Essays on Modern Derivatives Markets

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HANDELSHØJSKOLEN

Essays on Modern Derivatives Markets

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The CBS PhD School is an active and international research environment at Copenhagen Business School for PhD students working on theoretical and empirical research projects, including interdisciplinary ones, related to economics and the organisation and management of private businesses, as well as public and voluntary institutions, at business, industry and country level.

Foreword

This thesis is the product of my PhD studies at the Department of Finance and Center for Financial Frictions (FRIC) at Copenhagen Business School. The thesis consists of three self-contained essays, which can be read independently. The first two essays concern the impact of derivative instruments on their underlying markets, while the third essay (co-authored with Jesper Andreasen) analyzes the value of cash as a perpetual option.

The first essay investigates how the rebalancing of leveraged volatility products impacts the underlying volatility (VIX) futures market. I show that the daily rebalancing imposes substantial hidden costs on investors, but find no evidence that the impact is driven by predatory trading or harmful front-running of predictable rebalancing flows. The second essay demonstrates how dynamic hedging of derivatives portfolios that depend on several underlyings can induce a non-fundamental correlation between the underlying asset returns, even in the absence of any fundamental correlation. I provide empirical evidence for the model using two quasi-natural experiments from the Japanese corporate CDS market. In particular, I show that dynamic hedging of counterparty risk associated with currency swap portfolios can influence the correlation between credit and currency markets. The third essay uses option valuation techniques to derive the value of cash in the absence of a zero lower bound on nominal interest rates. The essay demonstrates that cash can have substantial option value when deeply negative nominal rates are possible.

This thesis was only possible due to the kind support of a number of people over the years. In particular, I would like to thank my two advisors David Lando and Fabrice Tourre for their continuous support, invaluable advice and always positive attitude. I am especially grateful to Jesper Andreasen, whose ideas have been inspirational in the writing of this thesis, as well as my former colleagues in Danske Markets, in particular Nicki Rasmussen and Martin Linderstrøm who taught me how finance is practiced in "the real world". I also thank Martin Oehmke for hosting my visit at London School of Economics in 2018.

Moreover, I am deeply grateful to my friends and PhD colleagues for their support. In this respect, I am especially grateful to Jakob Ahm Sørensen, Ben Knox and Jacek Przybyszewski (my cohort) for many great discussions (only occasionally about finance) and good times.

Most importantly, I am grateful to my beloved wife Anna, children Georg and Alice, and my parents for unconditional love and support throughout the years.

Non-technical introduction

A *derivative* is a financial instrument whose final payoff is *derived* from the value of one or more underlying assets. Naturally, in classical derivatives pricing causality is assumed to flow from the value of the underlying asset(s) to the value of the derivative. However, in the presence of certain frictions causality can reverse such that the derivatives market drives the underlying market instead of the other way around. I refer to instances of such reverse causality as *derivatives feedback effects*.

The literature distinguishes between informational and non-informational feedback effects (see, e.g., Ni et al. (2008) and Ni et al. (2020)). Informational feedback effects occur, for example, when the stock option market is quicker than the underlying stock market to process new information about the value of the underlying stocks. Non-informational feedback effects occur, for example, when the hedging transactions that derivatives dealers undertake are so large that they have a material impact on the price(s) of the underlying asset(s) (or the underlying market is not liquid enough to absorb such hedging trades without moving the price). Such feedback effects can increase or dampen volatility depending on the sign of derivatives dealers' *convexity* (in a sense that I make precise below). Loosely speaking: if we plot the total value of derivatives dealers' portfolios against the value of the underlying, does the curve bend upwards or downwards? If it bends downwards (negative convexity), then dealers' hedging activities tend to increase volatility and vice versa. For various reasons, dealers, as a group, often end up sitting on a negatively convex portfolio. The first two chapters in the thesis extend our knowledge about such non-informational feedback effects in the presence of negative convexity on the part of the dealer community.

In the first chapter of the thesis, I study the market impact of rebalancing flows from the issuers of leveraged volatility funds. To deliver on the returns they promise leveraged funds must buy additional futures contracts when the market is up and sell futures contracts when the market is down. The mechanical rebalancing provides a daily source of large, non-informational hedging flows to the underlying VIX futures market and is a natural laboratory for studying the market impact of such flows. Moreover, to minimize tracking error these flows are concentrated around the close of the market. I show that such pro-cyclical flows amplify volatility around the close of the market and impose a substantial implicit cost on investors (whose returns are tied to closing prices). In my sample, these implicit costs, due to the funds' collective market impact, are larger than the explicit fees charged by the issuers.

However, the main result of the paper relates to the role of *predictability* of such flows. It turns out that the rebalancing flows from the issuers of leveraged funds can be predicted by other investors with fairly high accuracy. When another trader's demand for liquidity can be predicted, it usually leads to concerns of front-running and predatory trading, i.e., other traders are assumed to act in a way that harms the liquidity-demanding traders. In this specific case, there are numerous of such concerns – both in the financial press (e.g., Rennison (2015), Lewis (2016) and Pfrang and Wigglesworth (2018)) and among academics (e.g., Pagano et al. (2019)). The predatory trading model in Brunnermeier and Pedersen (2005) is often cited in this respect, but their model also implies that competition between liquidity providers and the lack of a permanent component in liquidity traders' price impact will mitigate (or completely eliminate) the incentive to engage in predatory trading. In fact, the classical market microstructure models imply that order flow that can be credibly verified as uninformed should have limited market impact as liquidity providers prepare and compete to take the other side of such order flow. Admati and Pfleiderer (1991) characterize this situation as a *sunshine equilibrium* in which predictability of their order flow is beneficial to liquidity traders.

In fact, the uninformed nature of rebalancing flows and the relatively low cost of liquidity provision in the VIX futures market (an electronic limit order market) make a sunshine equilibrium a more likely outcome. Indeed, the empirical results strongly support the existence of a sunshine equilibrium around rebalancing flows. First, I find that *larger* rebalancing flows are associated with a *smaller* price impact coefficient (price impact per unit of rebalancing flow). Second, I find that a *higher* degree of predictability generates a *smaller* price impact. Specifically, rebalancing flows driven by market moves that occur early in the trading session are associated with a smaller price impact coefficient than rebalancing flows driven by returns that occur towards the end of the trading session. Finally, I find that a trading strategy that systematically trades in front of the daily rebalancing flows does not earn abnormal profits net of transaction costs: after an initial period of large profits, the profitability of such a trading strategy steadily declines. Together, these findings provide evidence in favor of a sunshine trading equilibrium in which more liquidity is allocated to larger and more predictable rebalancing flows.

From a policy perspective, this is an important conclusion because it leads to policy implications that are radically different from the ones put forth by those concerned with predatory trading. For example, Alexander and Korovilas (2013) propose that exchange-traded VIX products be indexed to average prices (e.g., volume-weighted over a day or over several days) instead of daily settlement prices to obscure the size and timing of rebalancing flows. However, such proposals are likely to be counterproductive because they increase the cost of liquidity provision by removing the coordinating role that the daily settlement serves for liquidity providers.

In the second chapter of the thesis, I investigate a novel source of non-fundamental correlation due to derivatives feedback effects. When the hedging demand from derivatives dealers in an illiquid market depends on the movements in another, more liquid market, this can create a correlation between asset returns in the two markets, even if they are fundamentally uncorrelated. Such cross-dependencies (in market terminology: cross-gamma) naturally arise in a number of situations of practical relevance, and in this chapter I investigate one such example: dynamic hedging of derivatives counterparty credit risk.

The chapter starts by solving a simple partial equilibrium model to illustrate the underlying mechanism and generate precise, testable predictions. In the model, there are two assets whose true values are fundamentally uncorrelated. There are two types of agents: fundamental investors and derivatives hedgers. Fundamental investors know the true value of each asset, but they are constrained in terms of their ability to arbitrage deviations of prices from true values in one of the markets (the illiquid market). Derivatives hedgers are endowed with a portfolio that depends on the prices of both assets. They do not care about true value, and their only objective is to neutralize (in market terminology: delta-hedge) the portfolio against changes in the prices of each of the underlying assets. In the real world, such preferences on the part of derivatives dealers can be motivated by risk limits or regulation that constrains the risk-taking ability of dealers (e.g., the "Volcker Rule"). I solve for the resulting equilibrium and show that a non-fundamental correlation between the two asset prices arises. The *sign* of the induced correlation is determined by the second-order cross-derivative ("$\frac{\partial^2 V}{\partial S_1 \partial S_2}$") of the derivative dealers' portfolio, and the *magnitude* is jointly determined by the cross-derivative and the degree of market illiquidity.

I use the model to derive testable hypotheses about the impact of counterparty risk hedging on the correlation between currency and credit (CDS) markets. When a dealer trades an unsecured derivatives contract with a client, she is exposed to the default of the client in states of the world where the contract has moved against the client. To protect against this risk, most dealers buy CDS protection (credit insurance) on their clients, and the required amount of credit protection moves with the value of the underlying contract. Hence, a "cross-dependence" arises, and if the CDS market is illiquid, then the model predicts that the hedging activities of dealers will induce a non-fundamental correlation between CDS spreads (the price of credit insurance) and the price of the underlying asset.

I find strong empirical support for such non-fundamental correlations driven by counterparty risk hedging. First, I show that dealers' hedging of the counterparty credit risk associated with SoftBank's currency swap portfolio induces a substantial, negative correlation between the dollar/yen exchange rate and SoftBank's credit (CDS) spread. In 2013, SoftBank rapidly increased the size of its currency swap portfolio, from zero to more than \$25bn, which I argue represents an exogenous shock to dealers' hedging demand. Second, I use a change in the accounting treatment of derivatives counterparty risk in Japan (which essentially forced dealers to start hedging) to show that dynamic counterparty risk management induces a significant change in the correlation between corporate CDS spreads and implied volatility in the currency market.

The third and final chapter of the thesis is not related to derivatives feedback effects. Instead, it asks the question: what happens to the value of physical currency if (when?) central banks drop the "peg" between physical currency and electronic money? Currently, central banks accommodate demand for physical currency at par value with the result that nominal interest rates are bounded from below at zero (or slightly below zero due to storage costs of physical currency). However, as pointed out by Rogoff (2017) and others, the existence of cash in unlimited supply constrains monetary policy at the zero lower bound. The starting point for the last chapter is that central banks drop the "peg" between electronic money and physical currency in order to eliminate the lower bound on nominal interest rates. We then ask: what is the price of cash, in terms of electronic deposits, in such a world? It turns out that there is a unique answer (given our choice of model for the nominal short rate) based on standard no arbitrage arguments and option pricing principles.

In particular, we show that the price of cash can be characterized as the value of a perpetual option and that there is a semi-closed form solution under certain restrictions regarding the dynamics of the nominal short rate. We find that the option value of cash can be substantial. For example, in a model calibrated to US dollar swap rates and interest rate option prices in March 2020, the premium of cash in terms of electronic deposits rose to around 30% in the absence of a peg and would have increased to more than 300% if the nominal short rate was -5%. In the absence of a lower bound on nominal rates, cash also exhibits strong volatility dependence, and a "perpetuity paradox" arises: the value of cash goes to infinity for certain parameter constellations that are not *ex ante* implausible. However, cash is also subject to early redemption risk, e.g., rather than restricting supply the central bank might decide to phase out paper currency completely. To assess the importance of the maturity dimension, we introduce the concept of a term structure of cash, which relates the value of cash to its expected maturity in the presence of early redemption risk. We find that a substantial fraction of the value of cash derives from the ability to hold on to it for (very) long periods of time.

Non-technical introduction (Danish)

Et derivat er et finansielt instrument, hvis endelige udbetaling afhænger af værdien af et eller flere underliggende aktiver. I den klassiske teori vedrørende prisfastsættelse af derivater antages det, at kausaliteten flyder fra værdien af det eller de underliggende aktiver til derivatets værdi. Ved tilstedeværelsen af visse friktioner kan kausaliteten dog vende om, således at derivatmarkedet driver det underliggende marked i stedet for omvendt. Jeg betegner forekomsten af en sådan omvendt kausalitet som *feedbackeffekter*.

Litteraturen skelner mellem informationsdrevne og ikke-informationsdrevne feedbackeffekter (se eksempelvis Ni et al. (2008) og Ni et al. (2020)). Informationsdrevne feedback-effekter opstår f.eks., når aktieoptionsmarkedet er hurtigere end det underliggende aktiemarked til at indarbejde nye oplysninger om værdien af de underliggende aktier. Ikke-informationsdrevne feedback-effekter opstår f.eks., når de afdækningstransaktioner, som derivathandlere foretager, er så store, at de har en væsentlig indvirkning på prisen på det underliggende aktiv (eller det underliggende marked ikke er likvidt nok til at absorbere sådanne afdækningstransaktioner uden at flytte prisen). Sådanne feedbackeffekter kan øge eller dæmpe volatiliteten afhængigt af fortegnet på dealernes konveksitet (på en måde, som jeg præciserer nedenfor). Løst sagt: Hvis vi optegner den samlede værdi af dealernes derivatporteføljer som funktion af værdien af det underliggende aktiv, bøjer kurven da opad eller nedad? Hvis den bøjer nedad (negativ konveksitet), så vil dealernes afdækningsaktiviteter øge volatiliteten og omvendt. Af forskellige årsager ender dealerne, som gruppe, ofte med en negativ konveks portefølje. De første to kapitler i afhandlingen udvider vores viden om sådanne ikke-informative feedbackeffekter ved tilstedeværelse af negativ konveksitet hos dealerne.

I afhandlingens første kapitel undersøger jeg markedseffekten af rebalanceringshandler fra udstedere af gearede volatilitetsfonde. For at levere det afkast, de lover, skal gearede fonde købe yderligere futureskontrakter, når markedet stiger, og sælge futureskontrakter, når markedet falder. Den mekaniske rebalancering giver et dagligt flow af store, ikke-informative afdækningshandler i det underliggende VIX-futuresmarked og er et naturligt laboratorium til undersøgelse af markedseffekten af sådanne handler. Desuden er disse handler koncentreret omkring markedets lukning for at minimere tracking-fejl. Jeg viser, at sådanne procykliske afdækningshandler forstærker volatiliteten omkring markedslukning og pålægger investorer en betydelig implicit omkostning (idet deres afkast er bundet til slutkurser). I min stikprøve er disse implicitte omkostninger, som følge af fondenes samlede markedspåvirkning, større end de eksplicitte gebyrer, der opkræves af udstederne.

Imidlertid vedrører kapitlets hovedresultat den rolle, som *forudsigelighed* af rebalanceringshandlerne spiller. Det viser sig, at rebalancerings-handlerne kan forudsiges af andre investorer med en høj grad af nøjagtighed. Når en investors efterspørgsel efter likviditet kan forudsiges, fører det normalt til bekymringer om "front-running" og "predatory trading", dvs. andre investorer antages at handle på en måde, der skader de investorer, som forudsigeligt efterspørger likviditet. I dette specifikke tilfælde er der flere sådanne bekymringer – både i den finansielle presse (f.eks. Rennison (2015), Lewis (2016) og Pfrang og Wigglesworth (2018)) og blandt akademikere (f.eks. Pagano et al. (2019)). Modellen i Brunnermeier og Pedersen (2005) nævnes ofte i denne henseende, men denne model indebærer også, at konkurrence mellem likviditetsudbydere og manglen på en permanent komponent i prispåvirkningen vil afbøde (eller helt eliminere) incitamentet til "predatory trading". Faktisk indebærer de klassiske markedsmikrostrukturmodeller, at ordreflow, som troværdigt kan verificeres som uinformeret, bør have begrænset markedspåvirkning, idet likviditetsudbydere forbereder sig og konkurrerer om at tage den anden side af sådanne ordrer. Admati og Pfleiderer (1991) karakteriserer denne situation som en *solskinsligevægt*, hvor forudsigeligheden af deres ordreflow er gavnlig for investorer, som efterspørger likviditet.

Faktisk bevirker den uinformerede karakter af rebalanceringshandlerne sammen med de relativt lave omkostninger ved likviditetsudbud på VIX-futuresmarkedet (et elektronisk "limit order"-marked), at en solskinsligevægt er det mest sandsynlige udfald i dette tilfælde. De empiriske resultater understøtter eksistensen af en solskinsligevægt i forbindelse med rebalanceringshandlerne. For det første finder jeg, at større rebalanceringshandler er forbundet med en mindre priseffektkoefficient (prispåvirkning pr. volumen). For det andet finder jeg, at en højere grad af forudsigelighed genererer en *mindre* prispåvirkning. Specifikt gælder det, at rebalancerings-handler som er drevet af markedsbevægelser, der finder sted tidligt i handelssessionen, er forbundet med en mindre prispåvirkningskoefficient end handler, som er drevet af afkast, der opstår mod slutningen af handelssessionen. Endelig finder jeg, at en handelsstrategi, der systematisk handler foran de daglige rebalanceringshandler, ikke genererer risikojusterede afkast efter fradrag af transaktionsomkostninger: Efter en indledende periode med store overskud falder profitabiliteten af en sådan handelsstrategi støt. Tilsammen peger disse resultater på en solskinsligevægt, hvor mere likviditet allokeres til større og mere forudsigelige rebalanceringshandler.

Fra et policy-perspektiv er dette en vigtig konklusion, fordi den fører til anbefalinger, der er radikalt forskellige fra de anbefalinger, der fremsættes af dem, der primært bekymrer sig om "predatory trading". For eksempel foreslår Alexander og Korovilas (2013), at børshandlede VIX-produkter indekseres til gennemsnitspriser (f.eks. volumenvægtet over én dag eller over flere dage) i stedet for daglige lukkekurser for at tilsløre størrelsen og timingen af rebalanceringshandlerne. Sådanne forslag vil formentlig være kontraproduktive, fordi de øger omkostningerne ved tilvejebringelse af likviditet, idet de fjerner den koordinerende rolle, som den daglige lukkekurs har for likviditetsudbyderne.

I afhandlingens andet kapitel undersøger jeg en ny kilde til korrelation mellem aktivpriser drevet af feedbackeffekter. Når afdækningsefterspørgslen fra derivathandlerne i et illikvidt marked afhænger af bevægelserne i et andet, mere likvidt marked, kan dette skabe en korrelation mellem afkast i de to markeder, selvom de fundamentalt set er ukorrelerede. Sådanne krydsafhængigheder (inden for markedsterminologi: kryds-gamma) opstår naturligt i en række situationer af praktisk relevans, og i dette kapitel undersøger jeg ét sådant eksempel: dynamisk afdækning af modpartsrisiko.

Kapitlet starter med at løse en simpel ligevægtsmodel for at illustrere den underliggende mekanisme og generere præcise, testbare forudsigelser. I modellen er der to aktiver, hvis sande værdier er ukorrelerede. Der er to typer af agenter: fundamentale investorer og derivat-hedgers. Fundamentale investorer kender den sande værdi af hvert aktiv, men deres evne til at arbitrere afvigelser i prisen fra den sande værdi er begrænset i det ene af markederne (det illikvide marked). Derivat-hedgers er udstyret med en portefølje, der afhænger af priserne på begge aktiver. De er ligeglade med den sande værdi, og deres eneste mål er at neutralisere (i markedsterminologi: delta-hedge) porteføljen mod ændringer i priserne på hvert af de underliggende aktiver. I den virkelige verden kan sådanne præferencer motiveres af risikogrænser (risk limits) eller af regulering, der begrænser dealernes mulighed for risikotagning (f.eks. "Volcker-reglen" i USA). Jeg løser for den resulterende ligevægt og viser, at der opstår en korrelation mellem de to aktivpriser, selvom de fundamentalt set er ukorrelerede. Fortegnet på den inducerede korrelation bestemmes af den andenordens krydsafledte ("$\frac{\partial^2 V}{\partial S_1 \partial S_2}$") i dealernes portefølje, og størrelsen på korrelationen bestemmes i fællesskab af den krydsafledte og graden af illikviditet i markedet.

Jeg bruger modellen til at udlede testbare hypoteser vedrørende indvirkningen af dynamisk afdækning af modpartsrisiko på korrelationen mellem valuta- og kreditmarkeder (CDS). Når en dealer handler en usikret derivatkontrakt med en kunde, er hun eksponeret mod kundens konkurs i fremtidige situationer, hvor kontrakten er et aktiv for dealeren. For at beskytte sig mod denne risiko køber de fleste dealere CDS-beskyttelse (kreditforsikring) på deres kunder, og den påkrævede mængde af kreditbeskyttelse ændrer sig med værdien af den underliggende kontrakt. Dermed opstår en "krydsafhængighed", og hvis CDS-markedet er illikvidt, forudsiger modellen, at forhandlerens afdækningsaktiviteter vil inducere en korrelation mellem CDS-spænd (prisen på kreditforsikring) og prisen på det underliggende aktiv.

Jeg finder stærk empirisk støtte til fordel for sådanne hedging-inducerede korrelationer drevet af modpartsrisikostyring. For det første viser jeg, at dealernes afdækning af modpartsrisikoen forbundet med SoftBanks valutaswap-portefølje genererer en betydelig, negativ korrelation mellem dollar/yen-valutakursen og SoftBanks kredit-spænd. I 2013 øgede SoftBank hurtigt størrelsen af sin valutaswap-portefølje fra nul til mere end $25 mia., hvilket jeg argumenterer for udgør et eksogent stød til dealernes afdækning. For det andet bruger jeg en ændring i den regnskabsmæssige behandling af modpartsrisiko for derivater i Japan (som effektivt tvang dealerne til at påbegynde en dynamisk afdækningsstrategi) til at vise, at dynamisk modpartsrisikostyring inducerer en signifikant ændring i korrelationen mellem japanske virksomheders CDS-spænd og implicit volatiliteter i valutamarkedet.

Det tredje og sidste kapitel i afhandlingen er ikke relateret til feedbackeffekter. I stedet stiller det spørgsmålet: Hvad sker der med værdien af kontanter, hvis centralbankerne dropper “peggen” mellem fysiske og elektroniske penge? I øjeblikket imødekommer centralbankerne efterspørgslen efter fysisk valuta fuldt ud til den pålydende værdi med det resultat, at nul bliver en nedre grænse for de nominelle renter (eller lidt under nul på grund af omkostningerne forbundet med opbevaring af kontanter). Som påpeget af Rogoff (2017) og andre begrænser eksistensen af kontanter i ubegrænset udbud imidlertid pengepolitikken, når de nominelle renter rammer nul. Udgangspunktet i det sidste kapitel er, at centralbanker dropper ”peggen” mellem elektroniske penge og kontanter for at eliminere den nedre grænse for de nominelle renter. Vi stiller derefter spørgsmålet: Hvad er prisen på kontanter, i enheder af den elektroniske bankkonto, i en sådan verden? Det viser sig, at der er et unikt svar (givet vores valg af model for den korte nominelle rente) baseret på standard “no arbitrage”-argumenter og optionsprisnings-principper.

Specielt viser vi, at kontantprisen kan karakteriseres som værdien af en option med uendelig løbetid, og at der findes en semi-lukket-form løsning under visse begrænsninger med hensyn til dynamikken for den korte nominelle rente. Vi finder, at optionaliteten indbygget i kontantværdien kan være betydelig. For eksempel steg præmien på kontanter til omkring 30% i fravær af nulgrænsen i en model, der var kalibreret til swaprenter og renteoptionspriser i amerikanske dollars i marts 2020. Ydermere ville præmien på kontanter være steget til mere end 300%, hvis den nominelle korte rente faldt til -5%. I fravær af en nedre grænse for nominelle renter udviser kontanter også stærk volatilitetsafhængighed, og der opstår et “perpetuity paradox”: Kontantværdien går mod uendelig for visse parameterkonstellationer, der ikke *ex ante* er implausible. Imidlertid indebærer kontanter også risikoen for førtidig indfrielse, centralbankerne kan f.eks. beslutte helt at udfase kontanter i stedet for blot at begrænse udbuddet. For at vurdere betydningen af løbetidsdimensionen introducerer vi en *terminsstruktur* for kontanter, der relaterer kontantværdien til den forventede løbetid, når der er risiko for førtidig indfrielse. Vi finder, at en betydelig del af kontantværdien stammer fra muligheden for at holde på kontanter over (meget) lange perioder.

Contents

Chapter 1

The Market Impact of Predictable Flows: Evidence from Leveraged VIX Products[†]

Abstract

What is the market impact of predictable order flow? Leveraged exchange-traded products are useful for answering this question because they generate daily rebalancing flows whose size, sign and timing are predictable. This paper presents new evidence from the market for leveraged volatility (VIX) products. I find that the daily rebalancing imposes a substantial implicit cost on investors, but there is no evidence that the impact is driven by predatory trading. On the contrary, I show that larger and more predictable flows have *smaller* price impact coefficients, and that trading ahead of rebalancing flows is not profitable after transaction costs.

[†]I thank David Lando, Lasse Heje Pedersen, Martin Oehmke, Fabrice Tourre, Christian Wagner, Paul Whelan and seminar participants at Copenhagen Business School and the Frontiers in Quantitative Finance 2019 Workshop at the University of Copenhagen. The paper has also benefited from conversations with a number of market practitioners and industry experts at Nomura, Barclays Investment Bank, Bank of America and Invest in Vol.

1.1 Introduction

The rise of passive and rules-based investing generates an increasing amount of predictable order flow. For example, when securities are added to or deleted from indices, when bonds are downgraded, when futures contracts held by ETFs are rolled, and when issuers of leveraged exchange-traded products rebalance their hedges, it leads to predictable order flow from certain market participants. How do such flows impact the market? Do strategic traders provide or withdraw liquidity in anticipation of such flows? This paper presents new evidence from leveraged exchange-traded products (ETPs) linked to VIX futures, whose daily rebalancing provides a frequent flow of large, predictable orders to the VIX futures market.

Anecdotal evidence suggests that there is extensive strategic trading around these flows. For example, according to a market participant quoted in the *Financial Times* "there is an ecosystem of traders that profits from trading in anticipation of ETP flows ahead of the settlement".[1] However, market participants disagree about the impact of such strategic trading. For example, Rennison (2015) quotes the head of strategy at an asset manager as saying that rebalancing flows from leveraged VIX products only have "a small impact, if at all", while a senior strategist at another firm argues that rebalancing flows cause significant volatility, and that their public disclosure exacerbates their market impact. This paper shows that neither view is correct. The daily rebalancing has a substantial impact on the VIX futures market, but it is not driven by predatory trading or front-running. On the contrary, the public disclosure facilitates increased liquidity provision that serves to mitigate the market impact of the rebalancing flows.

The literature contrasts two types of equilibria in the presence of predictable order flow. In a predatory equilibrium other traders strategically withdraw liquidity in order to maximize the price impact suffered by the liquidating trader (Brunnermeier and Pedersen, 2005). Hence, liquidity traders are hurt by other investors' knowledge of their trading flows and should therefore try to hide the size and timing of their orders. Conversely, in a sunshine equilibrium the liquidating trader optimally preannounces her liquidity demand to the market in order to attract liquidity providers and natural counterparties (Admati and Pfleiderer, 1991). In this case, a trader who can credibly demonstrate that her order flow is not motivated by private information is able to trade with limited price impact.

The nature of the equilibrium that emerges in a given situation depends on the circumstances and institutional details of the market, such as the degree of competition among

[1] "Wall Street's volatility products in the spotlight," by Christian Pfrang and Robin Wigglesworth, *Financial Times*, March 6, 2018. See also Alexander and Korovilas (2013) and Rennison (2015).

strategic traders and the extent to which strategic traders are able to correctly identify predictable order flow as uninformed. Bessembinder et al. (2016) demonstrate theoretically that a sunshine equilibrium can arise even in the presence of a single monopolistic trader, depending on the resiliency of the market (the rate at which the limit order book is refilled after an order shock). The only exception is when the price impact is entirely permanent, which is unlikely to be the case if strategic traders can verify that the order flow is uninformed.

In fact, the VIX futures market is not likely to sustain a predatory trading equilibrium for, at least, two reasons. First, an active trading-at-settlement (TAS) market for VIX futures provides a vehicle for preannouncement of predictable order flow. The TAS market allows market participants to commit in advance to trade at the daily settlement price, and it serves to verify order flow as being uninformed since a privately informed trader is unlikely to trade at a not-yet-known price that might incorporate some or all of her information (Pirrong, 2017).[2] Indeed, anecdotal evidence indicates that leveraged VIX products rely extensively on the TAS market, see, e.g., Rennison (2015), Levine (2018) and Pfrang and Wigglesworth (2018). Second, the limit order structure of the VIX futures market means that the barrier to entry for potential liquidity providers is low, consistent with the existence of an "ecosystem of traders" that seeks to profit from rebalancing flows.

My empirical analysis reveals two main findings. First, I find that rebalancing flows from leveraged VIX products exert an economically significant impact on late-day futures returns. The price impact is reversed over the following trading day and generates an implicit cost to investors in leveraged products who are effectively "buying high and selling low" as a result of their own presence in the market. The implicit cost is estimated at 2.4% p.a. during the sample period from November 30, 2010 to December 31, 2017. In my sample, the mean size of the rebalancing flows is 6.7% of average daily volume in the VIX futures market, on occasions reaching more than 50% of average daily volume. Not surprisingly, such a large demand for liquidity in a relatively short window of time has a significant market impact.

Second, I find no evidence of predatory trading or harmful front-running. In particular, I find that *larger* rebalancing flows are associated with a *smaller* price impact coefficient (price impact per unit of rebalancing flow), and that a *higher* degree of predictability generates a *smaller* price impact. Specifically, rebalancing flows driven by intraday returns that occur early in the day are associated with a smaller price impact coefficient than rebalancing flows driven by returns that occur late in the day. These findings are broadly consistent with a sunshine trading equilibrium in which more liquidity is allocated to larger and more predictable rebalancing flows. Finally, I find that a trading strategy that systematically trades ahead of rebalancing flows does not earn abnormal profits net of transaction costs:

[2]See Appendix 1.8 for a more detailed description of the TAS market.

after an initial period of large profits, the profitability of such a trading strategy steadily declines. As noted in Bessembinder (2015), this pattern is what one would expect in a setting where arbitrageurs gradually learn the nature and origin of rebalancing flows and increasingly allocate capital in order to intermediate these flows.

1.1.1 Related literature

The paper contributes to the literature on the economics of strategic trading. Brunnermeier and Pedersen (2005) develop an influential model of predatory trading in anticipation of an investor's need to liquidate a large position. In their model, strategic trading degrades market quality and maximizes the price impact suffered by the liquidity-demanding trader. In contrast, Admati and Pfleiderer (1991) develop a model of sunshine trading in which uninformed investors rationally make their trading plans public to attract liquidity providers and natural counterparties that can mitigate the price impact of their trades. Carlin et al. (2007) use a game-theoretic approach to study the trade-off between liquidity provision and predatory trading. In their model, strategic traders cooperate most of the time, but cooperation breaks down when stakes are high, leading to episodes of predatory trading. Choi et al. (2019) study the interaction between portfolio rebalancers and informed investors, but in a setting where the rebalancing demand is not publicly known *ex ante*. Petajisto (2011) finds that while index changes generate substantial costs to passive investors, predictability is desirable for investors as it helps coordinate the large spike in demand from passive funds on the effective day of the index change. In contrast, Chen et al. (2006) argue that index providers should reduce predictability in index composition to throw off predatory traders.

My results complement the empirical results of Bessembinder et al. (2016). They study the predictable monthly roll trades of a large oil ETF and show that bid/ask spreads are narrower, order book depth is greater, and market resiliency is larger on roll days compared to non-roll days, consistent with a sunshine equilibrium. In contrast, I provide direct evidence that larger and more predictable flows are associated with a smaller price impact coefficient, which–to my knowledge–is new to the literature and of primary importance to investors. Furthermore, my analysis is based on a larger and more frequent source of predictable order flow, which allow for better identification of the market impact. In particular, the relative size of the *daily* rebalancing flow in my sample (6.7% of average daily volume) is similar to the relative size of the *monthly* roll trades in their sample (5% of roll-day volume for the front-month contract, 10% of roll-day volume for the second contract), and my sample is substantially larger (I consider flows at the daily frequency from November 30, 2010 to December 31, 2017 compared to flows at the monthly frequency from March 1, 2008 to

February 28, 2009 in Bessembinder et al., 2016).

The paper also contributes to the literature on the impact of exchange-traded products (such as ETFs) on market quality. Tuzun (2014) and Shum et al. (2016) find that rebalancing flows from leveraged ETFs on stock indices amplify late-day price movements and volatility, especially at times of market stress where the rebalancing flows are large. Cheng and Madhavan (2009) analyze the mechanics of leveraged products and their implications for market volatility and liquidity. Alexander and Korovilas (2013) provide a comprehensive study of exchange-traded products indexed to VIX futures. They argue that the current construction of such products is sub-optimal and underpins large-scale speculative front-running of hedging flows. Todorov (2019) shows that ETP rebalancing is priced in the level of VIX futures. Finally, Pagano et al. (2019) analyze a number of potential risks associated with ETFs, including possible front-running of rebalancing trades. I contribute to this literature by analyzing the market impact of leveraged exchange-traded products in a setting where rebalancing flows represent a significant fraction of the underlying market volume.

1.2 Mechanics of leveraged exchange-traded products

A leveraged exchange-traded product is a financial instrument that promises a constant multiple β of the daily return of some underlying index. That is, the investor supplies initial investment capital of L_0 and the daily net asset value is then updated according to:

$$L_{t+1} = L_t \left(1 + \beta r_{t+1}\right) + f_t, \tag{1.2.1}$$

where r_{t+1} is the return on the underlying index from day t to day $t+1$, $\beta \neq 1$ is the leverage target, and f_t captures accrued interest and management fees (which is not modelled). Leveraged products with $\beta < 0$ are referred to as inversely leveraged products (or inverse products, for short).

Issuers of leveraged products generally engage in hedging transactions to neutralize the exposure to the underlying asset. Importantly, the hedging strategy of a leveraged product is *dynamic* in the underlying asset, i.e., to deliver the promised leverage, the issuers must rebalance the exposure to the underlying asset on a daily basis. Some issuers of leveraged products enter into customized total return swaps with derivatives dealers that relieve them from the daily rebalancing transactions. However, the potential for leveraged products to impact their underlying market is unlikely to depend on whether the issuers are hedging their exposure with OTC swaps or directly in the futures market. This is because the swaps used by the issuers to transfer the rebalancing risk to derivatives dealers are themselves almost surely delta-hedged in the futures market. The rebalancing demand ultimately ends up in the futures market whether the hedging is performed directly by the issuer or indirectly by the swap counterparty. I now derive the rebalancing demand, which is the main independent variable in the empirical analysis.

1.2.1 Rebalancing demand

I focus on leveraged products that track an underlying futures index. The futures index has price process S_t and the (nominal) contract size is m. The daily return is $r_t \equiv \frac{S_t - S_{t-1}}{S_t}$. Consider a leveraged fund i with target $\beta_i \neq 1$ with total assets $A_{i,t}$ on date t. The rebalancing demand of fund i is characterized by the following proposition.

Proposition 1.1 (Rebalancing demand). *The date-t rebalancing demand (in terms of the number of futures contracts) of leveraged fund i is given by:*

$$\Delta_{i,t} \quad = \quad \beta_i \left(\beta_i - 1\right) \frac{r_t}{1 + r_t} \frac{A_{i,t-1}}{m \times S_{t-1}}, \tag{1.2.2}$$

where β_i is the leverage target of fund i, r_t is the daily return of the underlying futures index from date $t-1$ to date t, S_{t-1} is the futures settlement price on date $t-1$, m is the futures contract size and $A_{i,t-1}$ is the assets under management of fund i on date $t-1$.

Proof. See Appendix 1.7. □

Equation (1.2.2) shows that i) the rebalancing demand has the same sign as the market return, i.e., a leveraged product buys when the market is up and sells when the market is down, and ii) there is no offset across leveraged long products ($\beta > 1$) and inversely leveraged products ($\beta < 0$), i.e., both long and inverse products rebalance in the same direction.

Together these properties imply that we may form the aggregate date-t demand of leveraged products, as a group, by summing the size of the rebalancing demand across all leveraged and inverse products traded in the market:

$$|\Delta_t| \equiv \sum_{i=1}^{M} |\Delta_{i,t}|\,, \tag{1.2.3}$$

where M is the total number of leveraged and inverse products that are traded in the market.

1.2.2 Simple example

It is helpful to go through a simple example to understand intuitively the properties of the rebalancing mechanics.

Consider a leveraged fund with target $\beta = 2$ on an underlying investable asset X with initial price $X_0 = \$100$. Interest rates are zero. The fund issues a single share at a net asset value of $L_0 = \$100$, borrows an additional $-\$100$ from the bank account B and buys two shares of X for \$200. On day 1, the underlying doubles in value from $X_0 = \$100$ to $X_1 = \$200$, i.e., $r_{1,X} = 100\%$. Then $L_1 = 2 \times X_1 + B_0 = \$400 - \$100 = \$300$, so the realized return on day 1 is:

$$r_{1,L} = \frac{L_1 - L_0}{L_0} = \frac{\$300 - \$100}{\$100} = 200\% = 2 \times r_{1,X}.$$

Thus, the fund is initially levered 2:1 as desired. Now consider what happens when the fund does not rebalance, i.e., it still holds two shares of the underlying after day 1 and owes $B_1 = -\$100$ to the bank. On day 2, the underlying doubles in value again from $X_1 = \$200$ to $X_2 = \$400$, i.e., $r_{2,X} = 100\%$. Then $L_2 = 2 \times X_2 + B_1 = 2 \times \$400 - \$100 = \$700$, so the realized return is:

$$r_{2,L} = \frac{L_2 - L_1}{L_1} = \frac{\$700 - \$300}{\$300} = 133\% < 2 \times r_{2,X}.$$

Hence, to keep leverage from falling below target the fund must buy more shares of the underlying when the market rises (a similar example shows that the fund must sell shares when the market falls). From Proposition 1.1, the fund needs to buy $\Delta_1 = 2 \times (2-1) \times \frac{100\%}{1+100\%} \times \frac{\$100}{\$100} = 2$ additional shares of the underlying at time 1. It borrows an additional $2 \times X_1 = \$400$ to pay for the new shares.

Now consider instead an inverse fund on the same underlying with leverage target $\beta = -1$. The fund issues a single share at an initial net asset value of $L_0 = \$100$, shorts one share of X and invests the proceeds in the bank account. Thus, it invests a total of $B_0 = \$200$ in the bank account consisting of the investors' capital plus the proceeds from the short sale.[3] On day 1, the underlying halves in value from $X_0 = \$100$ to $X_1 = \$50$, i.e., $r_{1,X} = -50\%$. Then $L_1 = -1 \times X_1 + B_0 = -\$50 + \$200 = \$150$, so the realized return on day 1 is:

$$r_{1,L} = \frac{L_1 - L_0}{L_0} = \frac{\$150 - \$100}{\$100} = 50\% = -1 \times r_{1,X}.$$

[3] In reality, the cash from the short sale would be pledged as collateral to the broker from which the shares are borrowed, but I abstract from such issues to focus on the rebalancing mechanics.

Thus, the fund is initially levered -1:1 as desired. Now consider what happens when the fund does not rebalance, i.e., it still holds a short position in 1 share of the underlying after day 1 and holds $B_1 = \$200$ in the bank. On day 2, the underlying halves in value again from $X_1 = \$50$ to $X_2 = \$25$, i.e., $r_{2,X} = -50\%$. Then $L_2 = -1 \times X_2 + B_1 = -1 \times \$25 + \$200 = \$175$, so the realized return on day 2 is:

$$r_{2,L} = \frac{L_2 - L_1}{L_1} = \frac{\$175 - \$150}{\$150} = 16.67\% < -1 \times r_{2,X}.$$

Hence, to keep leverage from falling below target the inversely leveraged fund must short additional shares of the underlying when the market falls (a similar example shows that the fund must buy back shares when the market rises). We see that the inversely leveraged fund *rebalances in the same direction* as the leveraged long fund, i.e., there is no offset in rebalancing flows across leveraged long and inversely leveraged products. Intuitively, when the market is up the leveraged long fund adds exposure while the inversely leveraged fund cuts exposure in order to support the leverage target. However, the inverse fund cuts exposure by *buying back* some of its shorts, so it ends up trading in the same direction as the leveraged long fund, but from the opposite starting point.

1.3 Price impact of predictable rebalancing flows

In this section, I empirically identify the price impact of leveraged exchange-traded products on VIX futures prices, and provide an estimate of the implicit cost to investors due to their own presence in the market. In the next section, I analyze whether strategic trading tend to increase or mitigate the market impact of rebalancing flows.

1.3.1 Market overview

The most actively traded leveraged VIX products are indexed to the *S&P 500 Short-Term Volatility Index* (SPVXSP), which represents a weighted portfolio of the first and second VIX futures contracts. The index is designed to replicate the return of a synthetic futures position with a constant maturity of 30 days, and the underlying contracts are rolled each day to ensure that the effective maturity is kept constant at 30 days.

The first exchange-traded volatility product was introduced by Barclays Capital in January 2009, while the first leveraged product was launched by Credit Suisse in November 2010. The hedging instruments used by the issuers of leveraged VIX products generally consist of a combination of futures contracts and OTC total return swaps. As an example, Table 1.1

reports the holdings of the ProShares Ultra VIX Short-Term Futures ETF (a leveraged long fund) as of February 22, 2018. This particular ETF held long positions in the two near-term futures contracts underlying the index as well as an OTC total return swap that directly references the index. As noted above, the impact of leveraged products on the underlying futures prices is unlikely to depend on the particular set of hedging instruments employed by the issuers.

In my sample, there were four leveraged exchange-traded volatility products tied to short-term VIX futures. I have mapped the universe of leveraged exchange-traded volatility (VIX) products using the *Bloomberg* system and *ETFdb.com*. In addition, I have used the comprehensive list of volatility ETPs maintained by Vance Harwood on his website *Six Figure Investing*[4] as a cross-check.[5] The four products are listed in Table 1.2.

Figure 1.1 shows the evolution of total assets managed by leveraged VIX products, grouped by leverage (inverse or long). Assets peaked in the second half of 2017 at around $3.5bn with the majority of assets invested in inversely leveraged products.

While the nominal size of the market for leveraged VIX products is small compared to, say, the market capitalization of the S&P 500, it is substantial compared to the underlying VIX futures market (of course, in risk exposure terms, the market is much larger than implied by the nominal size since VIX futures are substantially more volatile than the S&P 500). To give a sense of scale, Figure 1.2 plots the share of total open interest in the first two VIX futures contracts that can be attributed to leveraged VIX products assuming that the issuers hedge the exposure in the futures market on a gross basis, i.e., the hedge notional is given by $H_{i,t} = \beta_i A_{i,t}$ for each issued product i.[6] During the sample period, the share of open interest attributable to leveraged VIX products increased from close to zero in the beginning of 2011 to over 50% on a gross basis in the latter part of 2017 (peaking at almost 80% in 2016).

[4]See https://sixfigureinvesting.com/2010/12/volatility-tickers/.

[5]There were a number of smaller, inverse products that did not employ leverage (such as the iPath Inverse S&P 500 VIX Short-Term Futures), but since these funds do not rebalance their exposure they are not relevant for this study. Finally, there were a small number of registered funds linked to dynamic long-short strategies tied to short-term VIX futures, but assets under management in all of these funds were negligible throughout the sample.

[6]This is an accurate assumption for ETF products that holds the underlying futures directly or through total return swaps. However, issuers of exchange-traded notes (ETNs) are allowed to net exposures across their long and short offerings for hedging purposes, so the attribution somewhat overstates the hedging demand of ETN issuers with long and short offerings.

1.3.2 Data

From Chicago Board of Exchange (Cboe), I have intraday quote and trade data on the first two VIX futures contracts during regular trading hours (9.30 EST to 16:15 EST) from November 30, 2010 through December 31, 2017. From Bloomberg, I have data on total assets, leverage targets, daily prices and shares outstanding for all leveraged VIX products. From Bloomberg, I also obtain official settlement prices of the underlying VIX futures index (SPVXSP). Intraday index returns are calculated from the mid-quotes of the first two VIX futures contracts, sampled at the relevant time of the day, by applying the appropriate portfolio weights for that day. I construct the portfolio weights on each day from the SPVXSP index methodology available from Standard and Poor's website.

1.3.3 Rebalancing flows and late-day price pressure

To investigate the impact of rebalancing flows on the VIX futures market, we must first make an assumption regarding the timing of the rebalancing flows. To minimize tracking error, the managers of leveraged products will generally trade as close as possible to the daily futures settlement at 16:15 EST, e.g., by using the trading-at-settlement (TAS) market (described in detail in Appendix 1.8). However, the rebalancing flows can be expected to impact the market some time before the daily settlement time due to the arbitrage activity of other traders. In line with previous empirical studies, I assume that flows related to the daily rebalancing occur in the last 45 minutes of the trading day, i.e., in the window from 15:30 EST to 16:15 EST.[7] To provide additional justification for this assumption, Figure 1.3 plots the intraday cumulative abnormal return of the first two VIX futures contracts for the top-20 selling flows (upper panel) and the top-20 buying flows (lower panel) in the 60 minutes leading up to the daily settlement. I use the front-month S&P 500 E-mini futures as the market factor. The figure shows that abnormal returns starts to decrease (increase) significantly for the selling (buying) flows after 15:30 EST, consistent with the choice of rebalancing window.

I analyze the impact of the rebalancing flows by means of price impact regressions. The dependent variable is the change in the 1-month constant-maturity VIX futures price from 15:30 EST to 16:15 EST:

$$\Delta S_{t;15:30\to 16:15} \equiv S_{t,16:15} - S_{t,15:30},$$

[7]For example, Shum et al. (2016) likewise assume that rebalancing activities begin 45 minutes before the daily settlement based on conversations with industry experts and traders. All my empirical results have also been performed with window lengths of 15, 30 and 60 minutes with unchanged conclusions.

where $S_{t,x}$ denotes the last mid-quote prior to time x on date t. The main explanatory variable is the rebalancing flow in Equation (1.2.3) normalized by the 20-day average daily volume (ADV) in the underlying VIX futures contracts:

$$\text{Rebal}_t = \frac{1}{\text{ADV}_t} \sum_{i=1}^{M} \beta_i (\beta_i - 1) \frac{r_t}{1 + r_t} \frac{A_{i,t-1}}{m \times S_{t-1}}, \tag{1.3.1}$$

where M runs over the four leveraged exchange-traded products listed in Table 1.2 and ADV_t is the average daily volume in the first two VIX futures contracts over the past 20 trading days. Note that Equation (1.3.1) represents the *anticipated* rebalancing flow as seen from 15:30 EST, since this is what forms the basis for a strategic trader's decision to allocate or withdraw liquidity. Thus, there is no overlap between the returns on the right- and left-hand sides of the price impact regression below, and no simultaneity bias.

Figure 1.4 plots the normalized rebalancing flow in Equation (1.3.1) throughout the sample period. The mean size of the rebalancing flow is 6.7% of average daily volume, but it frequently spikes at much higher values. The sample maximum occurred on June 24, 2016 (the day after the Brexit referendum) where the rebalancing flow from leveraged products amounted to 58% of average daily volume.

The fundamental price impact regression relates the price change during the rebalancing window to the (signed) rebalancing flow:

$$\Delta S_{t;15:30 \to 16:15} = a + b \times \text{Rebal}_t + \gamma^\top \times \text{Controls}_t + e_t. \tag{1.3.2}$$

The coefficient b in Equation (1.3.2) measures the extent to which the rebalancing flow impact late-day futures prices. In particular, $b > 0$ implies that rebalancing flows amplify market moves leading up to the close. The control variables consist of the change in spot VIX (ΔVIX) and realized volatility during the rebalancing window. The realized volatility is computed as the square root of the sum of squared 1-minute futures returns from 15:30 EST to 16:15 EST:

$$RV_t = \sqrt{\sum_{t \in \{15:30;16:14\}} r^2_{t,t+1\,\text{min}}}.$$

Table 1.3 reports the results of the price impact regression in Equation (1.3.2). The price impact of the rebalancing flows is significant both statistically and economically. To interpret the magnitude of the estimated price impact, note that one standard deviation of the rebalancing flow in the sample equals 9.8%: without controls, a one-standard-deviation increase in the rebalancing flow is associated with a price change of $9.8\% \times 0.467 = 0.046$ vol points. Including both controls, the price impact associated with a one-standard-deviation increase is $9.8\% \times 0.394 = 0.039$ vol points. These numbers are economically significant when compared with the average quoted bid/offer spread of approximately 0.05 vol points in the sample.

1.3.4 Rebalancing flows and next-day price reversal

Since rebalancing flows are uninformed, the rebalancing-induced price pressure reported in Table 1.3 should be temporary. To test whether this is the case, I run the following regression:

$$\Delta S_{t-1 \to t} = a + b \times \text{Rebal}_{t-1} + \gamma^\top \times \text{Controls}_t + e_t, \tag{1.3.3}$$

where $\Delta S_{t-1 \to t}$ is the day-to-day change in the underlying futures price as measured from 15:30 EST on day $t-1$ to 15:30 EST on day t. The main explanatory variable is the rebalancing flow on day $t-1$. Complete reversal of prices corresponds to $b = 0$ in Equation (1.3.3): if the rebalancing flow on day $t-1$ has no predictive power over the full 24-hour return, then any price impact in the last 45 minutes of the day must be offset by a subsequent reversal from 16:15 EST on day $t-1$ to 15:30 EST on day t. The control variables are the contemporaneous change in VIX from 15:30 EST on day $t-1$ to 15:30 EST on day t and the realized volatility from 15:30 EST to 16:15 EST on day $t-1$.

Table 1.4 reports the results of the price reversal regression in Equation (1.3.3). With both controls (column 3), the estimated coefficient $\hat{b}$ is not significantly different from zero. I conclude that the price impact of rebalancing flows is temporary, consistent with the uninformed nature of the flows. The temporary late-day price pressure gives rise to an implicit cost to investors in leveraged products that I estimate below.

1.3.5 The implicit cost of rebalancing flows

The temporary price impact induced by the rebalancing flows generates an implicit cost to investors. The cost arises as investors in leveraged products are effectively buying high and selling low as a result of their own market impact. That is, when the market is up the late-day buying from leveraged products temporarily pushes up the daily settlement price and vice versa.

Based on the results above, we can estimate the implicit cost incurred by investors in leveraged VIX products as follows. During the sample period, the mean size of the rebalancing flow is 6.7% of average daily volume. From Table 1.3 the associated price impact is:

$$0.394 \text{ vol points} \times 6.7\%/\text{day} = 0.026 \text{ vol points/day}.$$

This is the average price impact suffered by investors in leveraged products on their daily rebalancing trades. To translate this into a dollar amount we multiply by the average vega (number of VIX futures contracts multiplied by contract size) transacted by the leveraged products as part of their daily rebalancing. The average vega in my sample is \$5.24 mio per vol point per day. This estimate is in line with estimates by market participants, see, e.g., Barclays Equity Research (2017). Thus, on an annualized basis the cost is:

$$\$5.24\text{mio/vol point} \times 0.026 \text{ vol points/day} \times 252\,\text{days} = \$34.3\text{mio}.$$

That is, investors have on average paid \$34.3mio per year in implicit trading costs during the sample period from November 2010 to December 2017. The average amount of assets invested in leveraged VIX products during the sample period is \$1.44bn, so the annualized percentage cost C to investors can be approximated as follows:

$$C = \frac{\$34.3\text{mio}}{\$1.44\text{bn}} = 2.4\%\,\text{p.a.}$$

Thus, investors have paid an estimated 2.4% p.a. in implicit trading costs attributable to the daily rebalancing flows. While this is a significant drag on returns, recall that the underlying futures index is extremely volatile, on the order of 75% p.a. For example, assuming that a short volatility strategy has the same long-term Sharpe ratio as the stock market, say $SR = 0.40$, then the expected return of an inverse volatility fund ($\beta = -1$) is on the order of $0.40 \times 75\% = 30\%$. From that perspective, an extra cost of 2.4% is perhaps not prohibitive. For comparison, Bessembinder et al. (2016) estimates an implicit cost of 3% p.a. for the United States Oil Fund (USO) due to the market impact of its monthly futures roll.

1.4 Strategic trading around rebalancing flows

In this section, I investigate how strategic trading impacts the provision of liquidity around rebalancing flows. While the choice between engaging in (harmful) predatory trading or (beneficial) liquidity provision is dynamic in nature, the empirical evidence is broadly consistent with a sunshine trading interpretation.

1.4.1 Price impact of large rebalancing flows

If strategic traders act in predatory manner and systematically withdraw liquidity ahead of rebalancing flows, then we should expect the price impact coefficient in Equation (1.3.2) to be larger on days when rebalancing flows are large, since this is where the expected profits from predatory trading are greatest.[8] To investigate this, I augment the price impact regression with a dummy variable for days when the rebalancing flow is large:

$$\begin{aligned} \Delta S_{t;15:30\to16:15} &= a + b \times \text{Rebal}_t + c \times \text{DL}_{t,x} \times \text{Rebal}_t \\ &\quad + \gamma^\top \times \text{Controls}_t + e_t, \end{aligned} \tag{1.4.1}$$

where $\text{DL}_{t,x}$ is a dummy variable that is equal to 1 if the size of the rebalancing flow (relative to 20-day average daily volume) exceeds the xth percentile in the sample distribution of rebalancing flows. I take $x \in \{30\%, 20\%, 10\%\}$. Hence, the coefficient c measures the change in the price impact coefficient for the 30%, 20% and 10% largest rebalancing flows, respectively.

Table 1.5 reports the results. Column (1) reports the results for the entire sample and the remaining columns (2) to (4) report the results including the dummy variables for the days with the 30%, 20% and 10% largest rebalancing flows. The estimated coefficients for the dummy variables are all negative and statistically significant implying that the price impact coefficient declines when rebalancing flows are large. This pattern is not consistent with a predatory equilibrium. On the contrary, it points to arbitrageurs that increase available liquidity in anticipation of large rebalancing flows.

One might be concerned that the smaller price impact coefficient on days with large rebalancing flows is due to issuers endogenously placing their rebalancing trades earlier in the trading session on such days. However, this concern is not warranted. Predatory traders optimally trade simultaneously with the liquidating trader (Brunnermeier and Pedersen, 2005) and, since the issuers primary objective is to trade as close as possible to the daily settlement to minimize tracking error, such trading would have to occur close to the time of the daily settlement. Indeed, the extreme spike in VIX futures around the daily settlement on February 5, 2018, which is widely understood to have been caused by leveraged ETP rebalancing, provides concrete evidence for the strong preference for trading close to the daily settlement time.

1.4.2 Do more predictable flows have higher price impact?

In a predatory equilibrium, a higher degree of predictability is associated with more predatory trading and a larger price impact. In contrast, a sunshine equilibrium implies that a higher degree of predictability is associated with a lower price impact because arbitrageurs

[8] Shum et al. (2016) interpret the predatory trading theory similarly. Based on the theoretical framework of Brunnermeier and Pedersen (2005) and Carlin et al. (2007), they state that "our hypothesis [is] that predation occurs when the leveraged ETF rebalancing trades are expected to be large".

have more time to arrange liquidity in advance. We can test this in our empirical setup as follows. The idea is that intraday returns that occur early in the day lead to more predictable rebalancing flows as they are known to other traders for a longer period of time. In contrast, intraday returns that occur late in the day are less predictable in the sense that strategic traders have less time to react to them.

I define the *early-day return* as the return from the previous day's settlement until 15:00 EST on the current day and I define the *late-day return* as the intraday return from 15:00 EST to 15:30 EST. I decompose the anticipated rebalancing flow into two components: the rebalancing flow based on the early-day return (high predictability) and the rebalancing flow based on the late-day return (low predictability). I then run the price impact regression based on the decomposed rebalancing flows:

$$\Delta S_{t;15:30\rightarrow 16:15} = a + b^{\text{early}} \times \text{Rebal}_t^{\text{early}} + b^{\text{late}} \times \text{Rebal}_t^{\text{late}} + \gamma^\top \times \text{Controls}_t + e_t. \tag{1.4.2}$$

Table 1.6 reports the results. The table shows that the price impact coefficient for rebalancing flows due to late-day returns is more than twice the size of the price impact coefficient for rebalancing flows due to the early-day returns. Hence, the more predictable flows have a substantially *smaller* price impact than the less predictable flows, again consistent with a sunshine equilibrium.

1.4.3 Is it profitable to trade ahead of rebalancing flows?

To what extent can strategic traders profit from trading ahead of predictable rebalancing flows? I consider a simple trading strategy that buys (sells) the underlying VIX futures contracts when the futures index is up (down) at 15:30 EST and unwinds the position 30 minutes later at 16:15 EST. Specifically, to mimic the trading pattern of the leveraged products, the strategy trades a portfolio of the first two futures contracts with portfolio weights equal to their respective weights in the underlying SPVXSP futures index. The idea is that when the market is up (down) at 15:30 EST, leveraged products (or their hedging counterparties) will be buyers (sellers) of futures contracts in the last 45 minutes of the trading day, and the strategy attempts to benefit from this knowledge by trading on the same side of the market.

I consider an investor that posts a certain amount of initial margin at inception, transacts the maximum number of contracts consistent with the posted margin and accumulates the profits (or losses) of the strategy in a bank account that accrues the 3-month T-bill rate. The cumulative return of the strategy at time t is given by the balance in the bank account at time t divided by the initial margin kept with the exchange. Due to the high turnover, the strategy is extremely sensitive to transaction costs. Table 1.7 reports the average bid/offer spread during the sample period for the first two VIX futures contracts. The spreads shown in the table are quoted as the number of vol points between the bid and the offer. For example, a bid/offer spread of 0.05 vol points means that the market is quoted as (say) 14.95/15.00.

Thus, based on the table above, a strategy that buys at the offer and sells at the bid will incur transaction costs of approximately 0.05 vol points per day. This provides one estimate of the transaction costs associated with the strategy.[9] In reality, the transaction costs are lower if the position is unwound in the TAS market (TAS is described in detail in Appendix 1.8). The bid/offer spread in the TAS market is lower than in the regular futures market; Huskaj and Norden (2015) reports that the bid/offer spread in the TAS market is approximately equal to 0.01 vol point in their sample. Thus, using their estimate, the transaction costs are approximately $\frac{0.05+0.01}{2} = 0.03$ vol points per day if the position is unwound in the TAS market instead of in the regular futures market. This provides a second (lower) estimate of the transaction costs associated with the strategy.[10]

Figure 1.5 shows the cumulative return of the strategy with zero transaction costs (red), with estimated transaction costs assuming that both legs of the trades are executed in the regular futures market (green) and with estimated transaction costs assuming that the second leg of the trade is unwound in the TAS market (blue).
Before transaction costs, the strategy is highly profitable, returning almost 1,300% since inception in November 2010. However, when I account for transaction costs the performance deteriorates quickly. Table 1.8 reports performance metrics for the strategy with transaction costs ranging from 0 to 0.05 vol points using the 3-month T-bill rate as the risk-free benchmark. For example, the annualized excess return and Sharpe ratio is 402.4% and 5.14, respectively, in the absence of transaction costs, falls to 84.7% and 1.08 with transaction costs of 0.02 vol points and become strongly negative with transaction costs of 0.04 vol points and above.

From Table 1.8 we see that the low value of the estimated transaction costs (0.03 vol points) is close to the boundary where the strategy becomes unprofitable over the sample

[9] We assume that the arbitrageur submit market orders. Transaction costs could be lowered by using limit orders, but at the risk of non-execution on the most profitable days.

[10] As described in Appendix 1.8, trades executed in the TAS market includes a market-determined differential to the settlement price. If the arbitrageur is systematically on the wrong side of the market, the effective spread in the TAS market will naturally be higher. However, the distribution of price differentials is tightly centered around zero. In a sample obtained from Bloomberg covering December 31, 2016 to December 31, 2017, the median price differential was zero, and 96% of TAS trades were priced within two ticks (0.02 volatility points) of the final settlement price.

period, while the strategy is extremely unprofitable over the sample period for the high value of the estimated transaction costs (0.05 vol points). Thus, it seems that any abnormal profits obtained from trading in front of the rebalancing flows are competed away over the sample period (partially or fully, depending on the actual transaction costs incurred). While this does not rule out the possibility of predatory trading, it is consistent with the presence of arbitrageurs that over time allocate an increasing amount of capital to provide liquidity to the uninformed rebalancing flows.

1.4.4 Are rebalancing flows mitigated by capital flows?

Ivanov and Lenkey (2018) note that capital flows (redemption and creation of shares) can potentially mitigate the daily rebalancing flows from leveraged products. In particular, if investors in leveraged products act in a contrarian manner by decreasing (increasing) their exposure on days when they realize a positive (negative) return, then capital flows provides a natural offset to rebalancing flows. Hence, we need to verify that the results above are not biased by offsetting capital flows. Net capital flows to a leveraged fund can mitigate the rebalancing demand of the fund if, and only if, the net capital flow is negatively correlated with the same-day return of the fund. This statement is formalized by the following proposition.

Proposition 1.2 (Capital flows). *Let $\Delta A_{i,t} \equiv \Delta N_{i,t} \times L_{i,t} \times S_t \times m$ denote the change in total assets due to net capital flows into leveraged fund i on date t, where $\Delta N_{i,t} \equiv N_{i,t} - N_{i,t-1}$ is the number of shares of fund i created or redeemed on date t and $L_{i,t}$ is the net asset value of leveraged fund i on date t. The mitigating potential of capital flows can be summarized as follows:*

$$\textit{capital flows mitigate the rebalancing demand of fund } i \iff corr\left[L_{i,t}, \Delta A_{i,t}\right] < 0$$

Proof. See Appendix 1.7. □

Figure 1.6 plots the correlation between daily returns and same-day (zero lag) and future capital flows for the leveraged VIX products in Table 1.2. Correlations for long and inverse products are shown separately. The figure shows that while capital flows for both types of products do exhibit a significantly negative correlation with *lagged* returns, there is no correlation with *same-day* returns (there is a slightly negative correlation for the inverse products, but the magnitude is economically insignificant). Since rebalancing flows are only be mitigated by same-day capital flows, we conclude that there is no offset from capital flows.

1.5 Discussion

I have shown that while rebalancing flows from leveraged VIX products induce a significant impact on late-day VIX futures returns and impose a substantial cost on investors, there is no evidence that the price impact is driven by harmful strategic trading. On the contrary, the price impact is best understood as compensation to liquidity providers for the large amount of liquidity that they provide during a short window of time rather than profits to predatory traders. Rather than being harmed by front-running of late-day rebalancing flows, investors benefit from the liquidity provision of arbitrageurs that allocate liquidity to take the other side. This is an important conclusion, because it leads to policy implications that are radically different from the ones put forth by those concerned with predatory trading. For example, Alexander and Korovilas (2013) propose that exchange-traded VIX products be indexed to average prices (e.g., volume-weighted over a day or over several days) instead of daily settlement prices to obscure the size and timing of rebalancing flows. However, such proposals are likely to be counterproductive because they increase the cost of liquidity provision by removing the coordinating role that the daily settlement serves for liquidity providers.

At the heart of such proposals lies the implicit assumption that the market impact is primarily due to the strategic traders rather than the issuers themselves. However, liquidity provision is not costless. For example, inventory holding costs (e.g., Stoll, 1978), risk-aversion of intermediaries (e.g., Grossman and Miller, 1988) and financial constraints of intermediaries (e.g., Adrian et al., 2014 and Du et al., 2019) all lead to a non-zero cost of liquidity provision that must be compensated by a price impact in equilibrium.

That being said, it is certainly possible that the indices underpinning leveraged products can be improved such that the futures market is better able to absorb large rebalancing flows. For example, the so-called "volmageddon" on February 5, 2018 (e.g., Sushko and Turner, 2018) revealed a number of weaknesses in the short-term VIX futures index construction, see Barton (2019) for a comprehensive discussion of this issue.

1.6 Conclusion

This paper analyzes the market impact of predictable order flow based on the daily rebalancing of leveraged VIX products. The daily rebalancing provides a frequent flow of large orders to the VIX futures market whose size, sign and timing can be accurately predicted in advance.

I find that rebalancing flows significantly impact late-day returns in the underlying

VIX futures market, and that the impact is reversed over the following day. As a result, investors in leveraged VIX products incur a substantial implicit cost, estimated at 2.4% p.a., due to their own presence in the market. However, there is no evidence that the market impact is exacerbated by strategic trading. On the contrary, strategic trading mitigates the price impact of rebalancing flows: larger and more predictable flows are associated with a *lower* price impact coefficient. In addition, there are no abnormal profits from systematically trading ahead of rebalancing flows after transaction costs, consistent with a sunshine equilibrium in which liquidity providers compete to take the other side of uninformed rebalancing flows.

An important policy implication is that proposals to obscure the size and timing of predictable flows are likely to be counterproductive because they increase the cost of liquidity provision. If policy makers are worried about the impact of leveraged products on market quality, they should focus on reforms that facilitate more diversity in indexes and innovations in market structure that enable liquidity provision to uninformed order flow.

1.7 Appendix A – Proofs

Proof of Proposition 1.1

The date-t required hedge notional of fund i with leverage target β_i is given by:

$$H_{i,t} = \beta_i A_{i,t}, \tag{1.7.1}$$

where $A_{i,t} \equiv N_{i,t} L_{i,t}$ is the assets under management of fund i at date t. Assuming that no capital flows ($N_{i,t+1} = N_{i.t}$) we have:

$$\begin{aligned} A_{i,t+1} &= N_{i,t+1} L_{i,t+1} \\ &= N_{i,t} L_{i,t+1} \\ &= N_{i,t} L_{i,t} \left(1 + \beta_i r_{t+1}\right) \\ &= A_{i,t} \left(1 + \beta_i r_{t+1}\right), \end{aligned}$$

where the first and last equality follow from the definition of $A_{i,t}$, the second equality follows from the no capital flows assumption, and the third equality uses the formula for the net asset value in Equation (1.2.1). At date $t+1$, the previous day's hedge is valued at $H_{i,t+1} = H_{i,t}\left(1 + r_{t+1}\right)$ while the required hedge is $H_{i,t+1}^{\text{target}} = \beta_i A_{i,t+1} = H_{i,t}\left(1 + \beta_i r_{t+1}\right)$ from Equation (1.7.1)-(1.7.2). Thus, the change in the hedge notional at date $t+1$ required to maintain a constant leverage factor – the rebalancing flow – is given by:

$$\begin{aligned} H_{i,t+1}^{\text{target}} - H_{i,t+1} &= H_{i,t}\left(1+\beta_i r_{t+1}\right) - H_{i,t}\left(1+r_{t+1}\right) \\ &= \beta_i A_{i,t}\left(1+\beta_i r_{t+1}\right) - \beta_i A_{i,t}\left(1+r_{t+1}\right) \\ &= A_{i,t}\beta_i\left(\beta_i - 1\right) r_{t+1}, \end{aligned}$$

where the second equality holds since $H_{i,t} = \beta_i A_{i,t}$ from Equation (1.7.1). To obtain the rebalancing flow in terms of the number of futures contracts, divide the above expression by the futures notional (price S_{t+1} times contract size m) at time $t+1$:

$$\begin{aligned} \Delta_{i,t+1} &\equiv \frac{A_{i,t}\beta_i\left(\beta_i - 1\right) r_{t+1}}{m \times S_{t+1}} \\ &= \beta_i\left(\beta_i - 1\right)\frac{r_{t+1}}{1+r_{t+1}}\frac{A_{i,t}}{m \times S_t}, \end{aligned}$$

where the last equality follows since $S_{t+1} = S_t(1+r_{t+1})$.

Proof of Proposition 1.2

First, write the total assets at time $t+1$ in terms of the assets at time t and the capital flow from t to $t+1$:

$$\begin{aligned} A_{i,t+1} &= N_{i,t+1}L_{i,t+1} \\ &= N_{i,t+1}L_{i,t}\left(1+\beta_i r_{t+1}\right) \\ &= A_{i,t}\left(1+\beta_i r_{t+1}\right) + \left(N_{i,t+1} - N_{i,t}\right)L_{i,t+1}, \end{aligned}$$

where the last equality follows from adding and subtracting

$$A_{i,t}\left(1+\beta_i r_{t+1}\right) = N_{i,t}L_{i,t}\left(1+\beta_i r_{t+1}\right).$$

Thus, the required adjustment in hedge notional from t to $t+1$, including capital flows, is:

$$\begin{aligned} H_{i,t+1} - H_{i,t}\left(1+r_{t+1}\right) &\equiv \beta_i A_{i,t+1} - \beta_i A_{i,t}\left(1+r_{t+1}\right) \\ &= \beta_i\left\{A_{i,t}\left(1+\beta_i r_{t+1}\right) + \left(N_{i,t+1} - N_{i,t}\right)L_{i,t+1}\right\} - \beta_i A_{i,t}\left(1+r_{t+1}\right) \\ &= A_{i,t}\beta_i\left(\beta_i - 1\right) r_{t+1} + \beta_i\left(N_{i,t+1} - N_{i,t}\right)L_{i,t+1} \end{aligned}$$

Divide by the futures notional $m \times S_{t+1}$ to obtain the demand in terms of the number of contracts at time $t+1$:

$$\Delta_{i,t+1} = \underbrace{\beta_i\left(\beta_i - 1\right)\frac{r_{t+1}}{1+r_{t+1}}\frac{A_{i,t}}{m \times S_t}}_{\text{rebalancing flow}} + \underbrace{\beta_i \frac{\Delta N_{i,t+1} L_{i,t+1}}{m \times S_{t+1}}}_{\text{capital flow}}$$

Now find the notional value (dollar value of futures notional) of the rebalancing demand on date $t+1$:

$$\begin{aligned}
\Delta^{\$}_{i,t+1} &\equiv mS_{t+1}\Delta_{i,t+1} \\
&= mS_t(1+r_{t+1})\Delta_{i,t+1} \\
&= \beta_i\left(\beta_i - 1\right) r_{t+1} A_{i,t} + \beta_i \Delta N_{i,t+1} L_{i,t+1} \\
&= \beta_i\left(\beta_i - 1\right) r_{t+1} A_{i,t} + \beta_i \Delta A_{i,t+1} \\
&= A_{i,t}\left\{\beta_i\left(\beta_i - 1\right) r_t + \beta_i \frac{\Delta A_{i,t+1}}{A_{i,t}}\right\},
\end{aligned}$$

where $\Delta A_{i,t+1} = \Delta N_{i,t+1} L_{i,t+1}$ is the notional (dollar value) of capital flows to leveraged fund i. Denote the total assets invested in leveraged products by $\beta_i = \beta$ by $A_t = \sum_i A_{i,t}$ and denote the net capital flow to these products by $\Delta A_{t+1} = \sum_i \Delta A_{i,t+1}$. By summation, the aggregate notional demand from these products (including both rebalancing and capital flows) is given by:

$$\Delta^{\beta}_{t+1} = \beta A^{\beta}_t \left\{\left(\beta - 1\right) r_{t+1} + \frac{\Delta A^{\beta}_{t+1}}{A^{\beta}_t}\right\}. \tag{1.7.2}$$

From Equation (1.7.2) it follows that capital flows will mitigate rebalancing flows provided that $\operatorname{corr}\left[\left(\beta - 1\right) r_{t+1}, \frac{\Delta A^{\beta}_{t+1}}{A^{\beta}_t}\right] < 0$. This is case if and only $\operatorname{corr}\left[r_{t+1}, \frac{\Delta A_{t+1}}{A_t}\right] < 0$ for leveraged long and $\operatorname{corr}\left[r_{t+1}, \frac{\Delta A_{t+1}}{A_t}\right] > 0$ for inversely leveraged funds, i.e., if capital flows are *negatively* correlated with the same-day return of the fund. This proves the first part of the proposition.

1.8 Appendix B – Trading-at-Settlement (TAS)

The net asset value of leveraged VIX products are based on the daily settlement prices in the VIX futures market which, for each contract, is obtained as the midpoint between the last bid and offer in the regular limit order book prior to the market close at 16:15 EST.[11] To achieve execution close to the daily settlement price and to signal that the rebalancing flow is uninformed, managers of leveraged products have the option to use the so-called *trading-at-settlement* (TAS) market. The TAS market consists of a separate limit order book, open until 16:12 EST, in which traders agree to transact at a market-determined differential to the daily settlement price. The price obtained in a TAS order is unknown at the order placement time. Instead, orders are priced as a spread to the daily closing price, e.g., a trader might place a limit order in the TAS limit order book to buy at $P-0.01$ where P is the daily closing price yet to be determined. By routing their rebalancing orders through the TAS market the ETP managers are effectively outsourcing trade execution to the traders providing liquidity in the TAS market. The TAS market is attractive to ETP managers for two reasons: i) they are certain to trade at or near the daily settlement price, and ii) bid/offer spreads are substantially lower, see Huskaj and Norden (2015) for a detailed comparison of the liquidity and trading costs in the regular market and the TAS market.

[11]However, if the midpoint is not a multiple of the minimum price increment, the daily closing price is rounded up to the nearest multiple of the minimum increment, cf. the CFE Rule Book available online at https://cfe.cboe.com/publish/cferulebook/cfe-rule-book.pdf.

Figure 1.1: **Assets in leveraged VIX products.** The figure shows total assets (in $ mn) invested in the leveraged VIX products listed in Table 1.2, grouped by leverage, during the sample period from November 30, 2010 to December 31, 2017.

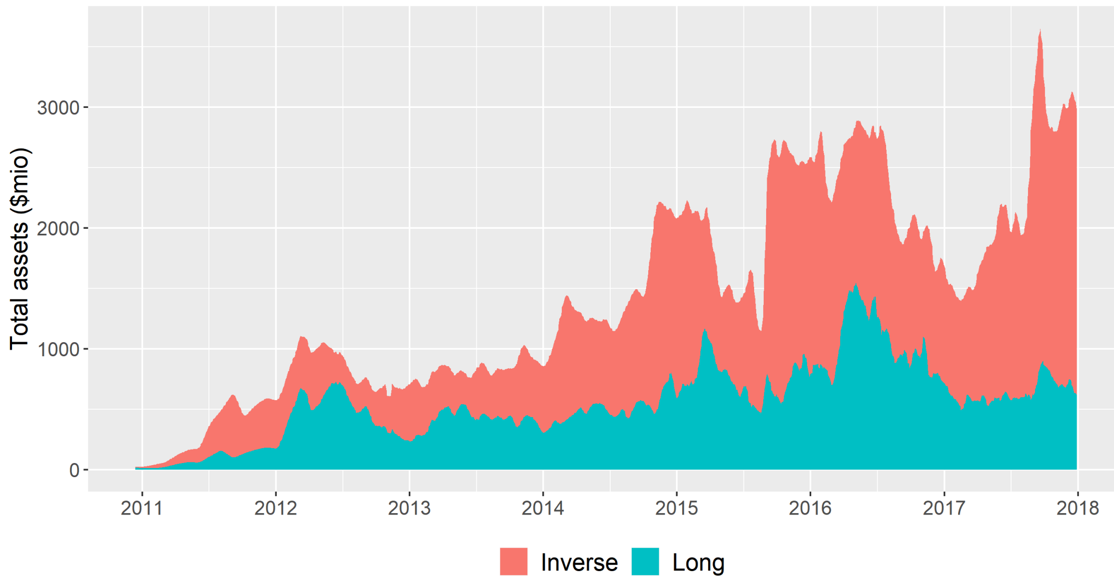


Figure 1.2: **Leveraged VIX products and the VIX futures market.** The figure plots the share of total open interest in the first two VIX futures contracts attributable to leveraged VIX products, grouped by issuer. The attribution assumes that the issuers fully hedge their exposure in the VIX futures market on a gross basis, i.e., the hedge notional is given by $H_{i,t} = \beta_i A_{i,t}$ for each issued product i.

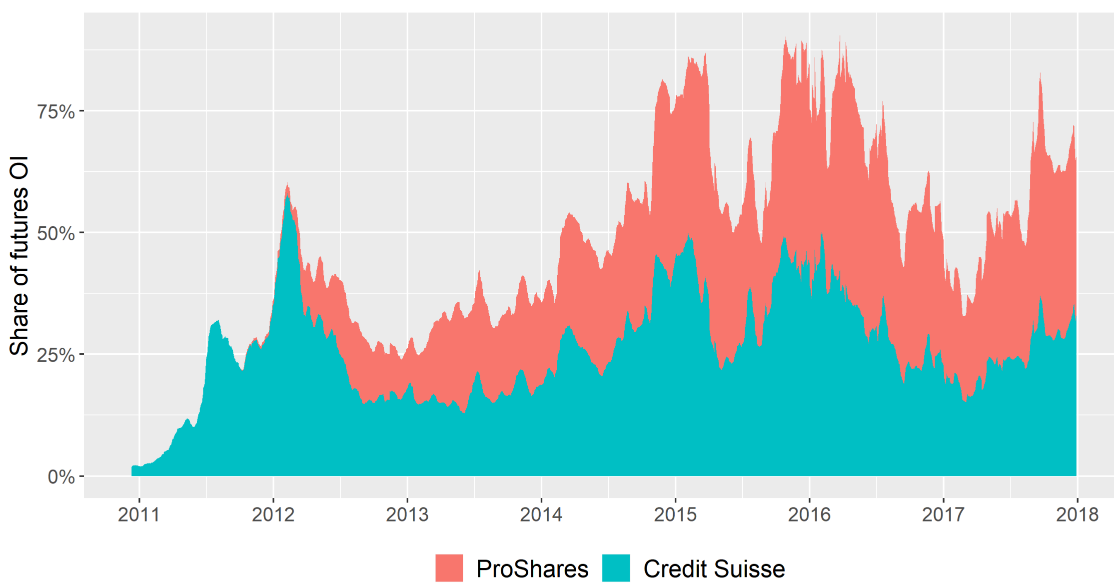


Figure 1.3: **Cumulative abnormal return on days with large rebalancing flows.** The figure plots the cumulative abnormal return of the first two VIX futures contracts for the top-20 selling flows (upper panel) and the top-20 buying flows (lower panel) in the 60 minutes leading up to the daily settlement. The cumulative abnormal return is computed with respect to the front-month E-mini S&P 500 futures contract, i.e., it is the cumulative return in excess of the return implied by the beta-adjusted return of the front-month S&P 500 futures contract.

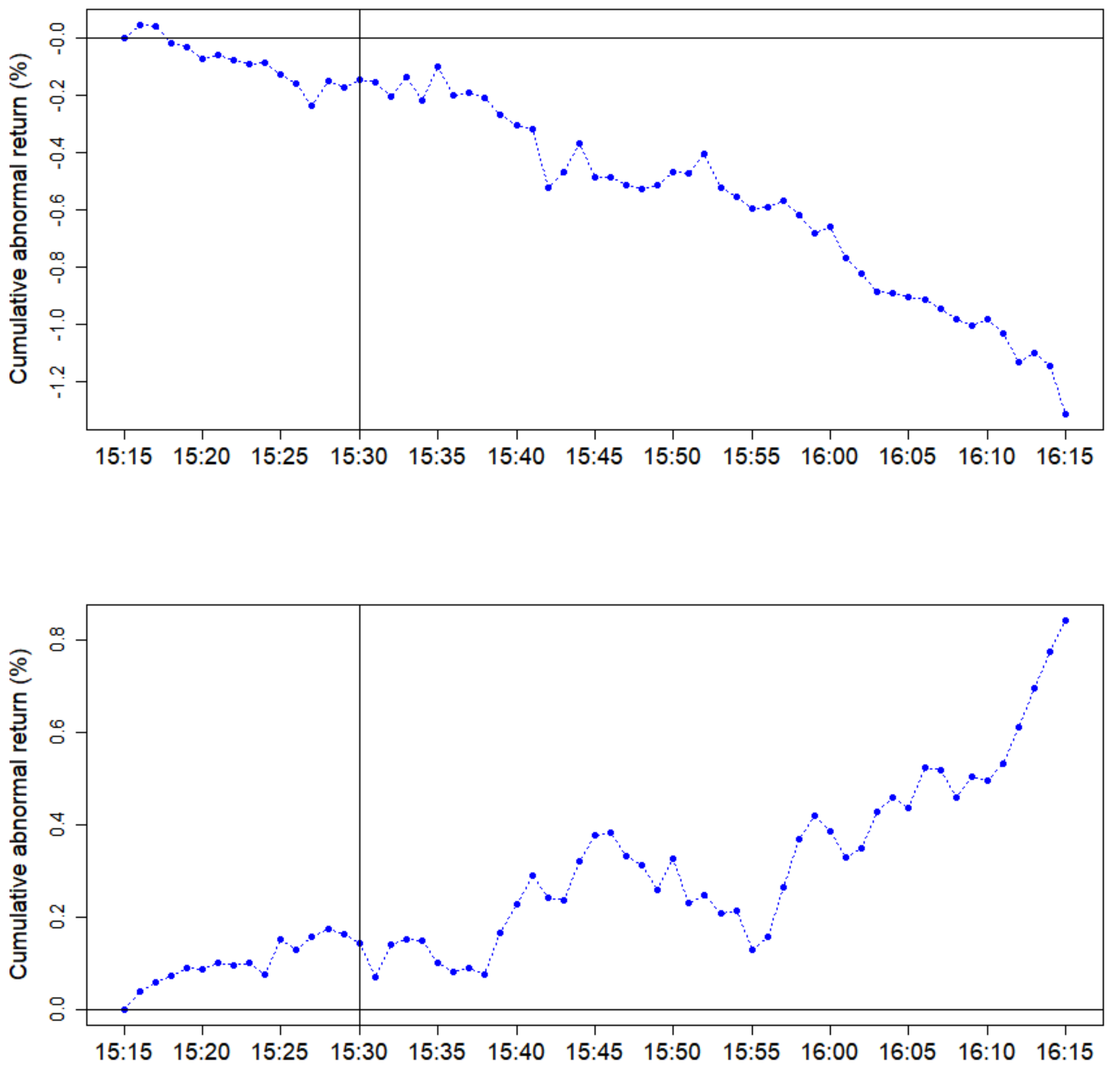


Figure 1.4: **Rebalancing flows of leveraged VIX products.** The figure plots the daily rebalancing flow from leveraged exchange-traded VIX products, as a fraction of 20-day average daily volume in the underlying VIX futures contracts, during the sample period from November 30, 2010 through December 31, 2017.

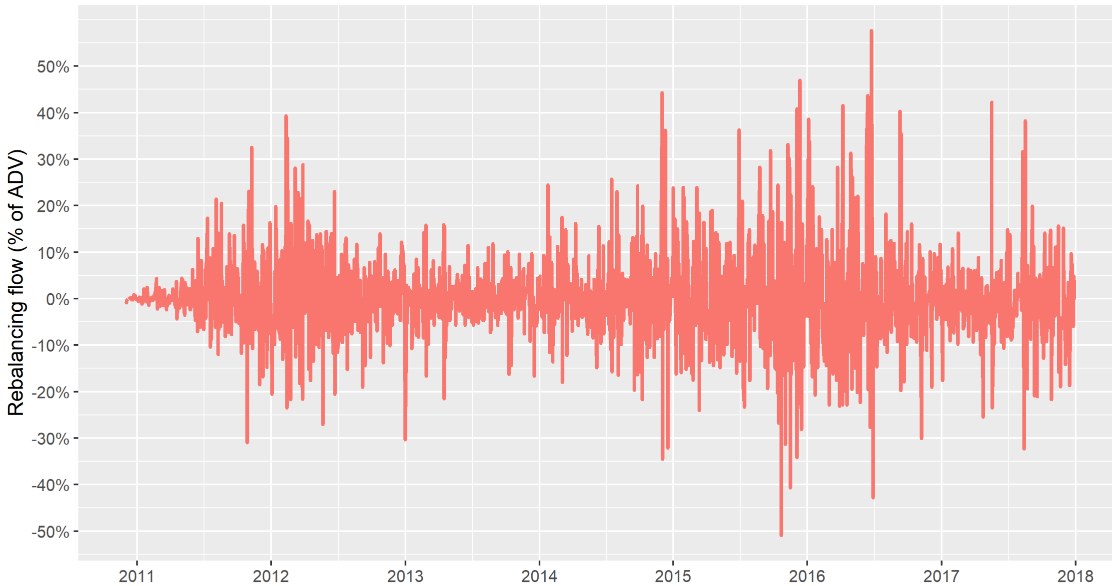


Figure 1.5: **Trading ahead of rebalancing flows.** Cumulative return for a strategy that trades ahead of anticipated rebalancing flows. The strategy buys or sells the first two VIX futures contracts, in proportion to their weights in the index, based on the sign of the predicted rebalancing flow at 15:30 EST. The position is unwound by placing an opposite order at 16:15 EST. The cumulative returns are shown for zero transaction costs (red), transaction costs based on the quoted spread in the regular futures market for both legs of the trade (green) and transaction costs based on the quoted spread in the regular futures market for the first leg of the trade and the quoted spread in the TAS market for the second leg of the trade (blue).

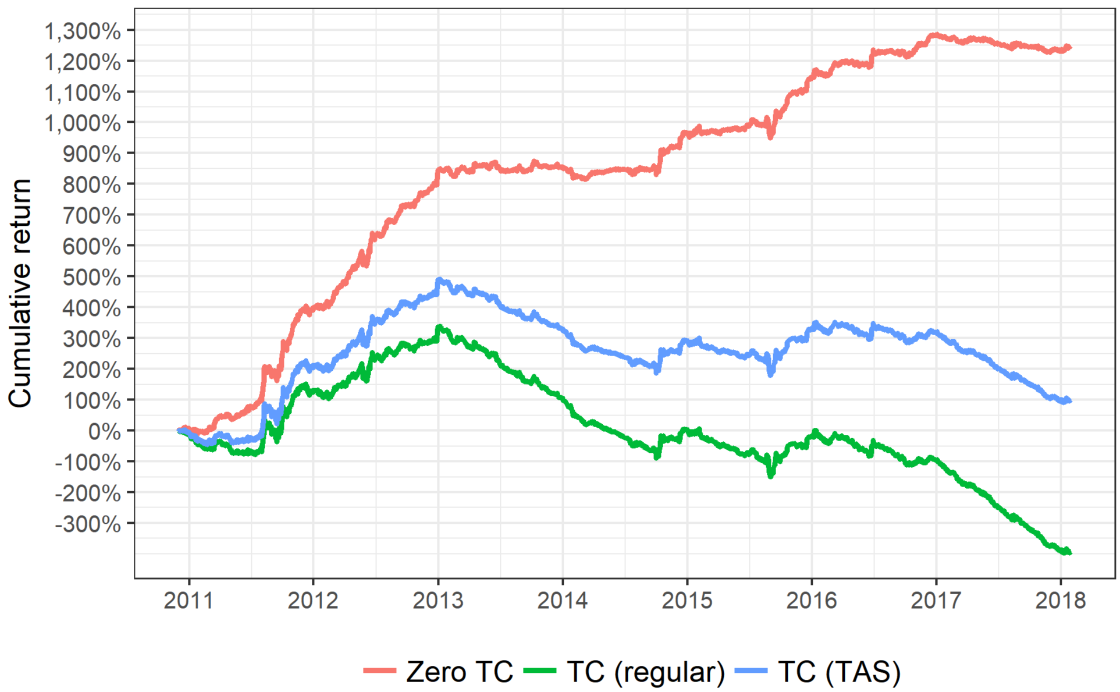


Figure 1.6: **Capital flows and returns of leveraged products.** The figure plots the correlation between daily returns of leveraged products and same-day and future capital flows. The figure plots separately the correlations for long and inverse products. The dashed line is the asymptotic 97.5% confidence level.

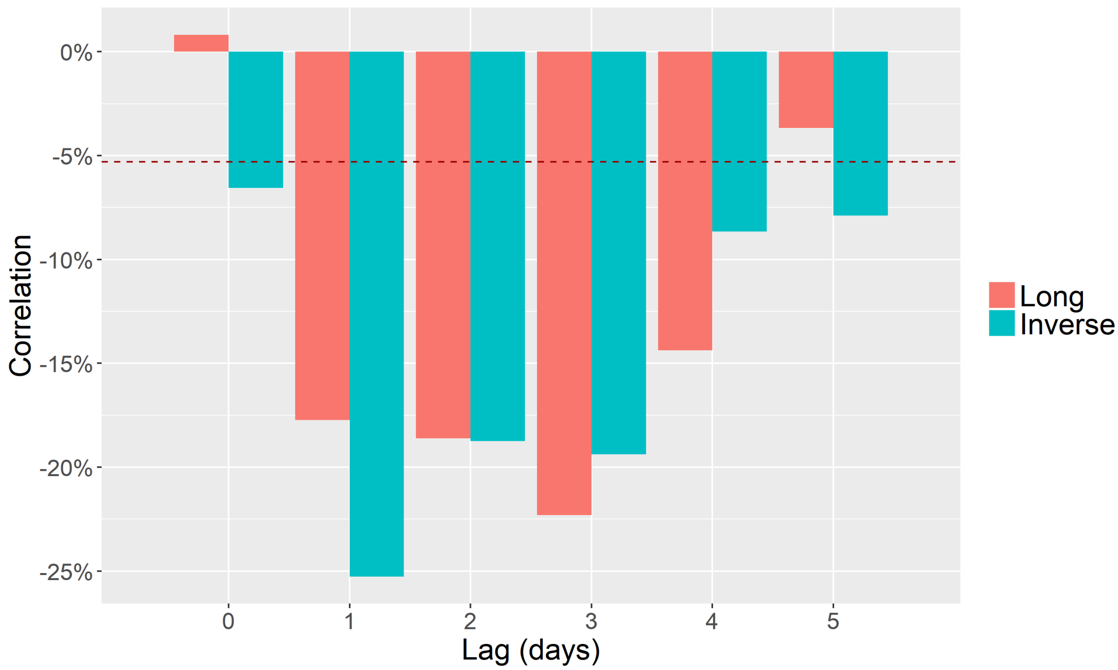


Table 1.1: **Holdings of ProShares Ultra VIX Short-Term Futures ETF.** The table shows the holdings of the ProShares Ultra VIX Short-Term Futures ETF (UVXY) as of February 22, 2018. The hedging trades consists of a mixture of the two near-term futures contracts underlying the S&P 500 VIX Short-Term Futures index and an OTC total return swap directly referencing the index.

Description	**Exposure ($)**	**Shares/Contracts**
Cboe VIX Future 03/21/2018 (UXH8)	258,291,750	14,290.00
Cboe VIX Future 04/18/2018 (UXJ8)	256,893,992	4,030,341.89
S&P 500 VIX Short-Term Futures Index Swap	83,895,000	4,760.00
Net Other Assets / Cash	299,393,117	299,393,117.30

Note: Values are from ProShares' website as seen on February 22, 2018.

Table 1.2: **Leveraged exchange-traded volatility products (ETPs).** The table lists the set of leveraged volatility ETPs indexed to the S&P 500 Short-Term Volatility Index that were actively traded during the sample period from November 30, 2010 to December 31, 2017.

Ticker	**Name**	**Issuer**	**Inception**	**Target**
XIV*	VelocityShares Daily Inverse VIX Short Term ETN	Credit Suisse	29-Nov-2010	-1
TVIX	VelocityShares Daily 2x VIX Short Term ETN	Credit Suisse	29-Nov-2010	+2
SVXY*	ProShares Short VIX Short-Term Futures ETF	ProShares	03-Oct-2011	-1
UVXY	ProShares Ultra VIX Short-Term Futures ETF	ProShares	03-Oct-2011	+2

Note: XIV was terminated and the leverage target of SVXY was reduced from -1 to -0.5 in February 2018 (subsequent to my sample) after the large spike in volatility on February 5, 2018.

Table 1.3: **Rebalancing flows and late-day price pressure.** The table reports the estimates from the price impact regression in Equation (1.3.2) (standard errors in parentheses). The dependent variable is the change in the 1-month constant-maturity VIX futures price from 15:30 EST to 16:15 EST on date t and the main independent variable is the anticipated rebalancing flow based on the intraday return from market close on date $t-1$ and up to 15:30 EST on date t (normalized by 20-day average daily volume). Control variables are the change in (spot) VIX during the rebalancing window from 15:30 EST to 16:15 EST (ΔVIX) and realized volatility (RV) computed as the square root of the sum of squared 1-minute futures returns from 15:30 EST to 16:15 EST. The sample period runs from November 30, 2010 to December 31, 2017.

	Dependent variable:		
	Futures price change from 15:30 to 16:15		
	(1)	(2)	(3)
Rebal_t	0.467***	0.425***	0.394***
	(0.074)	(0.043)	(0.045)
ΔVIX_t		0.548***	0.548***
		(0.010)	(0.010)
RV_t			3.109***
			(1.059)
Observations	1,750	1,750	1,750
Adjusted R^2	0.022	0.661	0.663
Note:			*p<0.1; **p<0.05; ***p<0.01

Table 1.4: **Rebalancing flows and next-day price reversal.** The table reports the estimates from the price reversal regression in Equation (1.3.3) (standard errors in parentheses). The dependent variable is the full 24-hour change in the 1-month constant-maturity VIX futures price from 15:30 EST on date $t-1$ to 15:30 EST on date t and the main independent variable is the rebalancing flow on date $t-1$ (normalized by 20-day average daily volume). Control variables are the change in (spot) VIX from 15:30 EST on date $t-1$ to 15:30 EST (ΔVIX) on date t and realized volatility (RV) on day $t-1$ computed as the square root of the sum of squared 1-minute futures returns from 15:30 EST to 16:15 EST on day $t-1$. The sample period runs from November 30, 2010 to December 31, 2017.

	Dependent variable:		
	Futures price change from 15:30 EST to 15:30 EST		
	(1)	(2)	(3)
Rebal_{t-1}	-0.151	0.206^{**}	0.08
	(0.193)	(0.084)	(0.085)
ΔVIX_t		0.496^{***}	0.498^{***}
		(0.006)	(0.006)
RV_{t-1}			12.709^{***}
			(2.032)
Observations	1,749	1,749	1,749
Adjusted R^2	-0.0002	0.811	0.815
Note:			$^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$

Table 1.5: **Price impact of rebalancing flows when flows are large.** The table reports the estimates from the price impact regression in Equation (1.4.1) including a dummy variable for large rebalancing flows (standard errors in parentheses). The dependent variable is the change in the 1-month constant-maturity VIX futures price from 15:30 EST to 16:15 EST on date t and the main independent variable is the anticipated rebalancing flow based on the intraday return from market close on date $t-1$ and up to 15:30 EST on date t. Control variables are the change in (spot) VIX during the rebalancing window from 15:30 EST to 16:15 EST (ΔVIX) and realized volatility (RV) computed as the square root of the sum of squared 1-minute futures returns from 15:30 EST to 16:15 EST. Column (1) reports the results without the dummy variable and the remaining columns (2) to (4) report the results with dummy variables for increasingly large rebalancing flows. The dummy variables capture the days for which the size of the rebalancing flow, scaled by 20-day average daily volume, exceeds the 30th, 20th and 10th percentile, respectively. The sample period runs from November 30, 2010 to December 31, 2017.

	Dependent variable:			
	Futures price change from 15:30 to 16:15			
	All	30%	20%	10%
	(1)	(2)	(3)	(4)
Rebal_t	0.394***	0.692***	0.637***	0.561***
	(0.045)	(0.137)	(0.101)	(0.073)
ΔVIX_t	0.546***	0.546***	0.546***	0.545***
	(0.010)	(0.010)	(0.010)	(0.010)
RV_t	3.109***	2.982***	2.960***	2.974***
	(1.059)	(1.059)	(1.059)	(1.058)
DL_t		−0.330**	−0.298***	−0.260***
		(0.144)	(0.111)	(0.090)
Observations	1,750	1,750	1,750	1,750
Adjusted R^2	0.663	0.664	0.664	0.664
Note:				*p<0.1; **p<0.05; ***p<0.01

Table 1.6: **Price impact and degree of predictability.** The table reports the estimates from the price impact regression in Equation (1.4.2) with rebalancing flows decomposed based on early-day and late-day price changes (standard errors in parentheses). The dependent variable is the change in the 1-month constant-maturity VIX futures price from 15:30 EST to 16:15 EST on date t and the main independent variables are the rebalancing flows based on, respectively, the intraday return from market close on date $t-1$ and up to 15:00 EST on date t (high predictability) and the intraday return from 15:00 EST to 15:30 EST on date t (low predictability). Control variables are the change in (spot) VIX during the rebalancing window from 15:30 EST to 16:15 EST and realized volatility (RV) computed as the square root of the sum of squared 1-minute futures returns from 15:30 EST to 16:15 EST. The sample period runs from November 30, 2010 to December 31, 2017.

	Dependent variable:		
	Futures price change from 15:30 to 16:15		
	(1)	(2)	(3)
$\text{Rebal}_t^{\text{early}}$	0.395***	0.397***	0.367***
	(0.075)	(0.044)	(0.046)
$\text{Rebal}_t^{\text{late}}$	1.640***	0.923***	0.884***
	(0.299)	(0.177)	(0.177)
ΔVIX_t		0.546***	0.544***
		(0.010)	(0.010)
RV_t			3.038***
			(1.057)
Observations	1,750	1,750	1,750
Adjusted R^2	0.030	0.663	0.665
Note:			*p<0.1; **p<0.05; ***p<0.01

Table 1.7: **Average bid/offer spreads of the first two VIX futures contracts.** The table reports the average of the quoted bid/offer spreads for the first two VIX futures contracts during the sample period from November 2010 through December 2017. The first row reports the average over the entire trading day from 9:30 EST to 16:15 EST, while the second row reports the average during the rebalancing window from 15:30 EST to 16:15 EST when the strategy is active.

	1st futures contract	**2nd futures contract**
9:00 EST – 16:15 EST	0.0517	0.0512
15.45 EST – 16:15 EST	0.0512	0.0509

Table 1.8: **Trading ahead of rebalancing flows.** Performance statistics for the strategy that trades ahead of anticipated rebalancing flows from November 2010 through December 2017. Excess returns and Sharpe ratios are calculated with respect to the 3-month T-bill rate. Performance statistics are calculated for transaction costs of 0, 0.01, 0.02, 0.03, 0.04 and 0.05 vol points.

Transaction cost	**0.00**	**0.01**	**0.02**	**0.03**	**0.04**	**0.05**
Excess return (p.a.)	402.4%	204.8%	84.7%	11.9%	−32.3%	−59.1%
Std. dev. (p.a.)	78.0%	78.0%	78.0%	78.0%	78.0%	78.0%
Sharpe ratio (p.a.)	5.14	2.62	1.08	0.15	−0.42	−0.75
# of days	1,649	1,649	1,649	1,649	1,649	1,649

Chapter 2

Dynamic Risk Management and Asset Comovement[†]

Abstract

When dealers' hedging demand in an illiquid market depends on movements in another, liquid market it can drive a correlation between returns in the two markets. I show that changes in dealers' demand for CDS protection for the purpose of counterparty risk management cause a non-fundamental correlation between credit and currency markets. The effects are economically significant. For example, I show that counterparty risk hedging associated with SoftBank's large currency swap portfolio substantially lowers the correlation between SoftBank's CDS spread and the USD/JPY exchange rate and accounts for around 25% of the weekly volatility of CDS returns.

[†]I would like to thank my advisors David Lando and Fabrice Tourre for valuable feedback, guidance and support. This paper has also benefited from conversations with various market participants; in particular, Jesper Andreasen, the XVA desk at Danske Bank and various industry experts from Nordea, Nomura and Bank of America.

2.1 Introduction

This paper studies a novel source of cross-asset correlation: movements in the price of a liquid asset that "spills over" to the price of an illiquid asset via the hedging activities of derivatives dealers. The sign and size of the induced correlation is jointly determined by the second-order cross-asset sensitivity (in derivatives jargon: cross-gamma) of derivatives dealers' portfolios and the degree of market illiquidity.

To build intuition and derive testable predictions, I develop a simple equilibrium model with two (generic) assets. The model is set in continuous time and has two types of agents: fundamental investors and derivatives hedgers. Derivatives hedgers do not take fundamental value into account in their asset demand: their only objective is to keep their portfolios delta-neutral at all times. Such inelastic demand on the part of derivatives dealers can be motivated by risk limits or regulatory constraints. The central friction in the model is that one of the assets is illiquid in the sense that fundamental investors require a price concession to arbitrage deviations from fundamental value. If the hedging demand in the illiquid market depends on movements in the liquid market then a non-fundamental correlation between the two assets can arise. For example, if a price increase in the liquid market leads to increased hedging demand in the illiquid market (positive cross-gamma) then a positive correlation between the two assets arises and vice versa.

Such cross-dependencies are explicitly present in exotic derivatives portfolios and structured products with multiple underlyings, but also arise naturally in other settings. One such setting is derivatives counterparty risk, which is the focus of this paper. When a dealer enters into an unsecured derivatives position – e.g., a currency swap – with a client, the dealer is exposed to the risk that the client defaults when the dealer is owed money.[1] The size of the counterparty risk exposure depends on the market value of the underlying asset: counterparty risk is low when the dealer is out-of-the-money and high when the dealer is in-the-money. In particular, the dealer must buy additional CDS protection on the client when the underlying asset moves against the client and sell back CDS protection when the underlying asset moves in favor of the client. Such buying and selling of CDS contracts, induced by moves in the underlying asset, will have an impact on CDS prices to the extent that CDS markets are not perfectly liquid. In fact, single-name CDS markets are increasingly illiquid. For example, the *BIS Quarterly Review* from June 2018 notes that "[a]fter an almost tenfold increase in the run-up to the GFC, the global CDS market has shrunk virtually without interruption since." Interestingly, the decrease in the size and liquidity of CDS markets has coincided

[1] While collateralization of inter-dealer trades is now mandatory, non-financial derivatives exposures are largely exempt from such requirements due to the substantial liquidity risk associated with derivatives collateral agreements, see, e.g., Biguri and Stahl (2019).

with an increased regulatory reliance on them, e.g., under Basel III [e.g., BCBS (2015)].

I analyze the impact of counterparty risk management on the correlation between Japanese corporate CDS spreads and the USD/JPY exchange rate based on two quasi-natural experiments. First, I use the rapid expansion of SoftBank's currency swap portfolio as a large shock to dealers hedging demand for the purpose of counterparty risk management. In 2013, SoftBank Group, a Japanese telecommunications company, began issuing a large amount of foreign currency debt – primarily, in U.S. dollars – that it swapped back to Japanese yen using long-dated currency swaps. The choice of SoftBank for this analysis reflects both the large size of SoftBank's long-dated currency swap portfolio and the rapid increase in the size of the currency swap portfolio from zero to more than $25bn in notional terms, which facilitates identification. Moreover, SoftBank's CDS contract is among the world's most actively traded corporate CDS contracts.[2]

Second, I use a change in the accounting treatment of derivatives counterparty risk for certain Japanese banks as a quasi-natural experiment. In Q1 2019, after pressure from the local regulator, a number of large Japanese banks started to report changes in the mark-to-market value of their derivatives counterparty risk, the so-called credit value adjustment (CVA). The empirical identification relies on the fact (which I motivate) that the banks initiated hedging strategies for derivatives counterparty risk at the same time in order to mitigate the resulting earnings volatility from changes in CVA. I test the model's predictions using the iTraxx Japan CDS index, which represents an equal-weighted portfolio of the 50 most liquid Japanese entities with investment grade ratings. Index CDS is widely used to hedge derivatives counterparty risk due to the limited depth and scope of single-name CDS markets, and much of the resulting hedging demand is likely absorbed by this index (which I also motivate).

For SoftBank, our main prediction is that counterparty risk management should *decrease* the correlation between SoftBank's CDS spread and the USD/JPY exchange rate. The empirical results strongly support this: the correlation between SoftBank's senior CDS spread and the USD/JPY exchange rate decreased from +1.5% to -22.1% after SoftBank initiated the expansion of its FX swap portfolio in Q4 2013. Regression results confirm the significance of the change in the CDS/FX correlation. Importantly, I find no impact if I replace CDS returns with returns on SoftBank's stock or senior unsecured bonds. That is, there is no significant change in either CDS/equity or CDS/bond correlations after the expansion of the FX swap portfolio, which alleviates endogeneity concerns that the change in correlation is driven by changes in the risk exposure of SoftBank's assets. The stock and senior unsecured

[2] In 2019, the SoftBank senior CDS contract was among the 20 most traded CDS contracts globally based on the average daily volume statistics published by DTCC.

bonds act as placebo instruments: they have similar exposure to market risk factors as the CDS contract, but are not affected by counterparty risk hedging. Based on the regression estimates, I find that counterparty risk hedging explains (at least) 25% of the weekly volatility of SoftBank CDS spreads after Q4 2013.

For the Japanese CVA accounting shift, the model's main prediction is that counterparty risk management should *increase* the correlation between the iTraxx Japan CDS spread and USD/JPY implied volatility (IV). The reason is that an increase in FX implied volatility increases the counterparty credit exposure of *all* dealers, regardless of their directional exposure to the USD/JPY exchange rate (which might partially cancel out across dealers as a group). Again, the empirical results provide strong support for a hedging-driven impact: the CDS/IV correlation increases significantly after the accounting switch, while there is no change in the equity/IV correlation using the Nikkei 225 stock market index as the placebo instrument. Similar to the iTraxx Japan CDS index, the Nikkei stock market index represents a diversified portfolio of large Japanese firms, but in contrast to iTraxx Japan it is unaffected by counterparty risk hedging. Similarly, there is no significant change in the correlation when replacing the date of the accounting switch with a range of placebo dates.

In summary, the empirical evidence shows that dynamic hedging of counterparty risk has a significant impact on cross-asset correlations.

2.1.1 Related literature

It is well-known that dynamic hedging (or replication) of derivatives contracts can lead to feedback effects in which the frequent rebalancing of dealers' delta-hedges affects the dynamics of the underlying asset. This strand of the literature began with the stock market crash in October 1987 in which portfolio insurance programs (dynamic replication of equity put options) is widely believed to have played a role. For example, Grossman (1988) argues that dynamic replication of securities can amplify volatility in the underlying market by hampering price discovery, while Gennotte and Leland (1990) develop a model of market crashes in which uninformed traders interact with program traders (hedgers) to produce cascading falls in prices. Jarrow (1994), Platen and Schweizer (1998), Sircar and Papanicolaou (1998), Frey and Stremme (1999), Schönbucher and Wilmott (2000) and Andreasen (2007) analyze the impact of dynamic option hedging on the underlying asset when the latter is not perfectly liquid. Avellaneda and Lipkin (2003) study an interesting example of a derivatives feedback effect in which dealers' delta-hedging of short-expiry options causes "pinning" around particular option strikes with large open interest. Ni et al. (2005) and Golez and Jackwerth (2012) present empirical evidence that rebalancing and unwinding of option dealers' delta-hedges near option expiry causes stock prices to "pin" or "cluster" around specific strikes. Furthermore, Ni et al. (2020) show that delta-hedging of stock options also has a substantial impact on the volatility of the underlying stock prices well before expiry. This paper demonstrates that hedging activity across different markets can impact the *correlation* structure of asset returns in equilibrium.

The paper also adds to the growing literature on frictions in single-name CDS markets. Klingler and Lando (2018) show that CDS premiums on highly-rated sovereigns are to a large extent driven by regulatory incentives to minimize capital held against counterparty credit risk.[3] Bongaerts et al. (2011) show that liquidity risk is priced in the cross-section of expected CDS returns, but find that the effect is economically small. Using a different measure of liquidity risk, Junge and Trolle (2015) find that liquidity risk, on average, accounts for 24% of CDS spreads. Qiu and Yu (2012) study the determinants of liquidity provision across single-name CDS markets. Pires et al. (2013) run quantile regressions of CDS spreads on various measures of illiquidity. I contribute to this literature by showing a novel way for illiquidity to affect CDS spreads, and I show that the effect is identifiable in the data and is economically significant.

Finally, the paper also provides empirical support to the recent literature on valuation adjustments for OTC derivatives. Early theoretical contributions include Johnson and Stulz (1987), Sorensen and Bollier (1994), Jarrow and Turnbull (1995) and Duffie and Huang (1996). More recently, Andersen et al. (2019) study valuation adjustments in a structural model of a dealer's balance sheet with a particular focus on funding valuation adjustments (the funding costs associated with unsecured OTC derivatives portfolios), while Cenedese et al. (2020) and Li and Zhang (2019) demonstrate empirically that valuation adjustments are important components of derivatives prices. This paper demonstrates that dynamical hedging of such valuation adjustments can have a significant impact on the correlation between CDS spreads and underlying market prices.

2.2 Derivatives hedging in a two-asset economy

In this section, I present a simple model with two assets to show how the hedging activity of derivatives dealers can induce a non-fundamental correlation across asset markets.

[3]Under Basel III derivatives dealers are required to assign capital to cover counterparty credit losses due to a widening of the counterparty's credit spread, the so-called "CVA capital charge". In contrast, under Basel II dealers only had to assign capital to cover actual defaults, not mark-to-market losses associated with an increase in the probability of counterparty default.

2.2.1 The market

There are two assets in zero net supply.[4] The price process of asset i is denoted by S_i for each $i \in \{1,2\}$. Each asset has fundamental value x_i that evolves according to:

$$dx_i(t) = \sigma_i dW_i(t) \quad i \in \{1,2\}, \tag{2.2.1}$$

where $\sigma_i > 0$ are positive constants and W_i are Brownian motions under the physical measure. Without loss of generality, we normalize the fundamental correlation to zero:

$$dx_1(t)dx_2(t) = 0 \quad \forall t \geq 0. \tag{2.2.2}$$

The market for asset 1 is perfectly liquid, so its price always equals fundamental value:

$$dS_1(t) = dx_1(t) \quad \forall t \geq 0.$$

In contrast, the dynamics of S_2 will be determined endogenously in the model. As we will see, the correlation between market prices will differ from the correlation between fundamental values in equilibrium:

$$dS_1(t)dS_2(t) \neq 0.$$

2.2.2 The agents

There are two types of agents in the economy: fundamental investors and derivatives hedgers. Since the demand for the liquid asset has no bearing on its price, we focus on the demand for the illiquid asset for each type of agent.

The fundamental investors know the fundamental value of the illiquid asset x_2, but have limited risk-bearing capacity. The net demand F of fundamental investors for the illiquid asset takes the following form:

$$F(x_2(t), S_2(t)) \quad = \quad A\left[x_2(t) - S_2(t)\right], \tag{2.2.3}$$

where $A \geq 0$ is a positive constant that captures the degree of market illiquidity.

The derivatives hedgers manage a derivatives portfolio whose value depends on the market prices of the two assets. The market value V of the derivatives portfolio is given by:

$$V \equiv G(t, S_1, S_2), \tag{2.2.4}$$

[4] The assets may themselves be derivatives (such as futures or swap contracts) and the specification below allows for negative asset values in line with this interpretation.

where G is the model used by the derivatives hedgers for valuation and hedging purposes. The model predictions do not rely on the exact functional form of G: as we will see later, it is the second-order derivatives of G that matter and, in particular, it is the *cross-derivative*, $G_{12} \equiv \frac{\partial^2 G}{\partial S_1 \partial S_2}$, that generates the model's key predictions.

The only concern of derivatives hedgers is to keep their portfolio delta-neutral at all times, so their demand B for the illiquid asset is given by:

$$B(t, S_1(t), S_2(t)) = -\frac{\partial G}{\partial S_2}(t, S_1, S_2). \tag{2.2.5}$$

Such preferences can be motivated by internal risk limits or regulation that constrains the risk-taking ability of dealers. Importantly, the delta with respect to S_2, $\frac{\partial G}{\partial S_2}$, in general depends on *both* S_1 and S_2.

2.2.3 Equilibrium

In equilibrium, the demand from fundamental investors and derivatives hedgers for the illiquid asset must sum zero:

$$F(x_2(t), S_2(t)) + B(t, S_1(t), S_2(t)) \;\; = \;\; 0 \tag{2.2.6}$$

The market clearing condition (2.2.6) relates the price of the illiquid asset, S_2, to the state variables $x_1 \equiv S_1$ and x_2. That is, after substituting the asset demand of each type of agent into Eqn. (2.2.6), we can solve for the dynamics of the illiquid asset price:

$$dS_2 \;\; \equiv \;\; dS_2(t, x_1(t), x_2(t))$$

The equilibrium dynamics are characterized by the following proposition that we prove in the appendix.

Proposition 2.1. *Consider the economy with two assets, fundamental investors and derivatives hedgers. The fundamental values of the assets are uncorrelated and evolves as:*

$$\begin{aligned} dx_1 &= \sigma_1 dW_1 \\ dx_2 &= \sigma_2 dW_2, \end{aligned}$$

where the σ_i are positive constants and the W_i are independent Brownian motions.

Imposing the market clearing condition, we obtain the dynamics of the asset prices in *equilibrium:*

$$dS_1 = \sigma_1 dW_1 \tag{2.2.7}$$

$$dS_2 = \left(\frac{G_{12}}{A+G_{22}}\right)\sigma_1 dW_1 + \left(\frac{A}{A+G_{22}}\right)\sigma_2 dW_2 + O(dt), \tag{2.2.8}$$

where $G_{ij} \equiv \frac{\partial^2 G}{\partial S_i \partial S_j}(t, S_1, S_2)$ *denotes the second-order partial derivatives of the dealers' pricing function and drift terms of order* $O(dt)$ *are left unspecified (they are not used).*

Proof. See 2.6. □

Proposition 2.1 shows that derivatives hedging can induce a non-fundamental component in the covariance structure of asset markets. In particular, the covariance of asset returns is given by:

$$\mathrm{Cov}\left[dS_1, dS_2\right] = \left(\frac{G_{12}}{A+G_{22}}\right)\sigma_1^2 \neq 0. \tag{2.2.9}$$

We see that the *sign* of the induced correlation is determined by the sign of $\frac{G_{12}}{A+G_{22}}$: if this quantity is positive (negative) then derivatives hedging increases (decreases) the correlation between the returns of the liquid asset and the illiquid asset. This is the main prediction from the model that we take to the data, since in applications we are usually able to infer the sign of this quantity from publicly available data.

Can we say anything about the *magnitude* of the induced covariance? To do so, we need to impose additional structure on the pricing function G of the derivatives dealer. Suppose that G is a product of the two underlying risk factors:

$$G(t, S_1, S_2) = g(t, S_1)S_2, \tag{2.2.10}$$

where $g(\cdot) \geq 0$ is a positively-valued function. As we will see in the next section, such a factorization holds approximately in the context of counterparty risk. In this case, we have:

$$G_{12} = \frac{dg}{dS}(t, S_1)$$
$$G_{22} = 0.$$

Moreover, from Eqn. (2.2.9) the induced covariance is:

$$\mathrm{Cov}\left[dS_1, dS_2\right] = \frac{dg}{dS}(t, S_1)\sigma_1^2.$$

In practice, it is difficult to use this expression to empirically identify the magnitude of the induced covariance, since the shape of the g function is hard to infer based on publicly available data.

2.3 Counterparty risk management

Dynamic hedging of counterparty risk can drive a correlation between liquid asset markets and illiquid credit default swap markets. As a concrete example, suppose that a dealer enters into an FX swap with a corporate client. The NPV of future losses due to the risk of counterparty default is referred to as the credit value adjustment (CVA) of the swap. Most dealers actively hedge CVA: in a survey conducted by Deloitte and Solum Financial Partners in 2013, 80% of surveyed banks indicated that they actively hedge CVA, and almost all surveyed banks indicate that they use credit default swaps for hedging [see Deloitte (2013)]. To understand the mechanics of counterparty risk management, consider the figure below.

The figure plots the exposure profile of a 10-year FX swap from the point of view of the dealer at time 0. The exposure at future time t is the expected loss from counterparty default at a time t, which is given by $\mathbb{E}_0[V_t^+]$ (a credit loss occurs only in the positive states). We consider three scenarios: the swap is initially at-the-money, $V_0 = 0$ (upper panel), in-the-money, $V_0 \gg 0$ (middle panel) or out-of-the-money, $V_0 \ll 0$ (lower panel). To hedge CVA, the dealer must buy CDS protection on the counterparty in proportion to the area under the exposure profile (the shaded region in the figure). The figure illustrates the dynamic nature of the dealer's counterparty credit exposure. Since the swap is initiated at zero NPV, the dealer starts with the exposure profile in the upper panel. While the value at inception is zero, the dealer is exposed to the risk that the counterparty defaults in a future scenario in which the underlying exchange rate has moved against the client. The middle panel of the figure illustrates how the dealer's exposure changes when the swap has moved against the client: the swap becomes an asset, similar to a loan, and the dealer must *buy more* CDS protection on the counterparty to remain hedged (the area under the exposure profile increases). In contrast, the lower panel of the figure shows what happens when the underlying exchange rate rate moves in favor of the client: the swap becomes a liability and the credit exposure decreases. In this case, the dealer must *sell back* some of the CDS protection on the counterparty to avoid being over-hedged. If the CDS market is illiquid, then such buying and selling of CDS contracts, induced by moves in the currency market, will have an impact on the dynamics of CDS spreads in equilibrium.

2.3.1 Model formalization

In terms of the model in the previous section, S_1 is the underlying asset price and S_2 is the spread of the counterparty's CDS that the dealer uses to hedge the counterparty credit risk. The CDS market is illiquid in the sense that fundamental investors require a price concession to take the other side of the dealers' hedging demand. For simplicity, we do not model the term structure of CDS spreads and assume that the CDS market at time t is characterized by a single, flat spread $S_2(t)$. Furthermore, in line with the model, we assume that the fundamental correlation between the the underlying asset price and the counterparty's credit spread is zero.

$G(t, S_1, S_2)$ is the credit value adjustment (CVA) of the dealer's derivatives portfolio with underlying (risk-free) value $V(t, S_1)$. To obtain a tractable expression for G, we make a number of additional assumptions:

1. The risk-free rate of interest is zero.

2. The dealer is not subject to default risk.

3. The counterparty default intensity $\lambda(u)$ is low enough so that $e^{\lambda(u)u} \approx 1$ for $u \leq T$.

Under assumptions 1 to 3, we can write the CVA in the dealer's pricing model as follows:

$$\begin{aligned} G(t, S_1, S_2) &\approx S_2(t) \int_t^T \mathbb{E}_t \left[V(u, S_1(u))^+ \mid S_1(t) \right] du \\ &= S_2(t) \times \mathrm{EPE}(t, S_1(t)), \end{aligned}$$

where we have defined the *expected positive exposure* as

$$\mathrm{EPE}(t, S_1(t)) \equiv \int_t^T \mathbb{E}_t \left[V(u, S_1(u))^+ \mid S_1(t) \right] du.$$

The expression above is quite intuitive: $S_2(t)$ is the cost of credit insurance per unit of exposure and the effective exposure for a derivatives portfolio is given by the expected positive exposure [see, e.g., Gregory (2012) and Canabarro and Pykhtin (2014) for details on pricing and risk management of CVA]. Hence, we have the factorization in Eqn. (2.2.10) with g and $\frac{dg}{dS}$ given by:

$$\begin{aligned} g(t, S_1) &= \mathrm{EPE}(t, S_1) \\ \frac{dg}{dS}(t, S_1) &= \frac{d}{dS}\mathrm{EPE}(t, S_1). \end{aligned}$$

The induced covariance between the exchange rate and the counterparty's CDS spread is therefore given by:

$$\mathrm{Cov}\left[dS_1, dS_2\right] \;=\; \sigma_1^2 \frac{d}{dS}\mathrm{EPE}(t, S_1(t)). \tag{2.3.1}$$

The *sign* of the induced correlation depends on whether the expected positive exposure increases or decreases with the value of the underlying: if EPE is increasing in the value of the underlying, then counterparty risk hedging induces a positive correlation between the underlying and the counterparty's CDS spread and vice versa. The *magnitude* of the induced correlation depends on the rate of change of the EPE with respect to the underlying asset price. In particular, for in-the-money portfolios the EPE will change at a faster rate than for out-of-the-money portfolios, because a change in the value of the underlying portfolio is more likely to affect a future state in which the portfolio value is positive ($\frac{d}{dS}\mathrm{EPE} = 0$ in the limit where the portfolio is so deeply out-of-the-money that there are no future states for which the portfolio value is positive).

In the empirical analysis below, we rely mainly on the model's predictions with respect to the sign of the induced correlation. While the magnitude of the induced correlation is difficult to identify empirically, we can still use the expression above to understand how certain developments are likely to affect the magnitude of hedging-induced correlations. For example, the secular decline in long-term interest rates over the past decade has pushed banks' unsecured interest rate swap portfolios deeply in-the-money. This is because banks mostly receive fixed in unsecured interest rate swaps with non-financial counterparties that swap their floating-rate (bank) debt to fixed [see, e.g., Rega-Jones (2020)]. Hence, we would expect counterparty risk hedging to have pushed the correlation between long-term interest rates and CDS spreads increasingly lower over the past decade (although such an effect is extremely difficult to disentangle empirically).

2.4 Empirical analysis

In this section, I conduct an empirical analysis of the impact of counterparty risk management on cross-asset correlations. The analysis relies on two quasi-natural experiments that shock the hedging demand of dealers for the purpose of counterparty risk management. The first shock stems from the rapid expansion of SoftBank's currency swap portfolio, while the second comes from a change in the accounting treatment of derivatives counterparty risk that effectively forced Japanese dealers to start dynamically hedging counterparty risk.

2.4.1 Data

I use market data on exchange rates, implied volatilities, stock prices, senior CDS spreads and senior unsecured bond prices obtained from the Bloomberg system. It is the senior CDS contracts that are relevant for counterparty risk hedging, since derivatives liabilities are *pari passu* with senior unsecured debt. The pricing source for the CDS quotes is CMA New York (CMAN).

I use weekly data throughout to minimize the influence of asynchronicity in the sampling of quotes across different markets and to minimize the impact of uncertainty regarding the exact timing of hedging trades (the CVA desks responsible for executing these trades on behalf of dealers generally have risk limits that allow for some discretion regarding the timing of their hedging transactions).

2.4.2 The expansion of SoftBank's swap portfolio

In this part, I use SoftBank's rapid expansion of its FX swap portfolio, from zero to more than \$25bn in notional terms, as a large shock to dealers' hedging demand, which allows for an empirical identification of the impact of counterparty risk hedging on SoftBank's CDS contract.

2.4.2.1 Background

SoftBank Group is a Japanese conglomerate which, in addition to operating a domestic telecommunications subsidiary, owns stakes in a number of domestic and foreign companies (despite the name, SoftBank is not a bank). It also manages the Vision Fund, the world's largest technology-focused venture capital fund, with assets of more than \$100bn in 2018. From 2013 through 2019, SoftBank made a number of large, debt-funded acquisitions and increased its stock of long-term debt from \$20bn in Q1 2013 to a staggering \$130bn in Q4 2019. Part of the new debt was issued in U.S. dollars and swapped back to Japanese yen via long-dated USD/JPY swaps entered into during the same period. For example, when SoftBank acquired Sprint Corporation in 2013, part of the financing was in the form of long-term bonds (due in 2020) issued in U.S. dollars and Euro and the 2013 annual report clearly states that the proceeds were swapped back to Japanese yen:

> With regards to above USD-denominated Senior Notes and Euro-denominated Senior Notes, the Company has entered into currency swap contracts with financial institutions and the amount of principal by redemption and interest payments in JPY are fixed. (p. 114)

Figure 2.2 plots the notional size of SoftBank's long-dated FX swap portfolio (left axis) and the total amount of outstanding long-term debt (right axis) based on information hand-collected from SoftBank's annual reports. The figure clearly shows that SoftBank started to expand its FX swap portfolio by the end of 2013 (vertical dashed line).

SoftBank uses long-dated FX swaps to convert long-term liabilities from foreign currencies, primarily U.S. dollars, to Japanese yen. Therefore, SoftBank is *long* U.S. dollars against Japanese yen in its FX swap portfolio, while the dealers are short. Since the key model predictions rely on this fact, I confirm that it is consistent with other information provided in the annual reports:

- First, the 2019 annual report (p. 156) contains additional details on the currency swaps entered into by SoftBank, and it states explicitly that for these swaps the receipts are in U.S. dollars and the payments are in yen, i.e., SoftBank is long U.S. dollars against Japanese yen.

- Second, the annual changes in the reported fair values of SoftBank's currency swaps from 2013 through 2019 are consistent with a short Japanese yen / long U.S. dollar position. For example, from March 31, 2014 through March 31, 2015 where the yen depreciated by around 15% against the dollar, SoftBank reports a corresponding gain in the fair value of its currency swaps of around 15%.

The model predictions below depends on SoftBank not posting collateral against its derivatives liabilities. Under a collateral agreement, derivatives dealers would not need to adjust their CDS hedges with the USD/JPY exchange rate, i.e., $\frac{\partial^2 G}{\partial S_1 \partial S_2} \approx 0$, because the increase in exposure would be offset by an equal increase in collateral held, and the hedging-induced correlation would disappear. Starting from 2015, the annual reports contain information on the specific liabilities against which collateral is pledged and, in the period from March 31, 2015 through March 31, 2018, no collateral was pledged against derivatives liabilities (as of March 31, 2019, a negligible amount, around \$2.5mio, was posted as derivatives collateral; for comparison, the negative market value of SoftBank's USD/JPY currency swaps alone was reported at \$385mio).[5]

Finally, the empirical identification requires that the increase in the size of the FX swap portfolio is exogenous with respect to the cross-asset correlations, i.e., that the expansion affects the correlation only through an increase in dealers' hedging demand. I address this concern below by using SoftBank's stock and senior unsecured bonds as placebo instruments;

[5]In fact, most non-financial derivatives users do not post collateral against their derivatives liabilities as documented by Biguri and Stahl (2019).

if these instruments are not affected by the increase, it is evidence that any impact on the CDS/FX correlation is driven by increased hedging demand.

2.4.2.2 Model predictions

To derive precise predictions, we need to establish (i) when SoftBank starts issuing long-dated FX swaps (since, according to the model, it is the dealers' hedging of the associated counterparty risk that drives a structural break in the correlation structure); and (ii) the sign of $\frac{d\text{EPE}}{dS}$, i.e., the sensitivity of dealer's expected positive exposure to changes in the dollar/yen exchange rate (since, by Eqn. (2.3.1), this will determine the sign of the induced correlation).

As for (i), I take December 31, 2013 as the treatment date after which I expect dealers' hedging of counterparty risk to affect the correlation structure of the market. SoftBank started to report non-zero holdings of long-dated FX swaps in 2013, the same year it started its long-term debt expansion (cf. Figure 2.2), which suggests that it had an internal policy of swapping its foreign currency debt issuance back to Japanese yen to hedge out the currency risk. While I only have annual data on FX swap notionals, quarterly data on the amount of outstanding long-term debt (obtained from Bloomberg) shows that SoftBank started expanding its debt issuance during the last quarter of 2013, which provides further support for the choice of treatment date. None of the results below are sensitive to the exact choice of treatment date.

As for (ii), recall that dealers are short U.S. dollars against Japanese yen in their currency swaps with SoftBank. Hence, their credit exposure to SoftBank increases when the USD/JPY cross decreases and vice versa. This means that the EPE sensitivity of the dealers is negative:

$$\frac{\partial \text{EPE}}{\partial \text{USD/JPY}} < 0.$$

To understand intuitively why this is true, consider what happens when the USD/JPY exchange rate decreases (the U.S. dollar depreciates). Since dealers are short the U.S. dollar, they will have a mark-to-market gain on their SoftBank swaps and their credit exposure to SoftBank will increase. Therefore, dealers must buy additional CDS protection on SoftBank to rebalance their hedges, which pushes up CDS spreads. So when USD/JPY decreases, spreads are pushed up, and vice versa.

Thus, Proposition 2.1 provides the following testable predictions regarding the correlation between the USD/JPY exchange rate and SoftBank CDS spreads:

(i) Hedging by derivatives dealers of SoftBank counterparty risk should induce a *structural break* in the correlation after December 31, 2013.

(ii) Hedging by derivatives dealers of SoftBank counterparty risk should have a *negative* impact on the correlation.

I proceed to test these predictions empirically.

2.4.2.3 Results

As a preliminary visual test, Figure 2.3 plots the 5-year rolling correlation between weekly USD/JPY returns and weekly changes in SoftBank's 5Y senior CDS spread (solid red line). The vertical dashed line marks the treatment date (December 31, 2013) after which we expect dealers' hedging of derivatives counterparty risk to affect the CDS/FX correlation. Indeed, there seems to be a structural break in the correlation around the treatment date, consistent with prediction (i). Moreover, the correlation changes from approximately zero to strongly negative, consistent with prediction (ii). The difference in correlation is both economically and statistically significant: the sample correlation declines from 1.5% in the period before December 31, 2013 to -22.1% in the period after December 31, 2013 ($t = 2.99$).

To alleviate endogeneity concerns that the change in the CDS/FX correlation is driven by a change in the risk exposure of SoftBank's underlying business that coincided with the increase in FX swap issuance, Figure 2.3 also shows the 5-year rolling correlation between weekly USD/JPY returns and weekly returns of SoftBank's publicly traded stock (dashed blue line). If the change in correlation was driven by a change in the currency exposure of SoftBank's assets, we should also observe a structural break in the correlation between SoftBank's stock price and the USD/JPY exchange rate. However, there seems to be no such structural break in the equity/FX correlation; indeed, the difference in the sample correlation before and after the treatment date is not statistically significant.

To further investigate whether the observed change in correlation is due to counterparty risk hedging, I consider the following regression:

$$R_{\mathrm{CDS},t} = \alpha + \beta \times R_{\mathrm{FX},t} + \gamma \times \mathrm{DD}_t \times R_{\mathrm{FX},t} + \boldsymbol{\theta}^\top \boldsymbol{X}_t + e_t, \tag{2.4.1}$$

where $R_{\mathrm{CDS},t}$ is the weekly return of SoftBank's 5Y CDS contract from the point of view of the protection buyer[6], $R_{\mathrm{FX},t}$ is the weekly return of the U.S. dollar against the Japanese yen, and DD_t is a dummy variable that is equal to 1 after December 31, 2013 and 0 otherwise. The vector of control variables $\boldsymbol{X}$ consists of the lagged levels of the VIX (as a proxy for the aggregate risk-bearing capacity of dealers) and the USD/JPY exchange rate (the primary driver of the market value of SoftBank's FX swap portfolio).

[6]The CDS return is computed as $5 \times \Delta S_t$, where ΔS_t is the weekly change in the 5-year CDS spread.

The main coefficient of interest in Eqn. (2.4.1) is γ: it captures the change in the correlation structure between SoftBank's CDS and the USD/JPY exchange rate due to counterparty risk hedging. However, as noted above, a change in the correlation could also be driven by a change in SoftBank's risk exposure (unrelated to counterparty risk hedging) that coincided with the increased FX swap issuance that is captured by the dummy variable. If this was the case, we should also observe a structural break in the correlation between the USD/JPY exchange rate and the prices of SoftBank's other liabilities. To address this issue, I consider SoftBank's publicly traded stock and (maturity-matched) senior unsecured bond as *placebo instruments*, i.e., instruments that are similarly exposed to other risk factors, but which are not affected by counterparty risk hedging.[7] Thus, I consider similar regressions as above with SoftBank's stock and bond returns, respectively, instead of CDS returns:

$$R_{\text{equity},t} = \alpha + \beta \times R_{\text{FX},t} + \gamma \times \text{DD}_t \times R_{\text{FX},t} + \boldsymbol{\theta}^\top \boldsymbol{X}_t + e_t, \tag{2.4.2}$$

where $R_{\text{equity},t}$ is the weekly return of the SoftBank stock; and

$$R_{\text{bond},t} = \alpha + \beta \times R_{\text{FX},t} + \gamma \times \text{DD}_t \times R_{\text{FX},t} + \boldsymbol{\theta}^\top \boldsymbol{X}_t + e_t, \tag{2.4.3}$$

where $R_{\text{bond},t}$ is the weekly excess return of the CDS-matched senior unsecured bond.[8]

Table 2.1 reports the results of regressions (2.4.1)-(2.4.3).[9] The estimated value of γ is negative and significant at the 5%-level for SoftBank's CDS returns and insignificant for SoftBank's stock and excess bond returns. This is evidence that the change in correlation is driven by counterparty risk hedging associated with SoftBank's increased FX swap portfolio and not by a change in the underlying risk exposure of SoftBank. Moreover, the magnitude of the estimated effect on CDS spreads is economically significant: a 1% increase in the USD/JPY exchange rate has no impact on CDS returns before December 31, 2013 and is

[7]Counterparty risk management relies on credit default swaps due to regulatory incentives and frictions associated with short selling of bonds. Arbitrage activity between the bond and CDS markets might lead bond spreads to absorb some of the price pressure from the CDS market, but various constraints imply that such activity is limited in practice [see, e.g., Gârleanu and Pedersen (2011) and Bai and Collin-Dufresne (2019)].

[8]The bond excess return $R_{\text{bond},t}$ is computed as $5 \times \Delta\text{ASW}_t$, where ΔASW_t is the weekly change in the Bloomberg mid-value of the local-currency asset swap spread for the CDS-matched bond. I select the CDS-matched bond as follows. I start by retaining only bonds issued by SoftBank that are senior unsecured, have no embedded optionality and are denominated in JPY (I filter out foreign currency bonds to avoid additional noise from cross-currency basis adjustments). I then divide the sample period into 6-month intervals, and for each interval I select the bond whose remaining time to maturity at the beginning of the interval is as close as possible to 5 years (the nominal maturity of the CDS contract) among the bonds with quoted asset swap spreads for the corresponding 6-month interval.

[9]Estimated coefficients for the control variables are omitted in this and the following tables, but can be found in Appendix 2.7.

associated with a -0.14% return after December 31, 2013. The weekly volatility of USD/JPY returns and CDS returns are 1.3% and 0.7%, respectively, in the post-treatment period from December 31, 2013 to December 31, 2019. Hence, from this regression, I estimate that counterparty risk hedging explains $\frac{0.14\times 1.3\%}{0.7\%} \approx 25\%$ of the weekly volatility of SoftBank CDS spreads.

As an additional robustness test, I also conduct placebo tests with fictitious treatment dates in the post-treatment sample from December 31, 2013 to December 31, 2019. Specifically, I run the CDS regression (2.4.1) with (annual) fictitious treatment dates from December 31, 2015 to December 31, 2018. Since the entire sample is after the actual treatment date, I expect the interaction coefficient to be insignificant for all fictitious treatment dates.[10] Table 2.2 reports the results with columns (1)-(4) corresponding to each of the fictitious treatment dates from December 31, 2015 to December 31, 2018. As expected, none of the interaction terms are significant. This provides further support for the conclusion that the change in the CDS/FX correlation after December 31, 2013 is driven by counterparty risk hedging.

2.4.3 The Japanese CVA accounting change

In this section, I exploit a mandatory change in the accounting treatment of derivatives counterparty risk by Japanese banks to identify the impact of counterparty risk hedging on CDS markets. After briefly describing the Japanese CVA accounting change, I use the theoretical model to derive precise predictions that I test empirically.

2.4.3.1 Background

In Q1 2019, after pressure from the local regulator, three large Japanese banks started reporting changes in the fair value of derivatives counterparty risk (CVA) as part of their earnings for the first time.[11] Notably, Japanese banks – with the sole exception of Nomura – had not previously reported changes in the fair value of CVA and, according to a number of industry sources, had neither priced nor hedged it [see Ivens (2017) and Davis (2019b)]. I assume that the affected banks started hedging derivatives counterparty risk at the same time that changes in CVA started to affect their earnings, i.e., at the end of Q4 2018. The following quote (from a February 2019 industry news article on the Japanese CVA shift) supports this assumption:

[10] This is not a perfect placebo test: as Figure 2.2 shows, SoftBank keeps expanding the size of its FX swap portfolio after the initial expansion in 2013, albeit at a much slower pace. However, this should bias the estimated coefficients *against* being insignificant, as I expect.

[11] The banks were Mitsubishi UFJ Financial Group, Mizuho, and Sumitomo Mitsui Banking Corporation.

> [O]nce the megabanks start accounting for CVA in their P&L, they face initial one-off revaluation losses as high as nine digits. From then on, CVA will be a regular feature of the P&L statement and will need to be measured and hedged to dampen earnings volatility. [Davis (2019b)]

Single-name CDS contracts for most Japanese firms are either non-existing or not actively traded (SoftBank being a notable exception). Therefore, it is likely that the Japanese dealer banks rely mainly on so-called proxy hedges based on more liquid CDS instruments, such as the iTraxx Japan CDS index, for pricing and hedging of CVA. Under current accounting rules, banks are allowed to use proxy instruments for mark-to-market purposes when the underlying single-name CDS is non-existing or so infrequently traded that the market data is deemed to be unreliable. Industry sources confirm that proxy hedging using index CDS is widespread and that the iTraxx Japan CDS index would be the most likely hedging instrument in this case [Davis (2019a), Davis (2019b)].[12] Figure 2.4 provide additional support for this assumption: the outstanding notional of the iTraxx Japan CDS index cleared through JSCC (the main clearing venue for CDS contracts in Japan) increased by 107% during 2019, while outstanding single-name CDS notional increased by only 30%.

2.4.3.2 Model predictions

As a first step, we establish that the USD/JPY is an important risk factor in the OTC portfolios of Japanese banks. The global statistics published by the *Bank for International Settlements* show that interest rate and foreign exchange derivatives constitute the largest and second-largest categories of OTC derivatives in terms of notional outstanding and gross market values. However, the extremely low volatility of Japanese interest rates (due, in part, to explicit yield curve control on the part of the Bank of Japan) means that many Japanese corporations likely do not hedge interest rate risk, and even if they do the resulting counterparty risk exposures are likely to be small since interest rate implied volatility is also extremely low. Within foreign exchange derivatives, the yen is third largest currency globally (after the dollar and the euro) with approximately 16% of all outstanding foreign exchange derivatives tied to the yen as of H2 2019. Moreover, Japanese firms have a natural demand for USD/JPY derivatives for the purpose of swapping dollar-denominated liabilities to yen or hedging of dollar-denominated cash flows. Taken together, these facts imply that the USD/JPY is likely to be an important risk factor in the OTC portfolios of Japanese

[12] For example, Davis (2019a) writes that "once CVA has been rolled out across their derivatives portfolios more broadly, they [the Japanese banks] will likely look to use swaps referencing a credit index such as iTraxx Japan or even iTraxx Europe."

banks.[13]

Unlike for the SoftBank CDS, the impact of counterparty risk management on the correlation between the iTraxx Japan CDS spread and the *level* of the USD/JPY exchange rate is ambiguous. This is because some firms are long U.S. dollars to hedge foreign bond issues on the liability side (e.g., SoftBank), while others are short U.S. dollars to hedge cash flow risk on the asset side. Such offsetting exposures to the USD/JPY exchange rate could mitigate, or cancel out, the CDS hedging pressure induced by changes in the USD/JPY exchange rate.

However, the model predicts an unambiguous increase in the correlation between the iTraxx Japan CDS spread and the *implied volatility* of the USD/JPY exchange rate. This is due to the option-like feature of CVA: the dealer suffers a loss when the counterparty defaults on a derivatives liability, but does not see a corresponding gain when the counterparty defaults on a derivatives asset. This asymmetry means that dealers are *short implied volatility* in the credit risk component of their derivatives portfolios. Importantly, this holds regardless of the directional exposure to the USD/JPY exchange rate, i.e., all dealers see an increase in their derivatives credit exposure when implied volatility increases, leading to an increased demand for CDS protection.

In terms of the model, the dealers' cross-gamma is always positive when we take S_1 to be implied volatility:

$$\frac{\partial \mathrm{EPE}}{\partial \mathrm{IV}} > 0.$$

Intuitively, when implied volatility goes up, expected future credit losses increase for all derivatives portfolios, which leads dealers to demand more CDS protection that pushes up spreads. That is, the chain of events that induce an increase in the correlation can be summarized as follows:

$$\text{FX volatility} \uparrow \Rightarrow \text{dealers' exposure} \uparrow \Rightarrow \text{dealers' CDS demand} \uparrow \Rightarrow \text{CDS spreads} \uparrow$$

In summary, we have the following testable predictions regarding the correlation between the USD/JPY implied volatility and iTraxx Japan CDS spreads:

(i) Hedging by derivatives dealers of counterparty risk should induce a *structural break* in the correlation after December 31, 2018.

(ii) Hedging by derivatives dealers of counterparty risk should have a *positive* impact on the correlation.

[13] In addition, I have checked the annual reports of a sample of large Japanese companies and they confirm that cross-currency swaps and forward contracts tied to the USD/JPY are prevalent, whereas interest rate swaps are less frequently reported.

I proceed to test these predictions empirically.

2.4.3.3 Results

I consider the sensitivity of the iTraxx Japan 5Y CDS spread to 1-year USD/JPY ATM implied volatility and investigate whether there is a structural break after December 31, 2018. To this end, I run the following regression:

$$R_{\text{iTraxx},t} \quad = \quad \alpha + \beta \times \Delta\text{ImpVol}_t + \gamma \times \text{DD}_t \times \Delta\text{ImpVol}_t + \boldsymbol{\theta}^\top \boldsymbol{X}_t + e_t, \tag{2.4.4}$$

where $R_{\text{iTraxx},t}$ is the weekly return of the iTraxx Japan 5Y CDS index from the point of view of the protection buyer, ΔImpVol_t is the weekly change in 1-year USD/JPY ATM implied volatility, and DD_t is a dummy variable that is equal to 1 after December 31, 2018 and 0 otherwise. As control variables $\boldsymbol{X}$, I include the lagged levels of the VIX, the USD/JPY exchange rate, and the 1-year USD/JPY ATM implied volatility.

In the placebo regression, I use the Nikkei 225 stock market index:

$$R_{\text{Nikkei},t} \quad = \quad \alpha + \beta \times \Delta\text{ImpVol}_t + \gamma \times \text{DD}_t \times \Delta\text{ImpVol}_t + \boldsymbol{\theta}^\top \boldsymbol{X}_t + e_t, \tag{2.4.5}$$

where $R_{\text{Nikkei},t}$ is the weekly return of the Nikkei 225 stock market index. Similar to the iTraxx Japan CDS index, the Nikkei stock market index represents a diversified portfolio of Japanese corporates, but is unaffected by counterparty risk hedging. The sample covers the 5-year period from December 31, 2014 to December 31, 2019, i.e., the sample period starts four years before the treatment date and ends one year after.

Table 2.3 reports the results of regressions (2.4.4)-(2.4.5). The estimated coefficient on the treatment dummy γ is statistically significant for the iTraxx Japan CDS index and insignificant for the Nikkei 225 stock market index. I conclude that there is a structural break in the CDS/IV correlation driven by increased counterparty risk hedging after December 31, 2018. The magnitude is economically significant as well: a one percentage point change in USD/JPY implied volatility is associated with an additional CDS return (for the buyer) of 0.21% after Q4 2018. In terms of the 5-year CDS spread, this estimate implies a hedging-induced spread widening of around 4 basis points (0.21%/5) for every percentage point increase in USD/JPY implied volatility after Q4 2018.

As an additional robustness test, I also conduct placebo tests with fictitious treatment dates in the pre-treatment sample from December 31, 2014 to December 31, 2019.[14] Specifically, I run regression (2.4.4) with (annual) fictitious treatment dates from December 31,

[14] I choose the pre-treatment sample for better statistical power, since the post-treatment sample is only one year long.

2015 to December 31, 2017. Since the entire sample is before the actual treatment date, I expect the interaction coefficient to be insignificant for the fictitious treatment dates. Table 2.4 reports the results with columns (1) through (3) corresponding to each of the fictitious treatment dates from December 31, 2015 to December 31, 2017. As expected, none of the interaction terms are significant in this case. This provides further evidence that the change in the CDS/IV correlation after the Japanese CVA accounting shift is driven by counterparty risk hedging.

2.5 Conclusion

In this paper, I show how dynamic hedging of derivatives portfolios on multiple underlyings can alter the covariance structure of asset returns in equilibrium. The model predicts that dynamic hedging induces cross-asset correlations that are proportional to the second-order cross-derivative of dealers' OTC portfolios.

I demonstrate the empirical relevance of the model by showing how counterparty risk hedging systematically affects Japanese corporate CDS markets. When a derivatives dealer enters into an uncollateralized derivative with a client, the dealer takes on credit exposure and the amount of exposure changes with the value of the underlying asset. Dealers have strong regulatory incentives to dynamically hedge counterparty credit risk via CDS, but, at the same time, CDS markets are becoming increasingly illiquid. Thus, the rebalancing of CDS hedges driven by changes in the underlying assets can drive correlations between the CDS spreads of hedging instruments and underlying asset markets.

The effects are economically significant. In the first part of the empirical analysis, I show that counterparty risk hedging associated with SoftBank's large, uncollateralized FX swap portfolio drives a substantial, negative correlation between SoftBank's CDS spread and the USD/JPY exchange rate. I estimate that counterparty risk hedging accounts for 25% of the weekly volatility of SoftBank's CDS returns. The large and rapid expansion of SoftBank's FX swap portfolio allow for a clean identification, but the SoftBank CDS contract is also important in its own right, being among the world's most actively traded corporate CDS contracts. In the second part of the empirical analysis, I show that counterparty risk hedging substantially increases the correlation between the iTraxx Japan CDS index and USD/JPY implied volatility.

These effects are unlikely to be specific to Japan as the underlying drivers–regulatory incentives to hedge counterparty risk with CDS contracts and declining CDS liquidity–are global, post-crisis phenomena.

2.6 Appendix A – Proof of Proposition 2.1

I solve a more general version of the model that allows for time- and state-dependent market illiquidity in both asset markets. Proposition 2.1 then follows as a special case.

As in the main text, let x_i and S_i for $i \in \{1, 2\}$ denote fundamental values and market prices, respectively, of the two assets. Assume that fundamental values evolve as follows under the physical measure:

$$dx_i(t) = \sigma_{i1}(t)dW_1(t) + \sigma_{i2}(t)dW_2(t) \quad i \in \{1,2\} \tag{2.6.1}$$

We want to solve for the asset price dynamics in equilibrium:

$$\begin{aligned} dS_i(t) &= \theta_{i1}(t, S_1(t), S_2(t))dW_1(t) + \theta_{i2}(t, S_1(t), S_2(t))dW_2(t) \\ &\quad + O(dt) \quad i \in \{1,2\} \end{aligned} \tag{2.6.2}$$

The asset demands from fundamental investors F and derivatives hedgers B are given by:

$$\begin{aligned} F_i(t, x_i(t), S_i(t)) &= A_i(t, S_1(t), S_2(t)) \left[x_i(t) - S_i(t)\right] \quad i \in \{1,2\} \\ B_i(t, S_1(t), S_2(t)) &= -\frac{\partial G}{\partial S_i}(t, S_1(t), S_2(t)) \quad i \in \{1,2\}, \end{aligned}$$

where $A_i(t, S_1(t), S_2(t))$ are positive functions that may depend on time and state, i.e., market illiquidity is time- and state-dependent in each of the markets. The solution to the general model is characterized by the proposition below.

Proposition 2.2. *Collect the covariance structure of the market prices and fundamental values in column vectors as follows:*

$$\begin{aligned} \boldsymbol{\theta}(t, S_1(t), S_2(t)) &\equiv [\theta_{11}, \theta_{12}, \theta_{21}, \theta_{22}]^\top \\ \boldsymbol{\sigma}(t, S_1(t), S_2(t)) &\equiv [\sigma_{11}, \sigma_{12}, \sigma_{21}, \sigma_{22}]^\top, \end{aligned}$$

where I omit $(t, S_1(t), S_2(t))$-arguments on the right-hand side for readability.

In equilibrium, the covariance structure of the market, $\boldsymbol{\theta} \equiv \boldsymbol{\theta}(t, S_1(t), S_2(t))$, solves the following matrix equation:

$$\boldsymbol{M}\boldsymbol{\theta} = \boldsymbol{\sigma},$$

where

$$\boldsymbol{M} \equiv \begin{bmatrix} 1+\frac{G_{11}}{A_1} & 0 & \frac{G_{12}}{A_1} & 0 \\ 0 & 1+\frac{G_{11}}{A_1} & 0 & \frac{G_{12}}{A_1} \\ \frac{G_{21}}{A_2} & 0 & 1+\frac{G_{22}}{A_2} & 0 \\ 0 & \frac{G_{21}}{A_2} & 0 & 1+\frac{G_{22}}{A_2} \end{bmatrix}.$$

As above, $G_{ij} \equiv \frac{\partial^2 G}{\partial S_i \partial S_j}(t, S_1, S_2)$ *denotes the second-order derivatives of the pricing model of the derivatives hedgers.*

Proof. We apply the market-clearing condition, $dF_i + dB_i = 0, \quad i \in \{1,2\}$, and match coefficients on each of the Brownian increments, dW_1, dW_2. From the market-clearing condition of asset 1 we get:

$$\begin{aligned} dF_1 + dB_1 &= 0 \\ [A_1(\sigma_{11}-\theta_{11}) + (G_{11}\theta_{11} + G_{12}\theta_{21})]\, dW_1 & \quad \Updownarrow \\ +\,[A_1(\sigma_{12}-\theta_{12}) + (G_{11}\theta_{12} + G_{12}\theta_{22})]\, dW_2 & \\ +O(dt) &= 0 \end{aligned}$$

Similarly, from the market-clearing condition of asset 2 we get:

$$\begin{aligned} dF_2 + dB_2 &= 0 \\ [A_2(\sigma_{21}-\theta_{21}) + (G_{21}\theta_{11} + G_{22}\theta_{21})]\, dW_1 & \quad \Updownarrow \\ +\,[A_2(\sigma_{22}-\theta_{22}) + (G_{21}\theta_{12} + G_{22}\theta_{22})]\, dW_2 & \\ +O(dt) &= 0 \end{aligned}$$

Setting all dW-terms to zero yields four equations in the four unknowns $[\theta_{11}, \theta_{12}, \theta_{21}, \theta_{22}]$ for each time t:

$$\begin{aligned} A_1(\sigma_{11}-\theta_{11}) + (G_{11}\theta_{11} + G_{12}\theta_{21}) &= 0 \\ A_1(\sigma_{12}-\theta_{12}) + (G_{11}\theta_{12} + G_{12}\theta_{22}) &= 0 \\ A_2(\sigma_{21}-\theta_{21}) + (G_{21}\theta_{11} + G_{22}\theta_{21}) &= 0 \\ A_2(\sigma_{22}-\theta_{22}) + (G_{21}\theta_{12} + G_{22}\theta_{22}) &= 0 \end{aligned}$$

Writing the system of equations in matrix form, we get Proposition 2.2. $\square$

Proposition 2.1 follows from the solution to the general model in Proposition 2.2 by letting $A_1 \to \infty$ and applying the following parameter restrictions:

$$\begin{aligned}
\sigma_{11}(t) &= \sigma_1 \in \mathbb{R} \\
\sigma_{12}(t) &= 0 \\
\sigma_{21}(t) &= 0 \\
\sigma_{22}(t) &= \sigma_2 \in \mathbb{R}
\end{aligned}$$

2.7 Appendix B – Full regression tables

Tables 2.5 to 2.8 report the full set of coefficients (including control variables) for all regressions in the main text.

Figure 2.1: **FX swap exposure profiles.** The figure plots the exposure profile, $\mathbb{E}_0\left[V_t^+\right]$, of a 10-year FX swap from the point of view of the dealer for three scenarios: the swap is at-the-money ($V_0 = 0$), in-the-money ($V_0 \gg 0$) or out-of-the-money ($V_0 \ll 0$). The dealer holds CDS protection on the counterparty in proportion to the area under the exposure profile (shaded region).

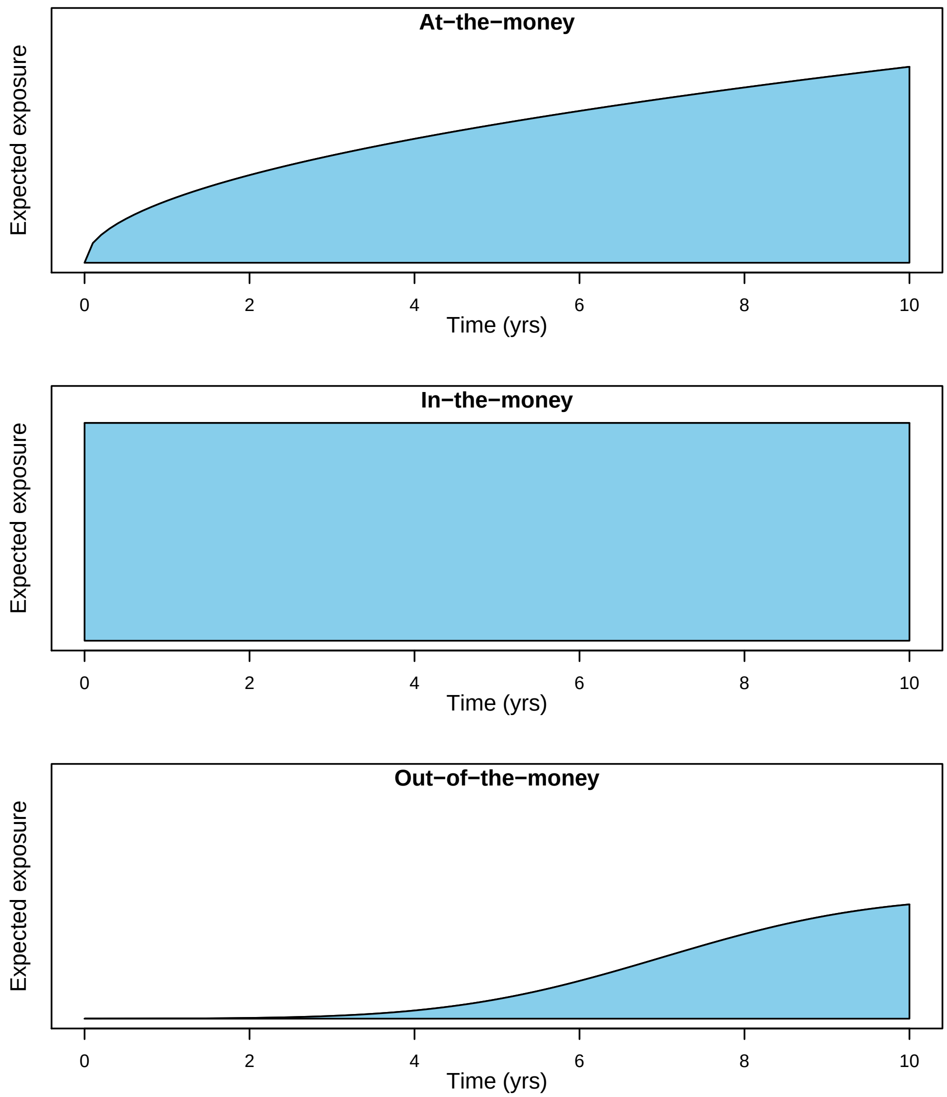


Figure 2.2: **SoftBank FX swap notional and long-term debt.** The figure plots the outstanding notional of SoftBank's long-term FX swaps (left axis) and the outstanding notional of SoftBank's long-term debt (right axis), both in billion USD. Long-dated is defined here as having a remaining maturity of more than one year. The vertical dashed line marks the treatment date (December 31, 2013) after which we expect dealers hedging of SoftBank counterparty risk to affect the CDS/FX correlation.

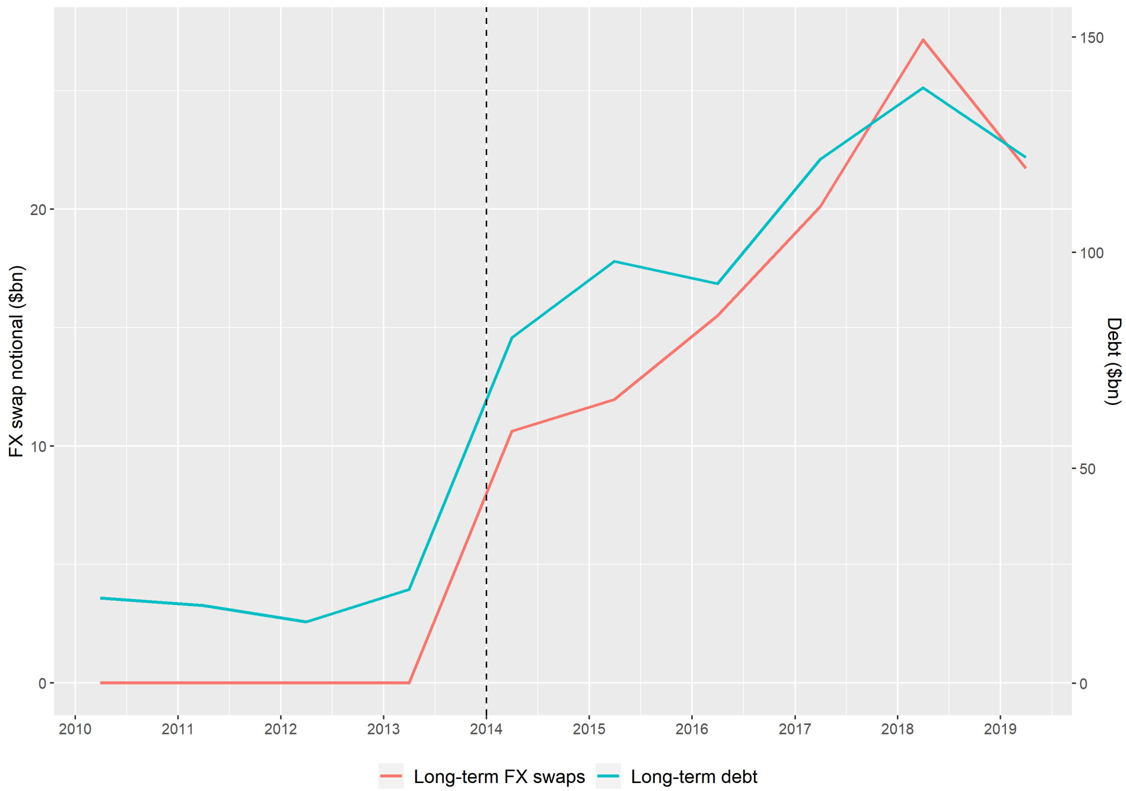


Figure 2.3: **CDS/FX correlation before/after the SoftBank FX swap expansion.** The figure plots the 5-year rolling correlation between weekly USD/JPY returns and weekly changes in SoftBank's 5Y senior CDS spread from December 31, 2009 through December 31, 2019 (solid red line). The vertical dashed line marks the treatment date (December 31, 2013) after which we expect dealers hedging of SoftBank counterparty risk to affect the CDS/FX correlation. The 5-year rolling correlation between weekly USD/JPY returns and the weekly returns of SoftBank's stock (placebo instrument) is also shown (dashed blue line).

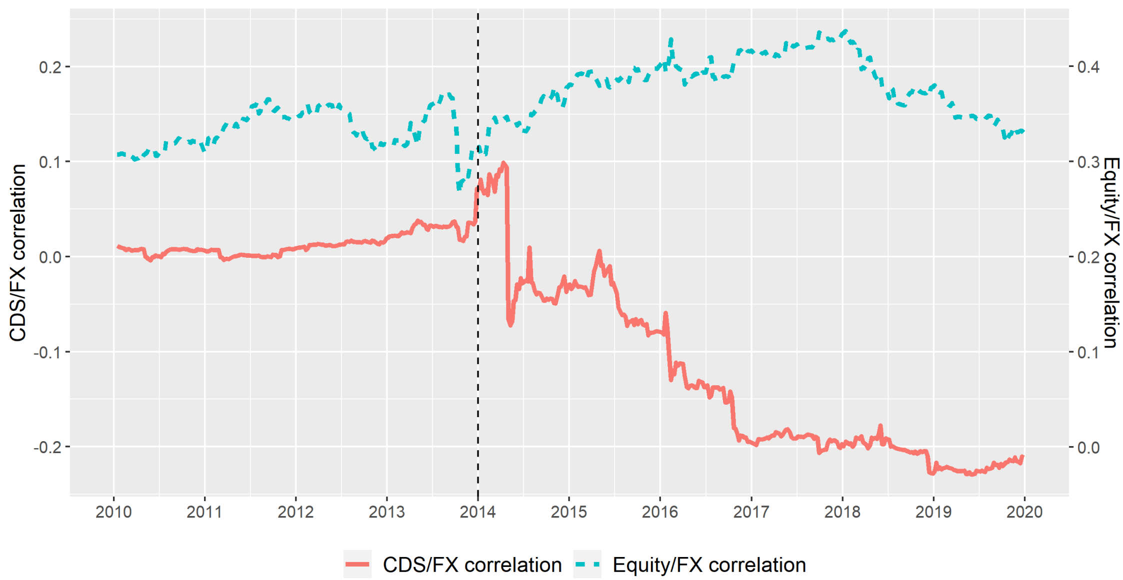


Figure 2.4: **Outstanding notional of Japanese CDS.** The figure plots the total cleared notional (in JPY billions) of iTraxx Japan CDS index contracts (blue) and Japanese single-name CDS contracts (red) as reported by the Japan Securities Clearing Corporation (JSCC).

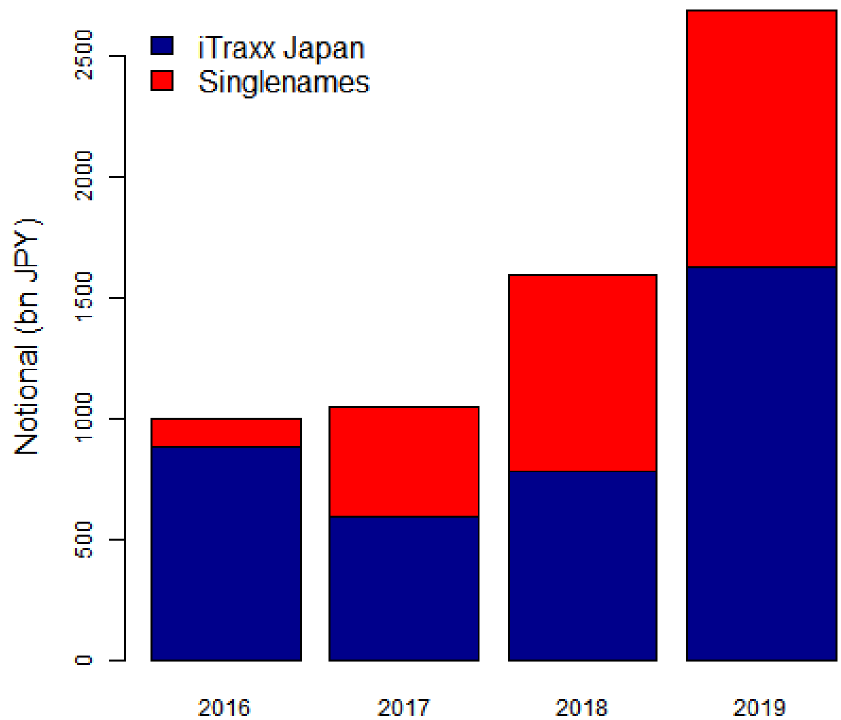


Table 2.1: **CDS/FX sensitivity before/after the SoftBank FX swap expansion.** The table reports the results of regressions (2.4.1)-(2.4.3). The left-hand side is the weekly return of SoftBank's 5-year senior CDS from the point of view of the protection buyer (column 1), the weekly return of the SoftBank stock (column 2) and the weekly excess return of the (maturity-matched) senior unsecured bond (column 3). On the right-hand side are the weekly USD/JPY return, the interaction between the weekly USD/JPY return and the treatment dummy (equal to 1 after December 31, 2013 and zero otherwise) and control variables. The control variables are the lagged levels of the VIX and the USD/JPY exchange rate (FX). Estimated coefficients for the control variables are omitted, but can be found in the appendix. The sample runs from December 31, 2009 to December 31, 2019. Standard errors are in parentheses.

	$R_{\text{CDS},t}$	$R_{\text{equity},t}$	$R_{\text{bond},t}$
	(1)	(2)	(3)
$R_{\text{FX},t}$	0.008	0.180***	0.013
	(0.049)	(0.036)	(0.023)
$R_{\text{FX},t}$ * DD_t	−0.140**	0.036	0.004
	(0.066)	(0.049)	(0.030)
Observations	505	505	505
R^2	0.026	0.125	0.008
Note:			*p<0.1; **p<0.05; ***p<0.01

Table 2.2: **Placebo test on treatment dates for the SoftBank FX swap expansion.** The table reports the results of regression (2.4.1) with fictitious treatment dates in the post-treatment sample. The left-hand side is the weekly return of SoftBank's 5-year senior CDS from the point of view of the protection buyer. On the right-hand side are the weekly USD/JPY return, the interaction between the weekly USD/JPY return and the treatment dummy (equal to 1 after the treatment date and zero otherwise) and control variables. The fictitious treatment dates are chosen annually from December 31, 2015 through December 31, 2018 (columns 1 through 4). The control variables are the lagged levels of the VIX and the USD/JPY exchange rate (FX). Estimated coefficients for the control variables are omitted, but can be found in the appendix. The sample runs from December 31, 2013 to December 31, 2019. Standard errors are in parentheses.

	$R_{CDS,t}$			
	(1)	(2)	(3)	(4)
$R_{FX,t}$	-0.161^{**}	-0.140^{***}	-0.115^{***}	-0.128^{***}
	(0.066)	(0.040)	(0.037)	(0.035)
$R_{FX,t}$ * DD_t	0.039	0.027	-0.100	-0.052
	(0.077)	(0.073)	(0.089)	(0.138)
Observations	302	302	302	302
R^2	0.058	0.058	0.062	0.058
Note:				*p<0.1; **p<0.05; ***p<0.01

Table 2.3: **CDS/IV sensitivity before/after the Japanese CVA accounting shift.** The table reports the results of regressions (2.4.4)-(2.4.5). The left-hand side is the weekly return of the iTraxx Japan 5-year CDS from the point of view of the protection buyer (column 1) and the weekly return of the Nikkei 225 stock market index (column 2). On the right-hand side are the weekly change of the 1-year USD/JPY ATM implied volatility, the interaction between the weekly implied volatility change and the treatment dummy (equal to 1 after December 31, 2018 and zero otherwise) and control variables. The control variables consist of the lagged levels of the VIX, the USD/JPY exchange rate (FX) and the 1-year USD/JPY ATM implied volatility (IV). Estimated coefficients for the control variables are omitted, but can be found in the appendix. The sample runs from December 31, 2014 to December 31, 2019. Standard errors are in parentheses.

	$R_{\text{iTraxx},t}$	$R_{\text{Nikkei},t}$
	(1)	(2)
ΔImpVol_t	0.177^{***}	-0.161^{***}
	(0.033)	(0.025)
$\Delta\text{ImpVol}_t * \text{DD}_t$	0.213^{**}	-0.023
	(0.104)	(0.078)
Observations	252	252
R^2	0.177	0.185
Note:	*p<0.1; **p<0.05; ***p<0.01	

Table 2.4: **Placebo test on treatment dates for the Japanese CVA accounting shift.** The table reports the results of regression (2.4.4) with fictitious treatment dates in the pre-treatment sample. The left-hand side is the weekly return of the iTraxx Japan 5-year CDS from the point of view of the protection buyer. On the right-hand side are the weekly change of the 1-year USD/JPY ATM implied volatility, the interaction between the weekly implied volatility change and the treatment dummy (equal to 1 after the treatment date and zero otherwise) and control variables. The fictitious treatment dates are chosen annually from December 31, 2015 through December 31, 2017. The control variables consist of the lagged levels of the VIX, the USD/JPY exchange rate (FX) and the 1-year USD/JPY ATM implied volatility (IV). Estimated coefficients for the control variables are omitted, but can be found in the appendix. The sample runs from December 31, 2014 to December 31, 2018. Standard errors are in parentheses.

	$R_{\text{iTraxx},t}$		
	(1)	(2)	(3)
ΔImpVol_t	0.150^{**}	0.201^{***}	0.167^{***}
	(0.060)	(0.041)	(0.037)
ΔImpVol_t * DD_t	0.032	−0.099	0.037
	(0.072)	(0.074)	(0.098)
Observations	201	201	201
R^2	0.157	0.164	0.157
Note:			*p<0.1; **p<0.05; ***p<0.01

Table 2.5: **CDS/FX sensitivity before/after the SoftBank FX swap expansion.** The table reports the results of regressions (2.4.1)-(2.4.3). The left-hand side is the weekly return of SoftBank's 5-year senior CDS from the point of view of the protection buyer (column 1), the weekly return of the SoftBank stock (column 2) and the weekly excess return of the (maturity-matched) senior unsecured bond (column 3). On the right-hand side are the weekly USD/JPY return, the interaction between the weekly USD/JPY return and the treatment dummy (equal to 1 after December 31, 2013 and zero otherwise) and control variables. The control variables are the lagged levels of the VIX and the USD/JPY exchange rate (FX). The sample runs from December 31, 2009 to December 31, 2019. Standard errors are in parentheses.

	$R_{CDS,t}$	$R_{equity,t}$	$R_{bond,t}$
	(1)	(2)	(3)
$R_{FX,t}$	0.008	0.180***	0.008
	(0.049)	(0.036)	(0.027)
$R_{FX,t}$ * DD_t	-0.140^{**}	0.036	-0.026
	(0.066)	(0.049)	(0.036)
VIX_{t-1}	0.015*	-0.005	-0.004
	(0.008)	(0.006)	(0.005)
FX_{t-1}	0.005	-0.002	0.000
	(0.003)	(0.002)	(0.000)
Observations	505	505	492
R^2	0.026	0.125	0.004
Note:			*p<0.1; **p<0.05; ***p<0.01

Table 2.6: **Placebo test on treatment dates for the SoftBank FX swap expansion.** The table reports the results of regression (2.4.1) with fictitious treatment dates in the post-treatment sample. The left-hand side is the weekly return of SoftBank's 5-year senior CDS from the point of view of the protection buyer. On the right-hand side are the weekly USD/JPY return, the interaction between the weekly USD/JPY return and the treatment dummy (equal to 1 after the treatment date and zero otherwise) and control variables. The fictitious treatment dates are chosen annually from December 31, 2015 through December 31, 2018 (columns 1 through 4). The control variables are the lagged levels of the VIX and the USD/JPY exchange rate (FX). The sample runs from December 31, 2013 to December 31, 2019. Standard errors are in parentheses.

	$R_{CDS,t}$			
	(1)	(2)	(3)	(4)
$R_{FX,t}$	-0.161^{**}	-0.140^{***}	-0.115^{***}	-0.128^{***}
	(0.066)	(0.040)	(0.037)	(0.035)
$R_{FX,t}$ * DD_t	0.039	0.027	-0.100	-0.052
	(0.077)	(0.073)	(0.089)	(0.138)
VIX_{t-1}	0.009	0.009	0.009	0.009
	(0.010)	(0.010)	(0.010)	(0.010)
FX_{t-1}	0.006	0.006	0.006	0.006
	(0.007)	(0.007)	(0.007)	(0.007)
Observations	302	302	302	302
R^2	0.058	0.058	0.062	0.058
Note:		$^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$		

Table 2.7: **CDS/IV sensitivity before/after the Japanese CVA accounting shift.** The table reports the results of regressions (2.4.4)-(2.4.5). The left-hand side is the weekly return of the iTraxx Japan 5-year CDS from the point of view of the protection buyer (column 1) and the weekly return of the Nikkei 225 stock market index (column 2). On the right-hand side are the weekly change of the 1-year USD/JPY ATM implied volatility, the interaction between the weekly implied volatility change and the treatment dummy (equal to 1 after December 31, 2018 and zero otherwise) and control variables. The control variables consist of the lagged levels of the VIX, the USD/JPY exchange rate (FX) and the 1-year USD/JPY ATM implied volatility (IV). The sample runs from December 31, 2014 to December 31, 2019. Standard errors are in parentheses.

	$R_{\text{iTraxx},t}$	$R_{\text{Nikkei},t}$
	(1)	(2)
ΔImpVol_t	0.177^{***}	-0.161^{***}
	(0.033)	(0.025)
ΔImpVol_t * DD_t	0.213^{**}	-0.023
	(0.104)	(0.078)
VIX_{t-1}	0.002	0.002
	(0.002)	(0.002)
FX_{t-1}	0.004^{**}	-0.003^{*}
	(0.002)	(0.001)
IV_{t-1}	-0.007	0.007
	(0.007)	(0.005)
Observations	252	252
R^2	0.177	0.185
Note:		$^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$

Table 2.8: **Placebo test on treatment dates for the Japanese CVA accounting shift.** The table reports the results of regression (2.4.4) with fictitious treatment dates in the pre-treatment sample. The left-hand side is the weekly return of the iTraxx Japan 5-year CDS from the point of view of the protection buyer. On the right-hand side are the weekly change of the 1-year USD/JPY ATM implied volatility, the interaction between the weekly implied volatility change and the treatment dummy (equal to 1 after the treatment date and zero otherwise) and control variables. The fictitious treatment dates are chosen annually from December 31, 2015 through December 31, 2017. The control variables consist of the lagged levels of the VIX, the USD/JPY exchange rate (FX) and the 1-year USD/JPY ATM implied volatility (IV). The sample runs from December 31, 2014 to December 31, 2018. Standard errors are in parentheses.

	$R_{iTraxx,t}$		
	(1)	(2)	(3)
ΔImpVol_t	0.150^{**}	0.201^{***}	0.167^{***}
	(0.060)	(0.041)	(0.037)
ΔImpVol_t * DD_t	0.032	−0.099	0.037
	(0.072)	(0.074)	(0.098)
VIX_{t-1}	0.003	0.003	0.003
	(0.003)	(0.003)	(0.003)
FX_{t-1}	0.003	0.003	0.003
	(0.002)	(0.002)	(0.002)
IV_{t-1}	-0.018^{*}	-0.018^{*}	-0.018^{*}
	(0.010)	(0.010)	(0.010)
Observations	201	201	201
R^2	0.157	0.164	0.157
Note:			$^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$

Chapter 3

Cash as a Perpetual Option†

Abstract

We consider the option value of cash when nominal interest rates are no longer constrained by the zero lower bound. We provide a general valuation principle and solve for the value of cash in semi-closed form under Vasicek (1977) dynamics for the nominal short rate. In the absence of a zero lower bound, cash can have substantial option value. However, the option value of cash is mitigated by the risk of early redemption by the central bank and we extend the valuation formula to include early redemption risk.

†We thank David Lando, Klaus Bjerre Toft, Kenneth Rogoff and a number of seminar and conference participants for valuable comments and feedback.

Introduction

What is the value of cash when nominal interest rates are not constrained by the zero lower bound? Here, we consider as cash any non-interest-bearing claim on the unit of account. We use paper currency as our motivating example throughout, but the definition also captures other forms of cash, such as certain kinds of digital currency, stored value cards and the like. We show that such claims can have significant option value when nominal interest rates can go negative. While nominal rates are currently bound from below by central banks' commitment to accommodate demand for paper currency at par value, the "peg" between physical currency and electronic deposits is likely to come under pressure in the face of declining natural rates of interest and persistently low inflation (e.g., Rachel and Summers, 2019). Indeed, there are increasing calls for central banks to go back to conducting monetary policy primarily by setting the short-term nominal rate of interest, potentially at deeply negative levels (e.g., Buiter, 2009, Kimball, 2015, Goodfriend, 2016 and Rogoff, 2017).[1]

The main contribution of the paper is to characterize the value of cash as the solution to an infinite-horizon optimal stopping problem and provide a semi-closed form solution. People optimally hold zero-yielding currency as long as the expected future value of not having to pay a negative nominal rate exceeds the opportunity cost of not receiving a positive nominal rate. Since cash does not expire, the optionality is perpetual in nature. We derive a general valuation formula for both finite and infinite maturity claims, but we focus on the value of infinite-maturity cash in a setting with normally distributed nominal short rates. In particular, we solve for the value of cash in the Vasicek (1977) model which provides a parsimonious description of an economy with nominal short rates that are occasionally deeply negative, while mean-reverting to a (usually positive) steady state.[2] In practice, however, the value of cash is constrained by the risk of early redemption, e.g., the central bank may at some point decide to redeem paper currency at par value. To capture early redemption risk, we extend the valuation formula to allow for redemption at the first jump time of a Poisson process.

In short, we find that the option value of cash can be substantial. For example, in a model calibrated to US dollar swap rates and implied cap volatilities in March 2020, the premium of cash over electronic deposits is around 30% in the absence of a peg and rises

[1] In recent years, central banks in developed markets have relied on large-scale asset purchases of public and private sector assets as their main instrument of monetary policy. Such indiscriminate buying by the central bank can lead to severe, economy-wide moral hazard problems, and the fact that monetary stimulus is usually given at the same time that risky assets fall in value only serves to reinforce the notion of a "central bank put". If the central bank could set short-term nominal rates at arbitrarily low levels to clear the market for loanable funds, the need for such "unconventional" measures would be greatly reduced.

[2] In Appendix 3.5, we show how to solve for the price of cash under a more general class of one-factor models for the nominal short rate.

to more than 300% if the nominal short rate falls to -5% (in fact, Curdia (2015) estimates that the federal funds rate should have been as low as -5% in order to clear the market during the depth of the financial crisis in 2008-09). The value of cash also increases rapidly with interest rate volatility, giving rise to a "perpetuity paradox": the value of cash goes to infinity for certain parameter constellations that are not *ex ante* implausible.

Numerical examples demonstrate that a substantial fraction of the value of cash derives from the ability to hold cash over a very long horizon. To assess the importance of the maturity dimension, we introduce the concept of a term structure of cash, which relates the value of cash to its expected maturity in the presence of early redemption risk (the expected maturity is given by $1/\lambda$ in the model with constant intensity λ of early redemption). We find that while early redemption risk significantly impacts the value of cash, a modest–but realistic–degree of early redemption risk does not severely limit the option value of cash.

Our paper is related to the extensive literature on the valuation of perpetual options, see, e.g., Mordecki (2002), Boyarchenko and Levendorskii (2003), Kyprianou (2004), Kühn and Kyprianou (2007), Emmerling (2012) and Donno et al. (2020). However, to our knowledge, we are the first to consider the value of cash as a perpetual option and to provide a semi-closed form solution.

The rest of the paper is structured as follows. Section 2 develops the general valuation principle for both finite and infinite claims, and solves for the value of cash with and without early redemption risk. Section 3 provides numerical examples in a calibrated model and investigates how the value of cash, in terms of electronic deposits, depends on the level of interest rates, the volatility of interest rates and the risk of early redemption. Section 4 concludes.

3.1 The value of cash

Consider the holder of cash when nominal interest rates can go negative. When the nominal short rate is positive, she foregoes interest income by holding on to the cash instead of depositing or investing in other short-term interest-bearing assets. On the other hand, by holding on to cash she obtains insurance against future episodes of negative nominal interest rates. At every point in time, she must balance the value of the future insurance (the continuation value) against the opportunity cost of not depositing (the exercise value).[3]

[3]For clarity of exposition, we set the storage cost of cash to zero throughout, but it would be straightforward to extend the analysis to include a positive storage cost of cash.

3.1.1 Valuation principle

In the absence of early redemption risk, the value of cash, in units of the electronic bank account, is given by the solution to the following optimal stopping problem:

$$C^{\infty} = \sup_{\tau \geq 0} \mathbb{E}\left[e^{-\int_0^{\tau} r(u)du}\right], \tag{3.1.1}$$

where r denotes the nominal short rate process, and the supremum is taken over all stopping times τ with respect to the filtration generated by r. To see why Eqn. (3.1.1) gives the value of cash, consider first a fixed maturity $T > 0$ and a given path of short rates $r(t)$ for $t \geq 0$. From standard rules of calculus we have:

$$1 = \int_0^T r(s)e^{-\int_0^s r(u)du}ds + e^{-\int_0^T r(u)du}. \tag{3.1.2}$$

Since Eqn. (3.1.2) holds path-wise, we can replace T by a random stopping time τ, and take the risk-neutral expectation on both sides:

$$1 = \mathbb{E}\left[\int_0^{\tau} r(s)e^{-\int_0^s r(u)du}ds\right] + \mathbb{E}\left[e^{-\int_0^{\tau} r(u)du}\right]. \tag{3.1.3}$$

Eqn. (3.1.3) represents a fundamental identity in fixed income, which says that one unit of the bank account at time $t = 0$ can be used to generate a stream of floating interest payments equal to the risk-free short rate (the first term on the right-hand side) and a repayment of principal (the second term) at time τ. Normally, both terms on the right-hand side are non-negative; however, allowing for negative nominal interest rates the present value of a future stream of interest payments can become negative, and the present value of the principal repayment can exceed par.

Consider now the holder of cash. She receives one unit of the electronic numeraire at the stopping time τ, but does not receive (or pay, if negative) any interest from 0 to τ. Thus, for a given stopping time τ, the value of cash, in units of the electronic bank account, is:

$$1 - \mathbb{E}\left[\int_0^{\tau} r(s)e^{-\int_0^s r(u)du}ds\right] = \mathbb{E}\left[e^{-\int_0^{\tau} r(u)du}\right],$$

where the equality follows from Eqn. (3.1.3). Since the cash holder decides when to deposit, the value of cash is obtained by taking the supremum over all possible stopping times τ, which yields Eqn. (3.1.1).

We note that $C^{\infty} \geq 1$, since a value of unity is obtained for $\tau = 0$, i.e., if we deposit today. Hence, the *cash premium*, defined as $C^{\infty} - 1$, is always non-negative. We start by characterizing the solution to the optimal stopping problem in Eqn. (3.1.1) for the finite maturity case, $\tau \leq T$ for some $T < \infty$, and we then let $T \to \infty$ to obtain the value of cash as a perpetual option. Subsequently, we extend the valuation to include early redemption risk.

3.1.2 Finite-horizon

We start by considering the finite-horizon version of the optimal stopping problem in Eqn. (3.1.1):

$$C^T = \sup_{T \geq \tau \geq 0} \mathbb{E}\left[e^{-\int_0^\tau r(u)du}\right]. \tag{3.1.4}$$

We define the optimal stopping region D for the problem (3.1.4) as the region of (t, r)-space where cash is optimally deposited in the bank. Assuming that the nominal short rate process is Markovian, the optimal stopping region is given by:

$$D = \left\{(t, r) \in \mathbb{R}^2 \, : \, r(t) \geq b(t)\right\},$$

where b is a monotonically non-increasing function (see Proposition 3.1 below). We call b the optimal exercise boundary, or simply the exercise boundary, as the holder of cash optimally deposits the cash when the short rate crosses the exercise boundary from below. The finite horizon problem is illustrated in Figure 3.1.
We have the following representation for the solution to the finite horizon problem.

Proposition 3.1. *Consider the finite-horizon optimal stopping problem:*

$$C^T = \sup_{T \geq \tau \geq 0} \mathbb{E}\left[e^{-\int_0^\tau r(u)du}\right].$$

Assume that the nominal short rate follows a Markovian diffusion process:

$$dr(t) = \alpha(t, r)dt + \sigma(t, r)dW(t),$$

where $W(t)$ is a Brownian motion under the risk-neutral measure, and $\alpha(\cdot, \cdot)$ and $\sigma(\cdot, \cdot)$ are continuous functions.

The solution to the finite-horizon optimal stopping problem has the following representation:

$$C^T(0) = P(0, T) + \int_0^T P(0, u)\mathbb{E}^u\left[r(u)1_{[r(u)>b(u)]}\right] du, \tag{3.1.5}$$

where $P(0,u)$ is the time-0 price of the u-maturity zero-coupon bond, $\mathbb{E}^u[\cdot]$ denotes the u-maturity forward measure, and $b : [0,T] \to \mathbb{R}_+$ is a positively valued, non-increasing function that satisfies

$$1 = C^T(u; b(u)) \quad u \geq 0,$$

where $C^T(u;x)$ denotes the value at time u when the nominal short rate is $r(u) = x$.

Proof. See Appendix 3.4. □

The intuition behind Eqn. (3.1.5) is the following: a claim that must be deposited at or before time T is equivalent to a T-maturity zero-coupon bond *plus* the (positive) interest accrued in the stopping region. Since $b(u) \geq 0$ for all u (it is never optimal to deposit cash when nominal rates are negative), the second term in Eqn. (3.1.5) is always non-negative.

3.1.3 Infinite-horizon

Taking the limit of Eqn. (3.1.5) as $T \to \infty$ yields the value of cash as a perpetual option. We note that a necessary condition for obtaining a finite price of cash is that

$$\lim_{T\to\infty} P(0,T) < \infty. \tag{3.1.6}$$

That is, the price of a perpetual zero-coupon bond must be finite. While this seems like an innocent condition, in Gaussian short rate models it requires a sufficient degree of mean reversion, which is easily violated when calibrating to market data in the current low-rate environment. Thus, it is possible to obtain an infinite value of cash under plausible parameter estimates, resulting in a variant of what White and Haghani (2019) refer to as the "perpetuity paradox". This apparent "paradox" arises when the prices of tradable fixed income securities imply an infinite value for a perpetual instrument (console bonds in the case of White and Haghani (2019), cash in our case) that people will obviously not be willing, or able, to pay an arbitrarily large amount of money for. While the economic interpretation of an infinite price of cash is interesting to think about, we leave further investigation of this aspect for future research.

Up until now, we have only assumed that the nominal short rate follows a Markovian diffusion process. However, we need to impose additional structure on the dynamics of the nominal short rate to obtain a tractable solution. In particular, assume that the nominal short rate has Vasicek (1977) dynamics under the risk-neutral measure:

$$dr(t) = \kappa\left[\theta - r(t)\right]dt + \sigma dW(t), \tag{3.1.7}$$

where $W(t)$ is a one-dimensional Brownian motion under the standard risk-neutral measure with respect to the electronic bank account. The model parameters are the speed of mean reversion $\kappa > 0$, the steady-state level $\theta \in \mathbb{R}$, and the (instantaneous) short rate volatility $\sigma > 0$. It is possible to derive our main results under more general specifications for the short rate, but at the cost of a substantial increase in the complexity of the resulting expressions. Ultimately, the Vasicek model captures the key feature that we want to capture: the absence of a lower bound on nominal interest rates. We can now proceed to solve for the value of cash as follows.

Proposition 3.2. *Assume that the nominal short rate follows Vasicek (1977) dynamics as in Eqn. (3.1.7), and that the following transversality condition holds:*

$$\theta > \frac{\sigma^2}{2\kappa^2}. \tag{3.1.8}$$

The solution to the optimal stopping problem in Eqn. (3.1.1) is finite and given by:

$$C^\infty(0) = \int_0^\infty P(0,u)\left[f(0,u)\Phi\left(\frac{f(0,u)-b}{v(u)}\right) + v(u)\phi\left(\frac{f(0,u)-b}{v(u)}\right)\right] du, \tag{3.1.9}$$

where $f(0,u) \equiv \frac{\partial \log P(0,u)}{\partial T}$ *is the time-*0 *forward rate for maturity* u*, and*

$$v(u)^2 \equiv \frac{\sigma^2}{2\kappa}\left(1 - e^{-2\kappa u}\right)$$

is the variance of $r(u)$ *as seen from time* 0*. The optimal exercise boundary* $b \in \mathbb{R}^+$ *solves:*

$$1 = C^\infty(u;b) \quad u \geq 0, \tag{3.1.10}$$

where $C^\infty(u;x)$ *denotes the value at time* u *when the nominal short rate is* $r(u) = x$*.*

Proof. See Appendix 3.4. □

3.1.4 Early redemption

As an infinite-maturity instrument, cash is subject to early redemption risk. For example, early redemption can occur if the central bank decides to phase out paper currency by redeeming the outstanding stock at par value. Alternatively, the central bank might commit to a gradual phase-out of currency, where a certain fraction of the stock is redeemed each period. To capture the risk of early redemption, we assume that it occurs at the first jump time of a Poisson process with associated intensity process $\lambda(t)$. We show in the appendix that the price of cash with early redemption risk has the following representation:

$$C^{\infty} = \sup_{\tau \geq 0} \mathbb{E}\left[\int_0^{\tau} \lambda(u) e^{-\int_0^s r(u)+\lambda(u)du} ds + e^{-\int_0^{\tau} r(u)+\lambda(u)du}\right]. \tag{3.1.11}$$

Intuitively, the first term inside the expectation captures the risk of early redemption before the optimal stopping time τ, while the second term represents the present value when cash is optimally deposited at time τ. To derive a semi-closed form solution, we make two additional assumptions. First, we assume that early redemption is independent of the path of nominal short rates; second, we assume that early redemption occurs with a constant intensity $\lambda \geq 0$.[4] Given these assumptions, the proposition below solves for the value of cash with early redemption risk.

Proposition 3.3. *Assume that the nominal short rate follows Vasicek (1977) dynamics as in Eqn. (3.1.7), and that the transversality condition (3.1.8) holds. Furthermore, assume that early redemption of cash at par value occurs independently at the first jump time of a Poisson process with constant intensity $\lambda \geq 0$.*

The solution to the optimal stopping problem in Eqn. (3.1.1) is then given by:

$$\begin{aligned} C^{\infty}(0) &= \int_0^{\infty} e^{-\lambda u} P(0,u)\left[f(0,u)\Phi\left(\frac{f(0,u)-b}{v(u)}\right) + v(u)\phi\left(\frac{f(0,u)-b}{v(u)}\right)\right] du \\ &+ \int_0^{\infty} \lambda e^{-\lambda u} P(0,u) du, \end{aligned} \tag{3.1.12}$$

where $f(0,u) \equiv \frac{\partial \log P(0,u)}{\partial T}$ is the time-0 forward rate for maturity u, and

$$v(u)^2 \equiv \frac{\sigma^2}{2\kappa}\left(1 - e^{-2\kappa u}\right)$$

is the variance of $r(u)$ as seen from time 0. The optimal exercise boundary $b \in \mathbb{R}^+$ solves:

$$1 = C^{\infty}(u; b) \quad u \geq 0, \tag{3.1.13}$$

where $C^{\infty}(u; x)$ denotes the value at time u when the nominal short rate is $r(u) = x$.

Proof. See Appendix 3.4. □

[4]Using a constant intensity parameter $\lambda \geq 0$ in Eqn. (3.1.11) also gives the value of cash for the case in which the central bank retires a deterministic fraction λ of the outstanding stock of currency each period.

3.2 Numerical examples

In this section, we investigate by means of numerical examples how the value of cash depends on its primary drivers: the level of interest rates, interest rate volatility and the intensity of early redemption risk. The unlimited maturity of paper currency means that the value is extremely sensitive to changes in the level of interest rates as well as their (implied) volatility, but the positive convexity is partially offset by early redemption risk.

Our benchmark model for valuation purposes is the Vasicek (1977) model best fitted to the USD swap curve and ATM implied cap volatilities (5-, 10- and 30-year maturity) as of March 17, 2020, the day after the Federal Reserve lowered the target range for the Federal funds rate to 0-0.25%. The calibrated model parameters are shown in Table 3.1.

3.2.1 Cash and the level of interest rates

We compute the cash premium by numerical integration of Eqns. (3.1.9)-(3.1.10). Figure 3.2 plots the cash premium, $C^{\infty}-1$, as a function of the current short rate, $r(0)$. The optimal exercise boundary $b^* = 2.59\%$ (found by numerically solving Eqn. (3.1.10)) is indicated by the vertical dashed line in the figure.

The figure illustrates the positive convexity of cash when interest rates fall: both the level and the slope of the value function increase rapidly as the nominal short rate falls. The cash premium at $r(0) = 0$ is 31.2% (the height of the dotted line in the figure). That is, after the Federal Reserve lowered rates on March 16, 2020, the cash premium would have increased to about 30% in the absence of a peg. Of course, in this setting nominal short rates can go much lower and the cash premium correspondingly higher. For example, if the central bank were to set the short rate at $r(0) = -5\%$, cash would trade at a premium of 325%, i.e., a physical dollar would trade for around 4.25 electronic dollars in that scenario (holding the model parameters constant at the values given in Table 3.1).

3.2.2 Cash and interest rate volatility

Figure 3.3 plots the cash premium as a function of interest rate volatility, σ. The vertical dotted line in the figure indicates the calibrated volatility as of March 17, 2020, and the vertical dashed line indicates the level of volatility σ^* that makes the transversality condition in Eqn. (3.1.8) binding:

$$\sigma^* = \sqrt{2\theta}\kappa \approx 0.78\%.$$

For $\sigma > \sigma^*$ the cash premium is infinite as the price of the underlying perpetual zero-coupon bond goes to infinity.

3.2.3 The term structure of cash

To investigate how the value of cash depends on early redemption risk, we compute the cash premium as a function of expected time to redemption, i.e., the term structure of cash. The cash premium subject to early redemption risk is computed by numerical integration of Eqns. (3.1.12)-(3.1.13) with constant intensity λ. The expected time to redemption is then given by $1/\lambda$.

Figure 3.4 plots the term structure of cash for three different starting points for the short rate, $r(0) \in \{-1\%, -2.5\%, -5\%\}$. The left panel plots the cash premium out to 500 years, while the right panel zooms in on the first 50 years. The figure shows that a substantial fraction of the value of cash derives from the ability to hold it over extremely long periods of time, particularly for low starting points for the short rate. For example, when the nominal short rate is -5% the premium of cash with an expected time to redemption of 50 years is approximately half the premium of perpetual cash. Naturally, the risk of early redemption also diminishes the value of cash as a hedge against deeply negative interest rates (we investigate this issue in more detail below) .

3.3 Conclusion

We characterize the value of cash as the solution to an infinite-horizon optimal stopping problem when nominal interest rates are not constrained by the zero lower bound. The general solution says that cash equals a perpetual zero coupon bond (the value of which is zero under certain parameter restrictions) *plus* a perpetual option to receive a zero nominal interest rate.

We derive a semi-closed form solution under Vasicek (1977) dynamics and investigate numerically the value of cash in a calibrated model. We show that the premium of cash, in terms of the electronic bank account, can be large and volatile. The cash premium can even go to infinity for certain model parameters that are not *ex ante* implausible, resulting in a "perpetuity paradox".

However, our numerical examples also reveal that a significant fraction of the value of cash derives from the distant future, and the risk of early redemption (or gradual phase-out) mitigates the value of cash.

3.4 Appendix A – Proofs

This section contains the proofs of the main results in the text.

3.4.1 Proof of Proposition 3.1

The existence of an optimal stopping time τ in Eqn. (3.1.4), and the associated non-increasing optimal stopping boundary $b : [0, T] \to \mathbb{R}$ follows from Theorem 13.2 in Peskir and Shiryaev (2006). Moreover, the optimal stopping boundary b is positively valued, since if $r < 0$ it always pays off to postpone the exercise decision. Let $B(t)$ denote the value of the (electronic) bank account at time t:

$$B(t) = e^{\int_0^t r(t)ds}.$$

Consider the discounted cash price $Z \equiv B^{-1}C^T$. The idea behind the proof is to split the dynamics of Z into a martingale and a non-martingale part:

$$dZ = dI + dM,$$

where M is a martingale with respect to the risk-neutral measure. Then, when we integrate and take the risk-neutral expectation, the martingale term drops out, and we are left with the value of cash.

By Ito's lemma, we have:

$$\begin{aligned} d\left(\frac{C^T(t)}{B(t)}\right) &= 1_{[r(t)>b(t)]}d\left(\frac{1}{B(t)}\right) + 1_{[r(t)<b(t)]}d\left(\frac{C^T(t)}{B(t)}\right) \\ &+ \frac{1}{2}\frac{1}{B(t)}\delta\left(r(t)-b(t)\right)\left[C_r^T(t+) - C_r^T(t-)\right]dt, \end{aligned} \tag{3.4.1}$$

where we use the fact that $C^T = 1$ in the stopping region. The Dirac delta term $\delta(\cdot)$ in Eqn. (3.4.1) appears due to a local time contribution at the exercise boundary, see, e.g., Theorem 1.2 in Revuz and Yor (2004). However, this term vanishes once we impose the smooth pasting condition at the exercise boundary:

$$C_r^T(t+) = C_r^T(t-).$$

Thus, after imposing the smooth pasting condition, we are left with:

$$\begin{aligned} d\left(\frac{C^T(t)}{B(t)}\right) &= 1_{[r(t)>b(t)]}d\left(\frac{1}{B(t)}\right) + 1_{[r(t)<b(t)]}d\left(\frac{C^T(t)}{B(t)}\right) \\ &= \underbrace{-1_{[r(t)>b(t)]}\frac{r(t)}{B(t)}dt}_{\text{non-martingale part}} + \underbrace{1_{[r(t)<b(t)]}\left(\frac{C_r^T(t)}{B(t)}\right)\sigma(t)dW(t)}_{\text{martingale part}}, \end{aligned} \tag{3.4.2}$$

where $W(t)$ is a Brownian motion under the risk-neutral measure, and $\sigma(t)$ is the volatility process of the (Markovian) short rate process. The second equality follows since, prior to exercise, C^T/B is a martingale under the risk-neutral measure by standard no-arbitrage arguments. Integrating Eqn. (3.4.2) from 0 to T and taking expectations under the risk-neutral measure:

$$\mathbb{E}\left[\frac{C^T(T)}{B(T)}\right] - \frac{C^T(0)}{B(0)} = -\int_0^T \mathbb{E}\left[1_{[r(u)>b(u)]}\frac{r(u)}{B(u)}\right] du.$$

Imposing the boundary condition $C^T(T) = 1$ and solving for $C^T(0)$, we get:

$$C^T(0) = P(0,T) + \int_0^T \mathbb{E}\left[1_{[r(u)>b(u)]}\frac{r(u)}{B(u)}\right] du,$$

where $P(0,T) \equiv B(0)\mathbb{E}\left[\frac{1}{B(T)}\right]$ denotes the price of the T-maturity zero coupon bond. Finally, applying a change-of-numeraire from the bank account to the u-maturity zero-coupon bond, we get the desired result:

$$C^T(0) = P(0,T) + \int_0^T P(0,u)\mathbb{E}^u\left[1_{[r(u)>b(u)]}r(u)\right] du.$$

3.4.2 Proof of Proposition 3.2

We start from the finite-maturity solution in Eqn. (3.1.5):

$$C^T(0) = P(0,T) + \int_0^T P(0,u)\mathbb{E}^u\left[1_{[r(u)>b(u)]}r(u)\right] du.$$

When we let $T \to \infty$ and impose the transversality condition, the first term vanishes, i.e., the value of a perpetual zero-coupon bond in the Vasicek (1977) model is zero when Eqn. (3.1.8) holds. To see why this is true, recall that the time-t price of the zero coupon bond maturing at time T in the Vasicek (1977) model is given by:

$$P(0,T) = e^{A(0,T)-B(0,T)r},$$

where

$$A(0,T) = \left(\theta - \frac{\sigma^2}{2\kappa^2}\right)[B(0,T) - T] - \frac{\sigma^2}{4\kappa}B(0,T)^2 \tag{3.4.3}$$

$$B(0,T) = \frac{1 - e^{-\kappa T}}{\kappa}. \tag{3.4.4}$$

Since $B(0,T) - T \to -\infty$ when $T \to \infty$, it follows that

$$P(0,T) = e^{A(0,T) - B(0,T)r(0)} \to 0$$

for $T \to \infty$ if, and only if, $\theta - \frac{\sigma^2}{2\kappa^2} > 0$. Moreover, since the Vasicek model is time-homogeneous, the exercise boundary becomes time-invariant as $T \to \infty$, i.e., $b(u) \equiv b \in \mathbb{R}_+$. Hence, letting $T \to \infty$, we get:

$$C^{\infty}(0) \;=\; \int_0^{\infty} P(0,u)\mathbb{E}^u\left[1_{[r(u)>b]}r(u)\right] du \tag{3.4.5}$$

To evaluate this expression, we recall that for a normally distributed random variable $X \sim \mathcal{N}(m, s^2)$ and $k \in \mathbb{R}$ we have:

$$\mathbb{E}\left[1_{[X>k]}X\right] = m\Phi\left(\frac{m-k}{s}\right) + s\phi\left(\frac{m-k}{s}\right).$$

Furthermore, under the u-maturity forward measure we have:

$$\begin{aligned}\mathbb{E}^u\left[r(u)\right] &= f(0,u)\\ \mathrm{Var}\left[r(u)\right] &= \frac{\sigma^2}{2\kappa}\left(1 - e^{-2\kappa u}\right).\end{aligned}$$

Hence, for $b \in \mathbb{R}$ we have:

$$\mathbb{E}^u\left[1_{[r(u)>b]}r(u)\right] = f(0,u)\Phi\left(\frac{f(0,u)-b}{v(u)}\right) + v(u)\phi\left(\frac{f(0,u)-b}{v(u)}\right), \tag{3.4.6}$$

where $v(u)^2 = \frac{\sigma^2}{2\kappa}\left(1 - e^{-2\kappa u}\right)$.

Finally, substituting Eqn. (3.4.6) into Eqn. (3.4.5) we get:

$$C^{\infty}(0) = \int_0^{\infty} P(0,u)\left[f(0,u)\Phi\left(\frac{f(0,u)-b}{v(u)}\right) + v(u)\phi\left(\frac{f(0,u)-b}{v(u)}\right)\right] du.$$

3.4.3 Proof of Proposition 3.3

Let τ^* denote the (random) early redemption time. We start by showing that the value of cash is in fact given by Eqn. (3.1.11). Clearly, the value of cash can be written as

$$\sup_{\tau>0} \mathbb{E}\left[e^{-\int_0^{\tau\wedge\tau^*} r(u)du}\right],$$

since cash is redeemed optimally at τ or at the early redemption time τ^*, whichever comes first. Now, for a particular stopping time τ, we have:

$$\begin{aligned}
\mathbb{E}\left[e^{-\int_0^{\tau\wedge\tau^*} r(u)du}\right] &= \mathbb{E}\left[\mathbb{E}\left[e^{-\int_0^{\tau\wedge\tau^*} r(u)du} \mid \tau\right]\right] \\
&= \mathbb{E}\left[\mathbb{E}\left[\int_0^{\tau} \lambda(u)e^{-\int_0^s r(u)+\lambda(u)du}ds + e^{-\int_0^{\tau} r(u)+\lambda(u)du} \mid \tau\right]\right] \\
&= \mathbb{E}\left[\int_0^{\tau} \lambda(u)e^{-\int_0^s r(u)+\lambda(u)du}ds + e^{-\int_0^{\tau} r(u)+\lambda(u)du}\right],
\end{aligned}$$

where the second equality follows from Proposition 3.1 in Lando (1998). The value of cash is then obtained by taking the supremum over all possible stopping times, which yields Eqn. (3.1.11).

The idea behind the proof is the same as before, i.e., we split the dynamics of the discounted cash price under the risk-neutral measure into a martingale and a non-martingale component, integrate and take the risk-neutral expectation.

Assume that early redemption occurs independently of r at the first jump time of a Poisson process with constant intensity λ. Consider the cash price discounted by the risk-free bank account, $Z \equiv B^{-1}C^T$:

$$\begin{aligned}
d\left(\frac{C^T(t)}{B(t)}\right) &= 1_{[\tau*\leq t]}d\left(\frac{1}{B(t)}\right) \\
&\quad +1_{[\tau*>t]}\left[1_{[r(t)>b(t)]}d\left(\frac{1}{B(t)}\right) + 1_{[r(t)<b(t)]}d\left(\frac{C^T(t)}{B(t)}\right)\right] \\
&= 1_{[\tau*\leq t]}d\left(\frac{1}{B(t)}\right) \\
&\quad +1_{[\tau*>t]}1_{[r(t)>b(t)]}d\left(\frac{1}{B(t)}\right) + 1_{[\tau*>t]}1_{[r(t)<b(t)]}d\left(\frac{C^T(t)}{B(t)}\right)
\end{aligned}$$

The first equality follows because $C^T(t) = 1$ whenever either i) early redemption has occurred; or ii) early redemption has not occurred, but cash is optimally exercised. By standard no-arbitrage arguments, the last term is martingale under the risk-neutral measure. Hence, integrating and taking the risk-neutral expectation, we get:

$$
\begin{aligned}
\mathbb{E}\left[\frac{C^T(T)}{B(T)}\right]-\frac{C^T(0)}{B(0)} &= -\int_0^T\left[1-e^{-\lambda u}\right]\mathbb{E}\left[\frac{r(u)}{B(u)}\right]du \\
&\quad -\int_0^T e^{-\lambda u}\mathbb{E}\left[1_{[r(u)>b(u)]}\frac{r(u)}{B(u)}\right]du \\
&= -\int_0^T\left[1-e^{-\lambda u}\right]P(0,u)\mathbb{E}^u\left[r(u)\right]du \\
&\quad -\int_0^T e^{-\lambda u}P(0,u)\mathbb{E}^u\left[1_{[r(u)>b(u)]}r(u)\right]du
\end{aligned}
$$

where the first equality follows from standard Poisson relations, and the second is a change of measure to the u-forward measure. Imposing the boundary condition $C^T(T)=1$ and rearranging:

$$
\begin{aligned}
C^T(0) &= P(0,T)+\int_0^T\left[1-e^{-\lambda u}\right]P(0,u)f(0,u)du \\
&\quad +\int_0^T e^{-\lambda u}P(0,u)\mathbb{E}^u\left[1_{[r(u)>b(u)]}r(u)\right]du
\end{aligned}
$$

To obtain a more intuitive expression, integrate the second term by parts and use the fact that $1=\int_0^T P(0,u)f(0,u)du$:

$$
\begin{aligned}
\int_0^T\left[1-e^{-\lambda u}\right]P(0,u)f(0,u)du &= \int_0^T P(0,u)f(0,u)du-\int_0^T e^{-\lambda u}P(0,u)f(0,u)du \\
&= 1-\int_0^T e^{-\lambda u}P(0,u)f(0,u)du \\
&= 1+\int_0^T e^{-\lambda u}\frac{\partial P(0,u)}{\partial T}du \\
&= 1+\left[P(0,u)e^{-\lambda u}\right]_{u=0}^{u=T}+\int_0^T \lambda e^{-\lambda u}P(0,u)du \\
&= -P(0,T)e^{-\lambda T}+\int_0^T \lambda e^{-\lambda u}P(0,u)du
\end{aligned}
$$

Substituting into the previous expression:

$$
\begin{aligned}
C^T(0) &= P(0,T) + \int_0^T \left[1 - e^{-\lambda u}\right] P(0,u) f(0,u) du + \int_0^T e^{-\lambda u} P(0,u) \mathbb{E}^u \left[1_{[r(u)>b(u)]} r(u)\right] du \\
&= P(0,T)\left[1 - e^{-\lambda T}\right] + \int_0^T \lambda e^{-\lambda u} P(0,u) du + \int_0^T e^{-\lambda u} P(0,u) \mathbb{E}^u \left[1_{[r(u)>b(u)]} r(u)\right] du
\end{aligned}
$$

Letting $T \to \infty$ and imposing the transversality condition:

$$
\begin{aligned}
C^\infty(0) &= \int_0^\infty \lambda e^{-\lambda u} P(0,u) du + \int_0^\infty e^{-\lambda u} P(0,u) \mathbb{E}^u \left[1_{[r(u)>b(u)]} r(u)\right] du \\
&= \int_0^\infty \lambda e^{-\lambda u} P(0,u) du \\
&\quad + \int_0^\infty e^{-\lambda u} P(0,u) \left[f(0,u) \Phi\left(\frac{f(0,u) - b}{v(u)}\right) + v(u) \phi\left(\frac{f(0,u) - b}{v(u)}\right)\right] du
\end{aligned}
$$

3.5 Appendix B – ODE representation

In this section, we show how to solve for the price of cash under an arbitrary one-factor time-homogeneous process for the short rate.

Proposition 3.4. *Assume that the nominal short rate follows a one-dimensional time-homogeneous diffusion process:*

$$dr(t) = \alpha(r) dt + \sigma(r) dW(t), \tag{3.5.1}$$

where $W(t)$ is a one-dimensional Brownian motion. The price of cash $C : (t, r) \mapsto [1, \infty)$ solves the following free-boundary problem:

$$
\begin{aligned}
AC &= 0, \quad r < b & (3.5.2) \\
1 - C &= 0, \quad r \geq b & (3.5.3)
\end{aligned}
$$

where $A \equiv -r + \alpha(r)\frac{\partial}{\partial r} + \frac{1}{2}\sigma(r)^2 \frac{\partial^2}{\partial r^2}$ is the infinitesimal generator of the diffusion process in Eqn. (3.5.1), and $b \in \mathbb{R}_+$ is the exercise boundary.

Numerically, the system (3.5.2)-(3.5.3) can be efficiently solved by iterating over the tri-diagonal ODE system:

$$\left[\mathbb{I}_{\left[C^{(h)}<1\right]} + \mathbb{I}_{\left[C^{(h)}\geq 1\right]} \bar{A}\right] C^{(h+1)} = 1_{\left[C^{(h)}<1\right]},$$

where $C^{(h)}$ is a $n \times 1$ vector representing the price of cash, $\bar{A}$ is the $n \times n$ (tri-diagonal) *finite-difference approximation of A, $\mathbb{I}_{[C^{(h)}<1]}$ is the $n \times n$ diagonal matrix whose ith diagonal is equal to 1 where $C^{(h)} < 1$, and zero otherwise (similarly for $C^{(h)} \geq 1$), and $1_{[C^{(h)}<1]}$ is the $n \times 1$ vector whose ith element is equal to 1 where $C^{(h)} < 1$, and zero otherwise.*

Proof. By the problem statement, $C = 1$ in the stopping region $D = \{(t, r) \in \mathbb{R}^2 : r(t) \geq b\}$, while in the continuation region $D^c = \{(t, r) \in \mathbb{R}^2 : r(t) < b\}$ the price of cash must obey the fundamental pricing PDE:

$$0 = -rC + \alpha(r)\frac{\partial}{\partial r}C + \frac{1}{2}\sigma(r)^2\frac{\partial^2}{\partial r^2}C \equiv AC.$$

This gives us the system (3.5.2)-(3.5.3). The ODE representation follows by discretizing the function $C : (t, r) \mapsto [1, \infty)$, and noting that $C \geq 1$ in the continuation region. We note that for numerical stability it is important to use so-called *winding* when solving the tri-diagonal system, i.e., A should be approximated by forward differences in the regions of (t, r)-space where the drift term $\alpha(r)$ is positive, and by backward differences in the regions where $\alpha(r)$ is negative. □

Figure 3.1: Illustration of the optimal stopping region and the exercise boundary for the finite horizon optimal stopping problem (3.1.4). The holder of cash optimally deposits when the short rate crosses the exercise boundary b from below.

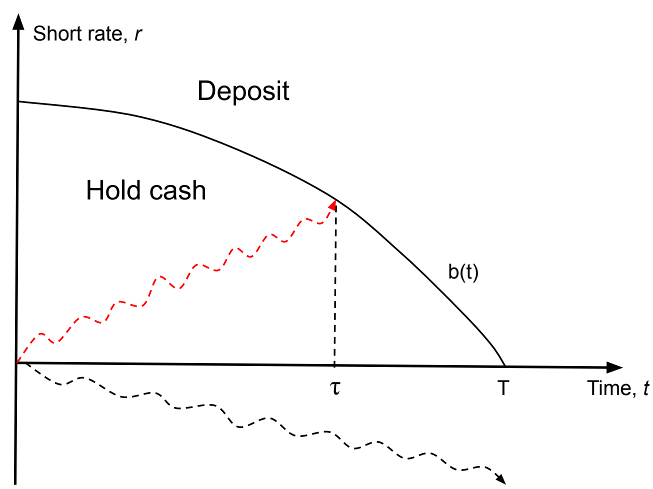


Figure 3.2: **The cash premium and the level of interest rates.** The figure plots the cash premium, i.e., the price of cash C^∞ minus one, in the Vasicek (1977) model as a function of the current short rate, $r(0)$. The vertical dashed line shows the optimal exercise boundary $b^* = 2.59\%$, and the vertical dotted line indicates $r(0) = 0$. The parameters of the model were obtained by best fitting to USD implied cap volatilities and the USD swap curve as of March 17, 2020. Parameter values are given in Table 3.1.

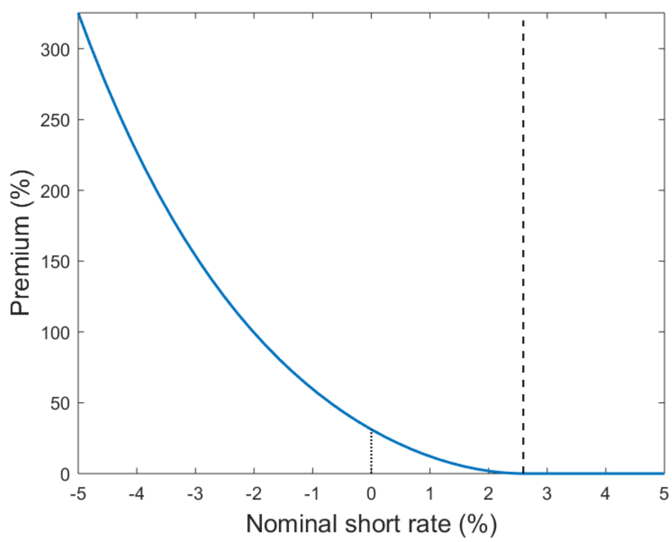


Figure 3.3: **The cash premium and interest rate volatility.** The figure plots the cash premium, i.e., the price of cash C^∞ minus one, in the Vasicek (1977) model as a function of interest rate volatility, σ. The vertical dotted line indicates the value of σ at the calibration date, and the vertical dashed line shows the value of volatility $\sigma^* \approx 0.78\%$ beyond which the price of cash is infinite. The parameters of the model were obtained by best fitting to USD implied cap volatilities and the USD swap curve as of March 17, 2020.

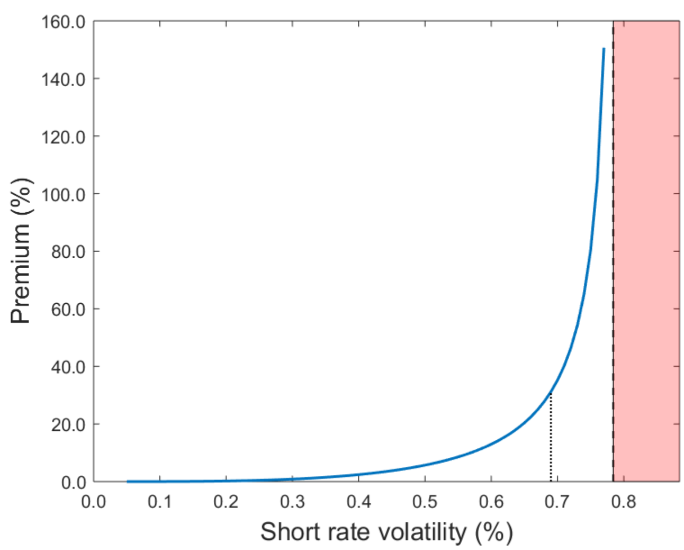
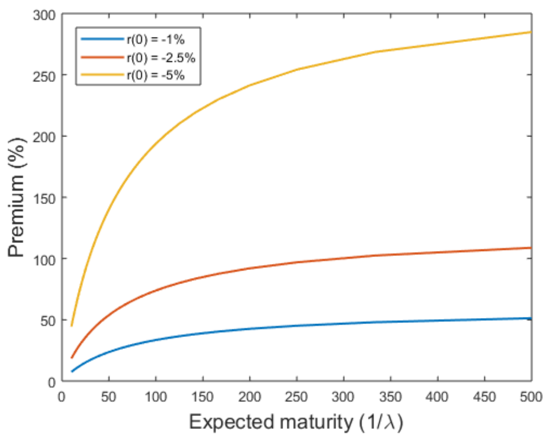


Figure 3.4: **The term structure of cash.** The figure plots the cash premium, i.e., the price of cash C^{∞} minus one, in the Vasicek (1977) model with constant intensity λ of early redemption as a function of expected time to redemption (given by $1/\lambda$). We consider three different starting points for the short rate, $r(0) \in \{-1\%, -2.5\%, -5\%\}$. The parameters of the model were obtained by best fitting to USD implied cap volatilities and the USD swap curve as of March 17, 2020.



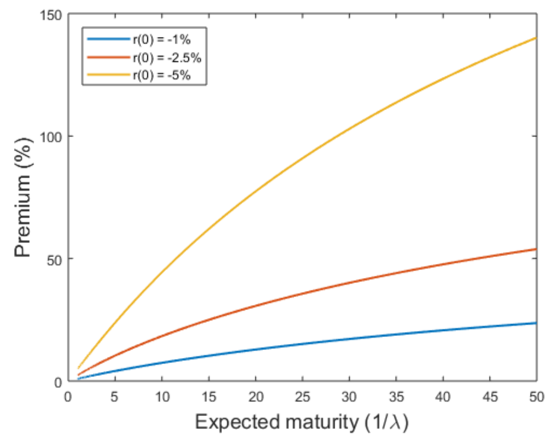


Table 3.1: **Benchmark model.** Parameters of the benchmark Vasicek model calibrated to the USD swap curve against 3-month Libor and ATM implied cap volatilities (5-, 10- and 30-year maturity) observed on March 17, 2020.

Parameter	**Value**
Long-term level (θ)	2.91%
Mean reversion (κ)	3.25%
Volatility (σ)	0.69%

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