process, which, in practice, takes time. For example, modifying redemption fees cost Terra one day, as someone had to make a proposal, users and validators needed to vote, and an agreement had to be reached. The speed of the UST collapse indicates that the governance process may be inefficient and slow in managing stablecoin prices when decisions need to be made promptly.

The pre-collapse ”success” of UST highlights that investors in cryptocurrency markets did not fully understand the economics of UST and Luna tokens and the risks associated with them. These events call for the need to educate and warn investors about the risks of investing in various DeFi protocols. Regulators should pay particular attention to redemption fees and redemption mechanisms of stablecoins in market turmoils.

More broadly, our analysis provides an example of how blockchain data can be used to increase transparency about major events in cryptocurrency markets, both for investors and regulators. In 2022, apart from the UST collapse, cryptocurrency markets were hit by a series of large shocks such as defaults of Celsius, Three Arrows Capital, Voyager Digital, and FTX. We hope that future research continues to use transaction-level data from blockchains and cryptocurrency exchanges to shed light on these events, which is ultimately important for building trust in cryptocurrency markets.

References

Ante, L., Fiedler, I., and Strehle, E. (2020). The influence of stablecoin issuances on cryptocurrency markets. *Finance Research Letters*, 41:1–10.

Aramonte, S., Huang, W., and Schrimpf, A. (2021). Defi risks and the decentralisation illusion. *BIS Quarterly Review*, 4.

Baumöhl, E. and Vyrost, T. (2020). Stablecoins as a crypto safe haven? not all of them! *Econstor working paper: 10419/215484*.

Baur, D. G. and Hoang, L. T. (2021). A crypto safe haven against bitcoin. *Economics Letters*, 38:1–7.

Bellia, M. and Schich, S. (2020). What makes private stablecoins stable? *SSRN working paper: 3718954*.

Borri, N. and Shakhnov, K. (2018). Cryptomarket discounts. *SSRN working paper: 3124394*.

Borri, N. and Shakhnov, K. (2022). The cross-section of cryptocurrency returns. *The Review of Asset Pricing Studies 12.3*, 12(3):667–705.

Cao, Y., Dai, M., Kou, S., Li, L., and Yang, C. (2021). Designing stable coins. *SSRN working paper: 3856569.*

Catalini, C., de Gortari, A., and Shah, N. (2021). Some simple economics of stablecoins. *MIT Sloan Research Paper: 6610-21.*

d'Avernas, A., Bourany, T., and Vandeweyer, Q. (2021). Are stablecoins stable? *Banque de France working paper*, 02-21.

Gorton, G. B., Ross, C. P., and Ross, S. (2022). Making money. *Unpublished working paper. NBER: w29710.*

Gorton, G. B. and Zhang, J. (2021). Taming wildcat stablecoins. *University of Chicago Law Review working paper*, 90.

Griffin, J. and Shams, A. (2020). Is bitcoin really untethered? *The Journal of Finance*, 75(4):1913–64.

Harvey, C., Ramachandran, A., and Santoro (2021). Defi and the future of finance. *John Wiley & Sons book*, pages 1–81.

Jarno, K. and Kolodziejczyk, H. (2021). Does the design of stablecoins impact their volatility? *Journal of Risk and Financial Management*, 14(2):42.

Kozhan, R. and Viswanath-Natraj, G. (2021). Decentralized stablecoins and collateral risk. *SSRN working paper: 3866975.*

Kristoufek, L. (2021). Tethered, or untethered? on the interplay between stablecoins and major cryptoassets. *Finance Research Letters*, 42:1–5.

Kwon, Y., Kim, J., Kim, Y., and Song, D. (2021). The trilemma of stablecoin. *SSRN working paper: 3917430.*

Li, Y. and Mayer, S. (2022). Money creation in decentralized finance: A dynamic model of stablecoin and crypto shadow banking. *SSRN working paper: 3757083.*

Lyons, R. K. and Viswanath-Natraj, G. (2021). What Keeps Stablecoins Stable? *SSRN working paper: 3508006.*

Makarov, I. and Schoar, A. (2020). Trading and arbitrage in cryptocurrency markets. *Journal of Financial Economics*, 135(2):293–319.

Mizrach, B. (2022). Stablecoins: Survivorship, transactions costs and exchange microstructure. *SSRN working paper: 3835219.*

Park, A. (2021). Conceptual flaws of decentralized automated market making. *Unpublished working paper. SSRN: 3805750.*

Schär, F. (2021). Decentralized finance: On blockchain-and smart contract-based financial markets. *FRB of St. Louis Review, SSRN working paper: 3843844.*

the EU Council Proposal (2022). Digital finance: agreement reached on european crypto-assets regulation (mica). *June 30 2022.*

the US President's Working Group Report on Stablecoins (2021). Press release. *November*

1 2021.

Uhlig, H. (2022). A luna-tic stablecoin crash. *NBER working paper: w30256*.

Wang, G.-J., Ma, X.-y., and Wu, H.-y. (2020). Are stablecoins truly diversifiers, hedges, or safe havens against traditional cryptocurrencies as their name suggests? *Research in International Business and Finance*, 54:1–18.

Wei, W. C. (2018). The impact of tether grants on bitcoin. *Economics Letters*, 171(C):19–22.

A Appendix

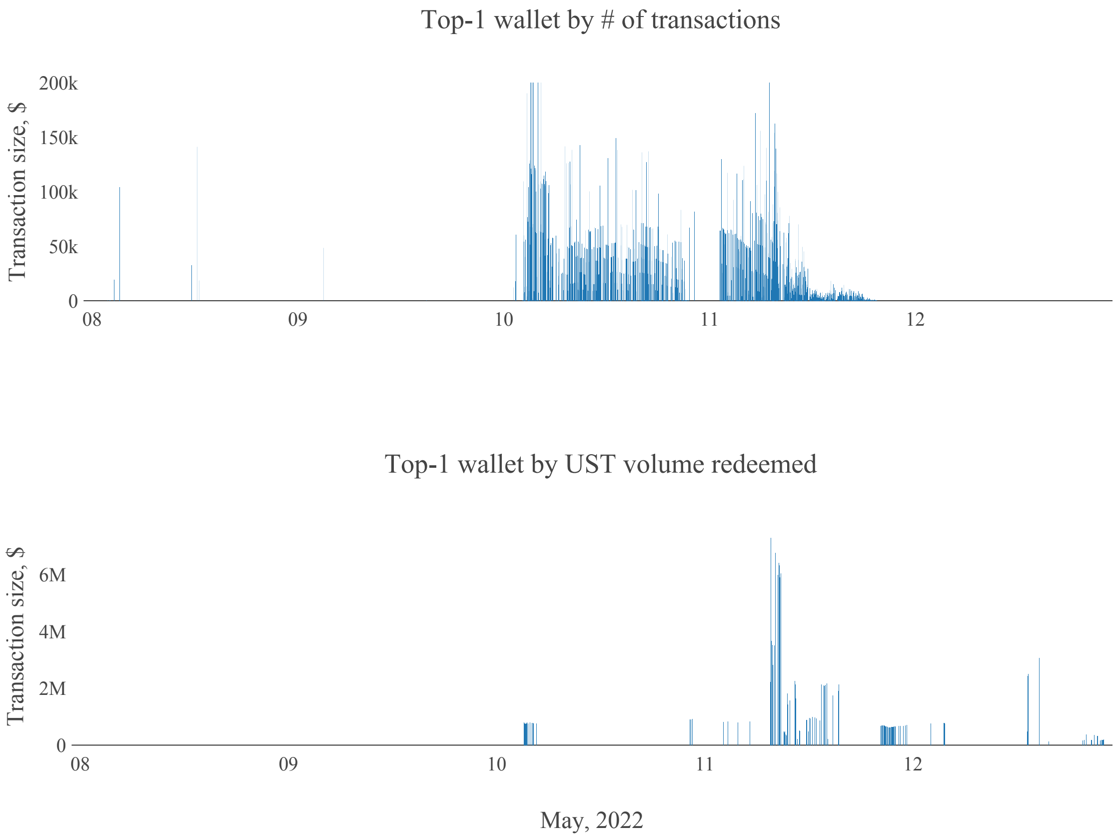


Figure 13: The figure shows transactions made by the top-1 arbitrageur in the Market Module of the Terra Station between May 8 and May 13, 2022. In the upper figure, the top-1 arbitrageur is defined as the wallet that made the largest number of redemption transactions (address: *(terra1hsh3ve4vrqnluccws9gwh5sg4jchuc352md2kw)*. In the bottom panel, the top-1 arbitrageur is the wallet that redeemed the largest volume of UST stablecoin (in $) (address: *(terra1hz0q2qgsgetaqwxds95angslxfyvkpzcfr4j9z)*.

.