The Market for Sharing Interest Rate Risk: Quantities and Asset Prices

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Abstract

We study interest rate risk sharing across the financial system using novel data on cross-sector interest rate swap positions. We show that pension funds and insurers (PF&I) are natural counterparties to banks and corporations: PF&I buy duration, whereas banks and corporations sell duration. However, demand is highly segmented across maturities, resulting in significant imbalances at various maturity points. We calibrate a preferred-habitat investors model with risk-averse arbitrageurs to study how demand imbalances interact with supply side constraints to impact swap spreads. Our framework helps quantify the spillover effects of demand shifts, which informs policy discussions on financial institutions' hedging requirements.

Keywords: Interest rate risk, Pension funds, Insurers, Banks, Corporations, Demand elasticities, Swap spreads

JEL classification: G11, G12, G15, G21, G22, G23, G24, G32

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Recent events, such as the US banking turmoil and the UK pension market crisis, highlight the extent to which many sectors in the economy bear interest rate risk. On one hand, pension funds and insurers provide long-dated liabilities, which make them vulnerable to a low interest rate environment (EIOPA, 2014). On the other hand, banks often engage in the opposite maturity transformation, lending long-term and borrowing short-term, which makes them particularly vulnerable to a rising rate environment (e.g., the Silicon Valley Bank crisis). Interest rate derivative markets provide investors the opportunity to share risks with other parts of the financial system. Indeed, the market for interest rate risk sharing, e.g., through swaps, is enormous, with approximately $500 trillion in outstanding gross notional as of 2022 (BIS, 2023).

Despite the critical role played by the interest rate swap market, we know surprisingly little about the extent of risk sharing among different types of institutions and how demand across sectors jointly affects asset prices. A key reason for this is that detailed cross-sector data on derivatives market, similar to what we have for equities and bonds, has been largely unavailable. As a result, the literature studying asset pricing dynamics (swap spreads) (Klingler and Sundaresan, 2019, Jermann, 2020, Hanson, Malkhozov, and Venter, 2022, Boyarchenko, Gupta, Steele, and Yen, 2018) generally lacks perspective from the quantity-side. Specifically, we lack systematic evidence on (a) the relative importance of the various end-user sectors and their contribution to demand imbalances; (b) how demand imbalances interact with supply-side frictions to determine equilibrium prices; and (c) whether demand shocks in one sector (e.g., regulation leading banks to hedge more) affect the hedging behavior of other sectors. These questions have far reaching implications for asset prices, risk mismatch across financial institutions, and the broader economy.

In this paper, we make progress on these questions by exploiting the most comprehensive trade-level cross-sector interest rate swaps data deployed in academic research to date. We examine how different sectors (banks, pension funds, insurers, asset managers, hedge funds, and corporations), each with unique hedging needs, engage in this market to share interest rate risk. We uncover partial risk transfers across sectors and persistent demand imbalances that are borne by dealers. Through the lens of a structural model, we quantify the effect of demand pressure on equilibrium prices (swap spreads) of different maturities, and in counterfactual analyses, we examine how demand shocks in one part of the financial system spill over to other parts through adjustment in asset prices.

Our analysis leverages Bank of England's confidential transactions and outstanding-positions data that cover all sectors of the economy and over 60% of the global swaps trading volume. The following features of the data allow us to comprehensively examine the full extent of this market's dynamics. First, at an investor level, we observe both the stock of its outstanding positions and the flow of new transactions, that together allow us to paint a comprehensive picture of its demand given the prices it faces. Second, we observe the exact counterparty for each trade. This facilitates the construction of granular sector classification to accurately calculate the extent of risk transfers at the sector level. Third, we observe detailed characteristics for each position and trade, including notional amounts, contracted fixed rate, trade direction, maturity, floating rate benchmark, and currencies. Thus, we can accurately compute risk exposures, capture the exact price at the time of the trade, and assess segmentation in risk sharing along dimensions such as maturity. Moreover, using the joint dynamics of swap prices and outstanding positions along the maturity curve, we can estimate user demand in different maturity segments in a fully flexible way, while also accommodating potential correlation between supply and demand side shocks. Finally, our data spans a time-period of over three years from 2019 to 2022, which allows for important time-series analyses on the evolution of risk transfers.

Although existing literature has looked at some individual sectors managing interest rate risk separately (e.g., Sen 2019, Jansen, Klingler, Ranaldo, and Duijm 2023, McPhail, Schnabl, and Tuckman 2023),[1] to the best of our knowledge, our paper is the first to examine all sectors jointly in the interest rate swap market and document their relative sizes and interactions across different market segments. Studying all the sectors together allows us to accurately compute demand imbalances along the maturity curve and draw asset pricing implications. Furthermore, the relative size and demand elasticities across sectors are also crucial for understanding the spillover effects of demand shocks from one part of the financial system to another.

We start by outlining the main facts on swap positions and trading across sectors. We focus on GBP swaps due to our largest coverage in this currency and our ability to observe the entire interest rate swap portfolio of UK entities. First, there are four main end-user segments: (a) funds (including hedge funds and asset managers), (b) pension, liability-driven investment funds, and insurers (together referred to as PF&I), (c) banks (excluding dealers), and (d) corporations.[2] In aggregate, funds usually hold the largest stock of outstanding net positions and have the largest trading volumes, followed by PF&I, banks, and corporations.

Second, to quantify the extent of risk transfers, we examine the direction of <u>net</u> outstanding positions. We construct two metrics: net swap exposures (receive minus pay fixed) and the duration risk of a one basis point parallel shift in interest rates (DV01). We find that there is significant heterogeneity in the direction of net outstanding positions <u>across</u> sectors. At an aggregate level, we find that PF&I receive fixed, i.e. they add duration to their portfolios with swaps. In contrast, banks and corporations do the opposite; they pay fixed, i.e. sell duration with swaps. Looking

[1] We provide a more exhaustive list of papers on individual sectors in the literature review.

[2] We also observe the holdings of the official sector that includes sovereign and supra-national institutions. However, as they are relatively few, we omit discussing them in detail.

within sectors at an entity level, we find that a large majority of entities within these sectors trade in one direction: PF&I receive fixed, and banks and corporations pay-fixed. Our finding is consistent with the sectors' opposite underlying balance sheet maturity mismatch: PF&I are typically net short duration while banks are typically net long duration. This pattern also suggests that PF&I are natural counterparties to banks and corporations in the swaps market.

In contrast to PF&I, banks, and corporations, the fund sector exhibits substantial heterogeneity in the direction of positions. We find that to a large degree this heterogeneity is explained by different trading strategies. Specifically, we categorize the funds universe into the following types: fixed income/bond, macro, quant/relative value, and other asset managers. Macro funds have the largest net outstanding positions and primarily pay fixed, similar to banks and corporations. Other asset managers generally receive fixed. In contrast, quant/relative value and fixed income funds frequently flip trading direction. The holding patterns of funds suggest that some funds behave like end-users (e.g., macro), while others behave like arbitrageurs (e.g., quant/relative value).

Third, holdings are highly segmented across maturities. Specifically, we group swaps into four groups: below 3 months, 3 months to 5 years, 5 to 10 years, and 10 years & above. PF&I largely hold long maturity swaps (10 years & above), and consistently do so throughout the sample period. A bulk of bank and corporate positions are in the short to intermediate bucket (3 months to 5 years). Finally, funds hold very short maturity swaps (below 3 months) and short to intermediate maturity swaps (3 months to 5 years). The segmentation along maturities is consistent with investors having preferred habitats (Vayanos and Vila, 2021).

Fourth, we evaluate how holdings evolve with changes in interest rates. We examine sensitivity of net exposures to lagged changes in the interest rate factor, which we construct as the first principal component of yields at the 3 month, 5 year, 10 year, and 30 year maturity points. We find that PF&I and banks trade in the opposite direction in response to shifts in rates, consistent with what we observe about the levels of net exposures. As rates fall, PF&I increase their net receive positions, but banks and corporations increase their net pay positions. In other words, PF&I buy (sell) duration, whereas banks and corporations sell (buy) duration in response to decline (rise) in rates. The opposite adjustment in demand from PF&I and banks also suggests that they are natural counterparties in this market.

Fifth, we turn to study the dynamics of dealer balances, which is the opposite side of the aggregate end-user net demand. We find that a large portion of PF&I positions is offset by the positions of banks and corporations, resulting in significant cross-sector netting. This reduces the aggregate net demand that needs to be met by the dealer sector. However, dealer imbalances still exist because even though PF&I trade in the opposite direction relative to banks and corporations, their demands are highly segmented across maturities, as discussed above. During our sample period, dealers receive on average fixed (are long duration) in short maturities and pay fixed (are short duration) in long maturities. On net, dealers have a negative duration.

Motivated by the empirical facts, we adapt a preferred-habitat investors model to study the asset pricing consequences of demand imbalances at different maturities and the spillover effects across sectors. We model end-users such as banks, corporations, and PF&I as preferred-habitat investors, who have downward-sloping demand for interest rate swaps of a specific maturity (Vayanos and Vila, 2021). Such demand arises because investors are exposed to interest rate shocks from other parts of their balance sheets and trading interest rate swap is a capital-efficient way to hedge that risk (Klingler and Sundaresan, 2019). Since, in general, investors can also use bonds for hedging, the relevant price for their demand for swaps is the swap spread, which captures the price of a swap relative to the maturity-matched bond. Defining price this way also nets out the direct impact of bond yields on swap rates.

We allow investors trading in different maturity segments to have different demand elasticities. In addition, there is a time-varying aggregate demand factor that shifts the demand curve in each maturity segment. Hence, all the sectors are subject to correlated demand shocks. Furthermore, we allow the exposure to the aggregate demand factor to be potentially heterogeneous across investors and of opposite signs, capturing the fact that macroeconomic conditions affect the hedging demand of investors differentially. Our empirical result on rate sensitivity suggests that at least part of this demand factor corresponds to the level of interest rates.

While preferred-habitat investors only trade in specific maturity segments, dealers, together with certain funds, act as arbitrageurs and trade across maturity groups to take advantage of the differences in prices. These arbitrageurs are risk-averse and face time-varying funding costs from holding swaps on their balance sheets (He, Nagel, and Song, 2022). Such funding costs could come from standard market risk requirements applicable to dealers holding financial instruments, or dealers' leverage constraints if they choose to hedge the interest rate risk by holding government bonds (Bicu-Lieb, Chen, and Elliott, 2020, Du, Hébert, and Li, 2023). We model the total cost incurred as linear in the net swap position held on arbitrageurs' balance sheet. Arbitrageurs' funding cost may vary over time as the rest of the dealers' balance sheets changes. Both the funding cost and the aggregate demand factor follow AR(1) processes, where the innovations are potentially correlated.

Next, we calibrate the model to match the average level of swap spreads and net imbalances, as well as their dynamics in each maturity segment. We first discretize the maturity space into four groups: below 3 months, 3 months to 5 years, 5 to 10 years, and 10 years & above, supported by our empirical fact that holdings are highly segmented across these maturity buckets. This also allows us to estimate the demand elasticity and exposure to the aggregate demand factor for each group in a non-parametric way. More specifically, we match the average swap spreads and end-users' net outstanding positions for all the maturity groups. These moments are informative about the average level of demand, demand elasticities, and the average funding cost. We also target the variances and co-variances between spreads and equilibrium quantities for each of the four maturity groups, which are informative about the dynamics of the state variables (the funding cost and the aggregate demand factor), as well as each sector's exposure to the demand factor. Our model can match all the moments reasonably well.

We find that the demand pressure (defined as the intercept of the demand function) is concentrated among investors trading in the short-to-intermediate maturity group (3 months to 5 years) and the long maturity group (10 years & above). The demand pressure in these two groups has the opposite sign — while investors in the short-to-intermediate group have a preference to pay fixed, investors in the long maturity group have a preference to receive fixed. In addition, investors in these two groups have the opposite exposure to the aggregate demand shock. Even though we do not impose any sign restrictions on demand parameters for investors in different maturity groups, the estimated demand pressure and exposure to shocks are consistent with the types of institutions trading in each group and match the reduced form facts. The demand parameters we uncover further confirm that investors in the short-to-intermediate group and long maturity group are natural counterparties to each other.

Furthermore, while preferred-habitat investors have inelastic demand in general, the relative comparison of elasticities across segments matches with the types of institutions trading in each maturity bucket. We find that investors in the shortest maturity group (below 3 months) have the most elastic demand, consistent with the fact that the dominant investors in this group are funds. Investors in the short-to-intermediate group are less elastic compared to those in the shortest maturity group, as a majority of investors are banks and corporations, who are less price sensitive compared to funds. Finally, investors in the longest maturity group, who are mostly PF&I, have the most inelastic demand.

We then use our model to quantify the contribution of different factors to the equilibrium swap spread curve. During our sample period, the average swap spreads are large and the swap spread curve features a hump-shaped pattern: the average swap spread first increases with maturity, reaching 20 basis points (bps) around the 5 year maturity point; it then decreases to negative 40 bps for swaps above 10 years. The literature has suggested both demand factors, such as pension fund hedging needs (Klingler and Sundaresan, 2019), and supply factors, such as dealer sector's balance sheet costs and risk aversion (Jermann, 2020, Du, Hébert, and Li, 2023), affect equilibrium spreads. Using the calibrated model, we study the relative importance of supply and demand factors for equilibrium prices, taking into account dealers' net position along the entire swap curve.

We find that investors' demand pressure, amplified by arbitrageurs' high risk aversion, plays a relatively more important role compared to dealers' linear funding cost. To quantify this, we first set the average funding cost to 0. This only leads to a 7 bps change in swap spreads across all maturity groups. We then set the average demand pressure for all sectors to zero, which brings the swap spread to almost 0 for all maturities. The magnitude of change from shutting down the demand pressure is larger than that from removing funding costs, highlighting the importance of local demand imbalances. However, the effect from demand imbalances would have been much smaller if the arbitrageurs were less risk averse. Hence, we emphasize that it is the interaction between end-users' large demand imbalance and arbitrageurs' risk aversion that generates large effects on swap spreads.

Next, we leverage the model to study how demand shifts in one sector affect other sectors through adjustments in swap spreads. Such demand shifts could come from regulatory changes that force one sector to hedge more interest rate risks. For example, the recent banking crisis led to discussions on whether banks' stress tests should employ more scenarios on interest rate changes.[3] Such measures could induce banks to increase their hedging demand in the swap market, particularly in the short-to-intermediate maturity group. Similarly, regulatory changes prompting pension funds to hedge more will also shift their demand in the longest maturity group. Considering demand shifts can also be motivated by cross-country comparisons: Hoffmann, Langfield, Pierobon, and Vuillemey (2019) document that banks in areas with different loan-rate fixation conventions in the mortgage market are exposed differentially to interest rate changes. This implies that banks residing in countries with fixed-rate mortgage convention tend to have higher hedging needs in the interest rate swap market than others, which could spillover to the PF&I sector through prices. We use our model to quantify how demand shifts in one sector affect the cost of hedging for investors in other maturity segments.

We interpret any change in banks' demand as shifting the demand of preferred-habitat investors in the short-to-intermediate group and any change in PF&I demand as shifting demand in the longest maturity group. In the event of sector-specific demand shocks, we find that a one-unit increase (about 12%) in demand pressure from banks raises swap spread in the long-end by about 60 bps. Because demand elasticities are small, quantities (other than the shocked sector) barely change while prices adjust significantly. This implies that when banks increase their hedging demand, it becomes cheaper for PF&I to hedge their positions, because the two sectors have opposite demand. A back-of-the-envelope calculation suggests that the economic effect is significant: it will save PF&I in the long maturity group almost $2 billion in hedging costs each year.

Similarly, if PF&Is are required to hedge more, it will also reduce the hedging cost for banks.

[3]For example, see IMF Blog (2023).

Specifically, for the same magnitude of demand pressure increase in the long-end, it reduces the average swap spread in the short-to-intermediate group by 75 bps, which roughly translates into a \$5.9 billion reduction in hedging costs for investors in that segment. The same magnitude of change in the long-end has a much larger impact on all swap spreads compared to the change in the short-end, because imbalances in the long-end are associated with higher risks for the dealer sector. Finally, the impact of demand shifts on swap spreads would be much smaller if investors have more elastic demand, as part of the shock will be absorbed by quantity changes instead of price changes.

Related literature. First, our paper contributes to the growing body of work that analyzes end-user participation in interest rate derivative markets. In particular, several papers have looked at risk management of individual sectors: Begenau, Piazzesi, and Schneider (2015), Hoffmann, Langfield, Pierobon, and Vuillemey (2019), McPhail, Schnabl, and Tuckman (2023) and Jiang, Matvos, Piskorski, and Seru (2023) study banks, Sen (2019) study insurers, Jansen (2021) and Jansen, Klingler, Ranaldo, and Duijm (2023) study pension funds, Kaniel and Wang (2020) study mutual funds, and Pinter and Walker (2023) study non-bank financial institutions. Our paper is the first to study the demand of all end-user sectors jointly, ascertain their relative size, and analyze their interactions across market segments. This cross-sector perspective helps us draw asset pricing implications and estimate spillover effects of localized demand shocks.[4]

Second, we contribute to the asset pricing literature by analysing the swap price determination. Negative swap spreads, i.e. the difference between fixed rates for long-dated interest rate swaps and the corresponding government bond rates, have long been a puzzle in asset pricing. Recent work shows the importance of both demand and supply factors. Klingler and Sundaresan (2019) argue that the demand to receive fixed rates from underfunded pension funds explains why swap spreads turned negative after the financial crisis. Jermann (2020) emphasizes that supply frictions alone can generate negative swap spreads in equilibrium. Hanson, Malkhozov, and Venter (2022) combine supply frictions and demand factors to estimate the relative importance of the two for explaining long-term swap spreads. We add to this literature in two important ways. First, on the demand side, we find that there is a large heterogeneity across maturity segments, which is masked in the aggregate net demand. In our model, we account for the end-user demand in each maturity segment separately and allow for heterogeneous demand elasticities and exposure to the aggregate shock. Such a detailed account of the quantity-side has been lacking in the literature so far due to unavailability of cross-sector holdings data. Second, on the supply side, dealers optimize their swap

[4] Baker, Haynes, Roberts, Sharma, and Tuckman (2021) document stylized facts on interest rate swaps usage using a one-day snapshot of cross-sector regulatory data in the US.

positions across all maturity segments jointly, subject to balance sheet constraints. Accounting for the segmentation of end-user demand and dealers' arbitrage activities across maturity segments is crucial for matching the shape of the average swap spread curve and for considering spillover effects among different sectors.

Finally, we build on the emerging literature on preferred habitat investors and how their demands impact asset prices (Vayanos and Vila, 2021). This framework has been used extensively to study the impact of monetary policy and investor demand on the yield curve of bonds (e.g., Greenwood, Samuel, and Vayanos 2016, Greenwood and Vissing-Jorgensen 2018). Recent work has combined arbitrageurs' wealth effect and balance sheet constraints in the preferred-habitat model (He, Nagel, and Song, 2022, Kekre, Lenel, and Mainardi, 2023). The framework has been applied to other asset classes, for example, the currency markets (Gourinchas, Ray, and Vayanos, 2023, Greenwood, Hanson, Stein, and Sunderam, 2023). Bahaj, Czech, Ding, and Reis (2023) analyze the UK inflation swap market and dealers' supply in the short-maturity and long-maturity segment. Focusing on the interest rate swap market, we leverage detailed quantity and price data in each maturity segment to estimate the demand elasticities and aggregate exposures in a non-parametric way, uncovering substantial heterogeneity across sectors.

1. Data

We use detailed position and transaction-level data in over-the-counter (OTC) interest rate swaps that cover all sectors of the economy, and where at least one of the counterparties to a trade is legally based in the United Kingdom (UK).[5] Our sample includes both UK headquartered entities, and UK branches and subsidiaries of any counterparty which may be headquartered in another jurisdiction. Our access to these data is enabled via the Bank of England by a key post-financial crisis reform, known as European Markets Infrastructure Regulation (EMIR), which seeks to improve derivative markets transparency by mandating the reporting of derivatives to trade repositories (TR). Reporting obligation under EMIR started in February 2014, where all OTC and exchange-traded derivatives contracted by EU and UK counterparties from August 2012 (or open at that point) had to be reported.[6] We source our data from two of the largest trade repositories, DTCC and UnaVista, that together constitute a 90% market share in interest rate derivatives (Abad et al.,

[5] OTC interest rate swap is the main instrument used for hedging interest rate risks. The Bank for International Settlements reports that OTC markets constitute over 85% of outstanding interest rate derivatives, and over 80% of those contracts are swaps (BIS, 2023).

[6] See here for more details on the UK EMIR reporting obligation. Note that trades starting January 2021 are reported under UK EMIR, while trades prior to 2021 are reported under EU EMIR. For the period under EU EMIR, we additionally observe trades between EU-domiciled banks and non-UK counterparties. However, as part of the post-EU-exit arrangements of the UK, trades between those entities are not covered starting 2021. For consistency, therefore, we exclude such trades from the earlier part of our sample.

2016). Our sample spans from July 2019 through December 2022. We restrict attention to this period because the reporting quality meaningfully improves starting mid-2019.

1.1. Coverage

Our data consist of single currency fixed-to-floating interest rate swaps (IRS) and overnight indexed swaps (OIS) referencing all floating rate benchmarks, currencies, tenors, and contracted by all types of counterparties. We estimate that our data cover at least 60% of the global swaps turnover denominated in any currency and 84% of the swaps denominated in GBP.[7] We arrive at these estimates based on the April 2022 triennial OTC derivatives turnover data from the Bank for International Settlements (BIS, 2022). Table A1 reports an average daily turnover of $3.4 trillion in April 2022 in our data, which compares with about $5 trillion of turnover reported by the BIS for all interest rate derivatives excluding options and complex swaps.[8] Within GBP swaps, we observe a daily average turnover of $287 billion, which is about 84% of the BIS estimate of $341 billion.

Our analysis focuses on GBP swaps due to our largest coverage in this currency and our ability to observe the entire interest rate swap portfolio of UK entities. Our vast coverage of this market is enabled by the fact that London serves as the center of global derivatives trading; BIS (2022) reports that 46% of all interest rate derivatives (amounting to $2.1 trillion) were traded in the UK in April 2022. Our data cover nearly all of these trades, plus swaps executed outside the UK involving a UK entity. To the best of our knowledge, this is the most comprehensive cross-sector interest rate swaps data deployed in academic research to date.

1.2. Outstanding Positions and Transactions

We source two types of complementary reports available from trade repositories: outstanding positions ("state files") and new transactions ("activity files") at an investor level. The stock of outstanding positions includes all trades contracted at any time in the past and open as on a given date, which helps us track the evolution of outstanding swap positions for each entity. The daily flow of new transactions includes trades contracted on a particular date and permits a more granular analysis of investors' trading activity along dimensions of maturities, prices, and volumes, in conjunction with current market conditions. These two reports jointly provide us with a complete picture of investor behavior in this market.

We extract 42 snapshots of outstanding position reports as of the beginning of each month from July 2019 through December 2022 for every investor in our sample. The trade-level variables we use

[7] Our overall coverage closely matches with Abad et al. (2016), who report that EU EMIR covered 70% of outstanding notional in global interest rate derivatives in 2015.

[8] This is after adjusting for double counting of reported trades (see Section 1.2).

from these reports include the outstanding notional, maturity date, identities of the counterparties, direction (receive or pay fixed), whether a trade is centrally cleared, and the underlying floating benchmark and currency. We use these variables to construct investor-level outstanding net position (expressed as net receive fixed rate notional), and the remaining maturity as of the date of report. Over the same period, we collect daily records of new transactions initiated in single currency fixed-to-floating swaps. The variables that characterize new transactions are similar to those in outstanding position files, with the addition of price (expressed as the fixed rate of the trade), which we use to calculate swap spreads. We also use the trading activity in certain maturities reported in the transactions data to validate the preferred-habitat assumption of investors because outstanding maturities in state files undergo natural decay with the passage of time.

Main data processing steps. Trade repositories' data suffer from some well-known reporting issues.[9] We therefore dedicate a significant amount of time to address these issues, which entails three major steps. First, we exclude likely erroneously reported trades. Specifically, closely following Abad et al. (2016), we drop trades below notional values of $1,000 and above $10 billion, filter out trades whose maturity date lies before the effective date or whose reporting date precedes the execution date,[10] and drop intra-group trades which, while not erroneous, may indicate risk transfers within a group and not necessarily trading in response to changes in market conditions.

Second, we remove duplicate trades. The most common cause of duplicates is the "dual reporting" requirement under EMIR, where each of the two counterparties needs to report a trade to a TR if they both fall under reporting obligation. Following Cenedese et al. (2020), we retain one copy of these trades using the unique trade identifier field. The second reason for duplicates is that, for centrally cleared trades, we observe the original trade contracted between the dealer and its client, and a "novation" trade that is a leg facing the centralized clearing house and a clearing member (usually the same or another dealer), both with different trade identifiers. Since we focus on end-user trades, this duplication does not affect our assessment of *client* level positions but it does lead to double counting of centrally cleared trades in the estimation of total turnover. Therefore, when estimating our data coverage, we halve the notional of centrally cleared trades. A third reason for duplicates is trade compression. Compression entails netting trades with similar economic characteristics at a counterparty level and re-booking a single entry of the net exposure to reduce the size of trading books. The raw positions data include both the original trades and the net trade arising out of compression exercise, which can lead to a miscalculation of outstanding positions. Therefore, we drop all trades tagged as compression.

[9] A recent report on EU EMIR data quality can be found here.

[10] Execution date refers to the trade date, reporting date refers to when the counterparty reports to TR (usually within 2 business days of execution date), and effective date refers to when the swap gets active.

In the final step, we construct our main variables. As floating rate benchmarks are typically not directly available under a single field, we construct them by concatenating information from multiple fields referencing the floating rate index (e.g., SONIA, LIBOR, SOFR), the currency, and the reset frequency. We also calculate swap spreads, defined as the difference between the swap fixed rate and the maturity-matched bond yield, by sourcing daily bond yields at six-monthly maturity intervals from the Bureau van Dijk Bank of England database. Finally, we convert notional values into USD equivalent for all non-USD swaps using the publicly available IMF daily FX database.

1.3. Sector Classification

We classify each entity in our dataset into either a Dealer, a Central Counterparty Clearing House (CCP), or one of the five end-user sectors: (a) Banks; (b) Funds (including hedge funds and asset managers); (c) Pension, Liability-driven investment (LDI) funds, and Insurers (together referred to as PF&I); (d) Corporate entities; and (e) Official institutions. Even though trade repositories have a reporting field for the counterparty sector, it is sparsely (and often erroneously) filled and not fully reliable. We leverage the non-anonymized unique identifier of each counterparty called the Legal Entity Identifier (LEI) to populate its sector using external databases.[11] In all, we allocate nearly 6,000 LEIs that trade across all currencies to one of these seven sectors.

We start by filling in the missing names and jurisdictions of the LEIs using the Global Legal Entity Identifier Foundation (GLEIF) public database. Then, we use CapitalIQ and Thomson Reuters to populate the sectors associated with the individual LEIs. This method works well for larger entities, however, a substantial number of LEIs also need to be manually classified using their names and details of incorporation. Manual classification is particularly helpful for funds, where a main fund family often has several separate legal entities that trade derivatives but are too small to be reported in standardized data sources.

An important part of our sector classification is to make an economically meaningful distinction between end-user "banks" and market-making "dealers". This distinction helps us capture hedging of interest rate risk arising out of banking activities separately from intermediation services. From the list of all the entities classified as banks, we carve out dealers, defined as entities that meet any of the following four criteria: members of a clearing house such as the LCH Ltd. (formerly London Clearing House) or the Chicago Mercantile Exchange (CME), globally systemically important banks (GSIBs), participating dealers defined by the Federal Reserve Bank of New York, or broker-dealers and non-bank liquidity providers that facilitate order-matching.[12] Membership of clearing houses

[11] LEI is a unique identifier for each legally distinct entity that engages in a financial transaction. Multiple LEIs may roll up into the same firm or fund family. The Office of Financial Research provides institutional details on how LEIs are constructed and used.

[12] We retrieve the list of clearing members directly from LCH Ltd. website. The corresponding list for

provides the sharpest identification of dealers because end-users are not allowed to directly clear trades with CCPs but large financial institutions and broker-dealers that meet certain minimum capital thresholds are.[13] Moreover, the list of CCP members is available both by product (e.g., interest rate derivatives) and LEI, which enables a direct matching with our database. We also verify that the entities we classify as end-user banks do not trade with other end-user sectors and do not directly face clearing houses, which lends credibility to our classification process.

The largest end-user sector by number of entities is funds. For example, a total of 1,045 funds trade GBP swaps during our sample period. The next largest set of end-users is Pension, LDI funds, and Insurers (PF&I). In the UK, some pension funds use LDI funds to manage their funding risk, predominately via increased exposure to gilts. Hence, we consider LDIs as part of the PF&I segment. A total of 747 PF&I entities traded GBP swaps during our sample period. Further, after carving out dealer entities, a total of 160 end-user banks trade GBP swaps in our sample. Finally, our data contains non-financial corporations and official sector entities (such as sovereign funds or supra-national institutions), which form the smallest end-user segment, with 272 corporations and 18 official sector entities trading GBP swaps.

2. Risk Exposures Across the Financial System

This section documents the main facts on outstanding positions and transactions in interest rate swaps for all end-user sectors. While we focus on GBP swaps, the main empirical patterns we document also exist more broadly in other currencies.

We start by constructing measures of interest rate risk exposure for outstanding positions and transactions. We compute the net signed dollar exposures (Q_t), defined as the total notional in receive fixed swaps minus the total notional in pay fixed swaps at an end-user investor level,

$$Q_t = \sum_p \text{Signed Notional}_{pt}, \tag{1}$$

where Signed Notional_{pt} is the gross notional of position (or trade) p at time t, signed *positive* for receive fixed and *negative* for pay fixed swaps. Thus, positive values of Q_t denote net receive fixed positions. For sector-level analyses, we aggregate this measure across all the investors within an end-user sector.

CME is available here. We source the list of GSIBs from the Financial Stability Board website, and the list of participating dealers from the Federal Reserve Bank of New York website.

[13]For example, the membership criteria of LCH Ltd. is defined here and includes "major financial groups (including the majority of the major investment banks), broker-dealers and specialist commodity houses." As of August 2023, there were 124 unique LEIs that qualified as LCH Ltd. clearing members for interest rate derivatives.

To account for the heterogeneity in exposures across maturities, we split positions into four maturity groups: below 3 months, 3 months to 5 years, 5 years to 10 years, and 10 years & above. For each segment, we compute the net dollar exposures as described in Equation 1 and label these variables $Q^{<3M}$, Q^{3M-5Y}, Q^{5Y-10Y}, and $Q^{\geq 10Y}$. We complement this measure with swaps' dollar duration, i.e. the dollar value of one basis point parallel shift in interest rates, which we label as DV01.[14]

2.1. Main End-user Segments and Size of Net Exposures

The interest rate swap market is dominated by funds, banks and PF&I, both in terms of outstanding positions and transaction volume. Columns (1) and (2) of Table 1 show the outstanding gross positions and net exposures (Q_t) held by each end-user sector in our sample as of February 1, 2022. In aggregate, funds held the largest stock of outstanding gross positions at $1.6 trillion, followed by PF&I at $1.3 trillion, banks at $472 billion, official sector at $98 billion, and corporations at $89 billion. Net exposures also follow similar patterns. Columns (3) and (4) report the average monthly gross and net transaction volumes for these sectors during our sample period. Similar to outstanding positions, funds have the largest trading volume, followed by PF&I and banks. However, the net notional relative to gross volumes is the smallest for funds, suggesting frequent two-way trading at a sector level.

Table 2 shows an LEI-level distribution of net exposures across sectors as of February 1, 2022. In our sample, 730 funds, 1,152 PF&I, 210 banks, 516 corporations, and 32 official institutions have outstanding GBP swap positions on this date. The average fund and bank is large, each holding $1.8 billion of net exposures, while the average PF&I and corporate entity holds $0.6 billion and $0.2 billion of net exposures, respectively.[15] We only observe a few very large official institutions. Because of their lower coverage and small size as a sector, we omit discussing them henceforth.

2.2. Trading Direction Across Sectors

We next examine the direction of net exposures of outstanding positions first at an aggregate level across sectors and then at an entity level within a sector.

First, there is significant heterogeneity in the direction of net exposures across sectors. Figure 1 shows the net outstanding positions aggregated for all entities for a given sector at a monthly level.

[14] Note that $DV01_t = \sum_p Notional_{pt} \times Duration_p$, where $Duration_p$ refers to the signed Macaulay duration of the fixed rate leg of the swap. We use currency and maturity-matched average bond yields over our sample period to calculate the swap duration for all tenors.

[15] Figure A1 plots the cumulative share of net outstanding positions within sector, displaying a large degree of concentration. For instance, in the funds sector the top 10 funds hold over 80% of all net outstanding GBP exposures in February 2022.

As a sector throughout the sample, PF&I receive fixed (they have *positive* net exposures), i.e. they add duration to their portfolios with swaps. In contrast, banks and corporations pay fixed (they have *negative* net exposures), i.e. they sell duration with swaps.[16] This suggests that PF&I are natural counterparties to banks and corporations in the swaps market.[17] In contrast to banks, corporations, and PF&I, funds flip trading directions: they typically receive fixed in the beginning of the sample and pay fixed in the later part of the sample, especially during the start of the 2022 rate hike cycle.

Second, we examine intra-sector heterogeneity in the direction of net exposures at the entity (LEI) level. We assign a value of +1 to LEIs that held a net receive fixed position and a value of -1 to LEIs that held a net paid fixed position as on a given date. Then, we calculate a sector-level "agreement score" as the simple average of these values. A high absolute score would imply significant homogeneity, while a score closer to zero would imply significant heterogeneity within a sector. Figure 2 plots the monthly time-series of the agreement score on the left-hand side axis and the proportion of entities in each sector that held net receive fixed positions on the right-hand side axis. Corporations, PF&I, and banks are mostly homogeneous, with the majority of entities trading in one direction. In particular, 83% of entities within corporations pay fixed, 80% of PF&I receive fixed, and 70% of banks pay fixed. Funds are more heterogeneous with an agreement score close to zero: roughly half the entities receive fixed (while the other half pay fixed) at any point in time.

Third, to better understand the trading strategy of funds, we split the fund sector into more granular categories. To do so, we scan the fund names to capture well known trading strategies, and classify them into the following types: (i) fixed income/bond, (ii) macro, (iii) quant/relative value, and (iv) other asset managers. Figure 3 plots the time-series of their net outstanding positions, and Table A2 shows their gross notionals and net exposures as of February 1, 2022.

We find that, to a large degree, heterogeneity in funds' direction of exposure is explained by the different types of trading strategies they adopt. Macro funds are the largest, accounting for 45% of fund sectors' gross notional held. They primarily pay-fixed, similar to banks and corporations. Their ratio of (absolute) net to gross position is 0.6, indicating that most of their holdings are in one direction and, therefore, they account for a large fraction of the total net (absolute) exposures of the fund sector (87%). Other asset managers, fixed income/bond, and quant/relative value funds

[16] Figure A2 shows consistent results for each end-user sector when we consider swaps denominated across all currencies in our sample.

[17] One may be concerned that we only observe partial holdings of non-UK entities in our data (the trades booked with a UK counterparty) and that these entities may exhibit a different behavior when trading with non-UK counterparties. However, we find consistent results when considering the net exposures of UK entities only (for whom we observe all trades). Figure A3 shows that the exposures held by UK PF&I and UK banks are also in opposite direction and are of comparable magnitude.

account for 25%, 18%, and 12% of gross notionals respectively. However, they frequently flip trading directions. For example, the ratio of (absolute) net to gross position for quant/relative value funds is only 0.03, implying that they hold large positions that net out, consistent with their perceived role of exploiting relative value, e.g., across the term structure. Overall, some funds behave like end-users (e.g., macro), while others behave like arbitrageurs (e.g., quant/relative value).

2.3. Segmentation Across Maturity

We next show that holdings of the various end-users are highly segmented across maturities. Figure 4 panels (a) through (d) show the breakdown of net exposures in the four maturity groups - below 3 months, 3 months to 5 years, 5 years to 10 years, and 10 years & above, respectively. First, PF&I swap holdings are consistently concentrated in the long-maturity group (10 years & above) throughout the sample. In contrast, a bulk of bank and corporate positions are in the short to intermediate maturity groups (3 months to 5 years and 5 years to 10 years), and remain so throughout the sample. Finally, funds hold very short maturity swaps (below 3 months) and short to intermediate maturity swaps (3 months to 5 years). While their trading in the below 3 months segment is quite volatile, they largely pay the fixed rate in the 3 months to 5 years segment, just like banks, particularly during the recent years of the sample. Figure A4 confirms that all fund types predominantly hold short and intermediate maturity swaps.

The extent of segmentation looks even starker when we look at the maturity distribution of new transactions. Panel A of Table 3 shows the fraction of LEIs within a given end-user sector that trades at least 50% of their total volume of swaps in a single maturity bucket. About 90% of LEIs for any given end-user sector have a majority of their trading in a single maturity bucket, which we define to be an LEI's *dominant* maturity bucket. Panel B of Table 3 shows the distribution of the fraction of trades in the dominant maturity bucket for LEIs in each end-user sector. The average bank and fund has over 80% of its trades in its dominant bucket. The average PF&I has 73%, and the average corporate entity has 90% of trading in its respective dominant bucket. Overall, the holdings and trading behavior of end-users show strong segmentation along the dimension of maturity, consistent with investors having preferred habitats.

2.4. Sensitivity to Interest Rates

Next, we examine the impact of changes in macroeconomic conditions on investors' swap exposures. Specifically, we consider movements in the level of interest rates, which could either affect hedging needs (via shifts in the duration mismatch of the underlying balance sheet) or alter expectations of future swap returns. We estimate a model of the form

$$\Delta Q_{i,t} = \alpha_i + \beta \Delta Rate_{t-1} + \epsilon_{i,t}, \tag{2}$$

where $\Delta Q_{i,t}$ is the monthly change in the net outstanding position (as defined in Equation 1) for investor i at time t in its dominant maturity bucket. We define the dominant maturity buckets as: below 3 months for funds, 3 months to 5 years for banks and corporations, and 10 years & above for PF&I.[18] The independent variable $\Delta Rate_{t-1}$ denotes the change in the monthly average of the first principal component (PC) extracted from daily UK government bond (gilt) yields for maturities 3 months, 5 years, 10 years, and 30 years. We use lagged changes to mitigate the simultaneity problem to some extent. We also use the yields for 3 months, 5 years, 10 years, and 30 years as separate regressors for robustness. Finally, we include investor fixed effects.

Table 4 reports the estimation results. Swap positions across sectors are sensitive to changes in interest rates, but there is striking cross-sector heterogeneity in the direction and the magnitude of the sensitivities. All five panels of Table 4 show that β (i.e. the loading on the change of rates) is negative for PF&I and positive for banks and corporations. In other words, as rates fall, PF&I buy duration and increase their net receive fixed exposures, whereas banks and corporations sell duration and increase their net pay fixed exposures. More specifically, for a one percentage point decline in the first principal component of yields, the average entity in the PF&I sector increases its net receive fixed exposure by 2.6%, and the average bank and corporation increases their net pay fixed exposure by 3% and 1.9% respectively.[19] The opposite adjustment in demand from PF&I and banks further suggests that they are natural counterparties in the swap market. Finally, funds also exhibit some sensitivity, to changes in the 10-year and 5-year yields in particular, in a pro-cyclical manner similar to the PF&I sector.

Discussion on end-user demand. The net positions of PF&I, banks, and corporations appear consistent with the hedging needs arising out of their respective underlying balance sheet maturity mismatch. Moreover, their trading behavior (i.e. the sensitivity of changes in positions to shifts in interest rates) is also consistent with the sectors' underlying interest rate mismatch.

PF&I face liabilities that are both long-dated and embed fixed rate guarantees. However, the asset side of PF&Is' balance sheet contains government and corporate bonds, which typically have shorter maturities than liabilities (EIOPA, 2014, Domanski, Shin, and Sushko, 2017). As

[18]The dominant maturity group assigned to a sector is the one with the majority of its trading volume (see Table A3).

[19]To obtain the sensitivities of the yield changes in terms of percentage change in holdings, we divide the coefficients in Panel A of Table 4 by the average investor-level net position in Table 2 for the corresponding sector.

a result, the duration of their assets is shorter than that of their liabilities, i.e. the sector has a negative duration gap and is therefore exposed to decline in interest rates. A pension fund or an insurer wanting to close the mismatch between assets and liabilities with swaps would need to receive the fixed rate. Moreover, as interest rates increase, the discounted liabilities of the PF&I sector fall and the duration of its liability decreases, reducing the need to receive fixed rates as a hedge. Therefore, as rates decline (increase), PF&Is should want to increase (decrease) duration, i.e. increase (decrease) their swap position to receive fixed.

In contrast to PF&I, we observe that banks in our sample (most of which are located in the UK) pay fixed rate and decrease duration as rates decline. Moreover, the total exposure from their swap position constitutes an economically meaningful portion of their underlying exposures.[20] Ordinarily, we expect banks to have a positive duration gap because their assets, which include fixed rate mortgages, have longer duration than their liabilities, which are mainly short-term deposits. If so, a bank wanting to close the mismatch between assets and liabilities with swaps would need to pay the fixed rate, i.e., have a negative position in swaps. While our finding is consistent with the basic business model of banks, it is in contrast to US banks, who do not seem to meaningfully hedge their interest rate risks with swaps (McPhail et al., 2023). There are several institutional differences between the US and the UK banking sector that may help reconcile the findings. First, UK (and European) banks face higher regulatory pressure to hedge their interest rate risk (Wilkes, 2023a,b), compared to their US counterparts. Second, UK banks have higher deposit betas (Walker, 2023), which implies larger duration mismatch on the banks' balance sheets.[21] Finally, US banks face high prepayment risk from mortgages and to hedge that risk, they need to receive the fixed rate (Hanson, 2014). This is less applicable to UK banks as mortgage prepayment is often associated with a penalty (Benetton, 2021).

Similar to banks, corporations in our sample primarily hedge the interest rate risk arising out of floating rate debt issuance. Therefore, they demand to pay fixed rate swaps to hedge the risk from the fluctuations in short-term floating rates, consistent with the predictions in Titman (1992).

2.5. Aggregate Net Demand and Dealer (Im-)balances

We turn to understanding the dynamics of aggregate net end-user demand and dealer balances. Since swaps are in zero net supply, dealers take the other side of end-user demand, and their net

[20]For the UK banks in our sample, we find that a 100 bps upward shift in the yield curve would lead to a 4.9% decrease in their equity due to a decrease in the market value of their swap positions, as of April 1, 2022.

[21]Sticky deposits provide banks a natural hedge against their longer-dated assets (Drechsler, Savov, and Schnabl, 2021). Thus, the extent of duration mismatch crucially depends on banks' deposit betas.

position is the opposite of the aggregate net end-user demand. Dealer balance is defined as

$$\textit{Dealer Balance}_t = -\sum_s Q_t^s, \tag{3}$$

where s denotes all the five end-user sectors, including banks, funds, PF&I, corporations, and official institutions.

Figure 1 and Figure A2, which we discussed above, also overlay the dealer sector balances (in brown). We observe that a large portion of PF&Is' net receive fixed positions is offset by banks' and corporations' net pay fixed positions. This cross-sector netting reduces the total aggregate net demand that is supplied by the dealer sector.

However, two factors impede cross-sector netting and add to dealer imbalances across maturities. First, even though PF&I trade in the opposite direction relative to banks and corporations, their respective demands are highly segmented across maturities (Figure 4). The bulk of PF&I trading is concentrated in longer maturities (10 years & above) while that of banks and corporations is in short and intermediate maturities (up to 5 years). As a result, dealers consistently receive the fixed rate in the 3 months to 5 years tenor and pay the fixed rate in longer tenors. This exposes dealers to swap spread fluctuations in each maturity bucket. Another way to see this is through dealers' net DV01 (dollar value of one basis point parallel shift in the yield curve) position, depicted in Figure A5. Dealers consistently bear the risk of a downward parallel shift in the yield curve because long-tenor PF&I trades receive a higher weight in this risk measure. These results are consistent with the literature on negative swap spreads (Boyarchenko, Gupta, Steele, and Yen, 2018, Klingler and Sundaresan, 2019, Hanson, Malkhozov, and Venter, 2022), and evidence of dealer imbalances in other markets (e.g., S&P 500 index options (Gârleanu, Pedersen, and Poteshman, 2008), inflation swaps (Bahaj, Czech, Ding, and Reis, 2023)).

Second, funds tend to amplify the magnitude and volatility of net demand absorbed by dealers. For example, macro funds, which act like end-users, trade large volumes in the 3 month to 5 year bucket in the same direction as banks, especially at the start of the interest rate hiking cycle in 2022. Their demand substantially increased the net receive fixed position absorbed by dealers in that maturity segment. Furthermore, in the shortest-tenor (below 3 months) segment, funds are the dominant investor type and they frequently change the direction of their net exposure, inducing volatility in the net demand that dealers need to absorb. These two factors worsen dealer imbalances further in different parts of the term structure, exposing them to non-parallel movements in rates in addition to the residual dollar duration.

Overall, we note that dealers (and some funds) participate in all maturities of the swap curve, often with different directional exposure in different maturity buckets. For a large part of our sample period, dealers receive fixed (are long duration) in short maturities and pay fixed (are short duration) in long maturities. In the sections that follow, we model dealers and these funds as "arbitrageurs" who optimize their positions across maturity buckets taking into account swap spread fluctuations and funding cost shocks.

3. Model and Calibration

Since both quantities and prices are determined endogenously in equilibrium, we construct a model to match the price and quantity dynamics and to study the interactions among the different sectors in the swap market. Given that our empirical results suggest strong segmentation along the maturity dimension, we construct and estimate a model with preferred-habit investors similar to Vayanos and Vila (2021). We then apply the model to study how different demand-side and supply-side factors contribute to equilibrium swap spreads and how demand shifts in one sector affect the hedging cost for the other sectors.

3.1. Model

Time is continuous $t \in [0, \infty)$. The maturities of swaps lie in $(0, \infty)$. To fully control for the impact of interest rate movements, we focus on swap spreads instead of the fixed rate in the swap contract. We denote by $s_t(\tau)$ the swap spread of swaps with maturity τ at time t. The corresponding price $P_t(\tau) \equiv \exp(-\tau s_t(\tau))$ captures the value of a fixed stream of payments in the swap contract *relative to* the value of a government bond with the same maturity.[22] This price captures the relative cost of hedging interest rate risk in the swap market versus doing so in the cash market.

We assume in the very short-term market, the swap spread is always 0. That is,

$$\lim_{\tau \to 0} s_t(\tau) = 0 \quad \text{for} \quad t \geq 0. \tag{4}$$

Preferred-habitat investors. Preferred-habitat investors have demand for swaps with a specific maturity and only trade swaps of that maturity. We verify empirically that this is true for most clients such as PF&Is, corporations and banks. In addition, some funds that specialize in a specific maturity bucket are also preferred-habitat investors in our model, as discussed in Section 2.2. Following Vayanos and Vila (2021), investors with habitat τ have demand for swaps in maturity

[22] To see this, denote the fixed rate in the swap contract by $y_F(\tau)$; the present value of this fixed stream of payments is $P_F = \exp(-\tau y_F(\tau))$. Similarly, denote the yield of a zero-coupon government bond by $y_T(\tau)$; its price is then $P_T = \exp(-\tau y_T(\tau))$. Under $P \equiv P_F/P_T$, $P = \exp(-\tau(y_F(\tau) - y_T(\tau))) = \exp(-\tau s(\tau)))$.

bucket τ

$$Q_t(\tau) = -\alpha(\tau)log(P_t(\tau)) - \theta_0(\tau) - \sum_{k=1}^{K} \theta_k(\tau)\beta_{k,t} \tag{5}$$

where $\alpha(\tau)$ is the demand elasticity; θ_0 captures the average demand and $\theta_k(\tau)$ captures the sensitivity of demand to the aggregate demand factor β_k. Investors in different maturity buckets may be exposed to similar demand shocks, such as the level of the interest rate, but the extent to which they are affected could be different, as captured by $\theta_k(\tau)$. For example, Table 4 suggests that banks and PF&Is tend to be affected by the interest rate changes in opposite directions. Finally, if $Q_t(\tau) > 0$, investors are receiving fixed; otherwise, investors are paying fixed.

We specify the demand for swaps as the relative price of swaps to bonds, as investors can choose to hedge either in the cash or swap market. Hedging with swaps can be more capital efficient, but the swap demand would be weaker if the swaps are more expensive relative to bonds of similar maturity.

Arbitrageurs. Arbitrageurs are risk-averse agents who can trade *across* maturity buckets and do not have any preference for specific maturities. Arbitrageurs include dealers as well as certain funds who get funding from dealers in order to conduct arbitrage activities across maturity buckets.

We assume that for each unit of swap held, the arbitrageur faces a cost c_t at time t, which reflects funding costs and/or balance sheet frictions. This cost could come from multiple sources. First, if the dealer hedges the interest rate risk by holding government bonds, then the government bonds take up balance sheet space and may lead to tighter leverage constraints (Bicu-Lieb et al., 2020, He et al., 2022, Du et al., 2023). If the dealer chooses not to hedge his interest rate risks, then he faces higher capital charges because of standard market risk requirements applicable to financial instruments.[23] In either case, this imposes a cost for dealers holding swaps. Second, in addition to market risks, a sizable fraction of the swaps are not centrally cleared. In this case, the dealer is required to hold additional capital against counterparty risk, which is costly as well.[24] Finally, in some cases, hedge funds are the ones performing the role of arbitrageurs in this market. Since hedge funds typically obtain funding from the dealer sector, dealers' balance sheet costs would get passed on to the hedge funds in the form of funding costs (Boyarchenko, Gupta, Steele, and Yen, 2018). Since longer maturity swaps entail larger market risk, one may argue that this funding cost should be maturity dependent. In Appendix C, we consider an extension where the funding cost

[23]For details on market risk capital requirements see e.g., The Basel Framework.

[24]The Basel committee on Banking Supervision stipulates capital requirements for costs associated with the default of a counterparty, via Counterparty Credit Risk capitalization, or with changes in the credit quality of a counterparty, via the Credit Valuation Adjustment.

depends on τ.

Arbitrageurs maximize a mean-variance objective over instantaneous changes in wealth dW_t. Denote the arbitrageur's position for swaps in maturity bucket τ as $X_t(\tau)$,

$$dW_t = \int_0^\infty X_t(\tau)\left(\frac{dP_t(\tau)}{P_t(\tau)} - c_t\right) d\tau \tag{6}$$

where $\frac{dP_t(\tau)}{P_t(\tau)}$ is the return of holding swaps of maturity τ.

The arbitrageur's problem is

$$\max_{\{X_t(\tau)\}_{\tau=0}^{\infty}} \left[\mathbb{E}_t(dW_t) - \frac{a}{2} Var\left(dW_t\right)\right] \tag{7}$$

where $a \geq 0$ is the arbitrageur's risk aversion coefficient. Arbitrageurs benefit from the differences in swap spreads in different maturity buckets. However, they face risks from the time-varying funding cost c_t and the swap spread fluctuations.

Dynamics and market clearing. The state variables can be represented by a $(K+1)\times 1$ vector $g_t \equiv (c_t, \beta_{1,t}, ..., \beta_{K,t})^\top$. We assume that g_t is stationary and follows the process

$$dg_t = -\Gamma(g_t - \bar{g})dt + \Sigma dB_t \tag{8}$$

$$\bar{g} \equiv \left(\bar{c}, 0, ..., 0\right)^\top \tag{9}$$

where Γ and Σ are constant $(K+1)\times(K+1)$ matrices; dB_t is a $(K+1)\times 1$ independent Brownian motion. Γ governs the speed of mean-reversion and Σ governs the variance and covariance of shocks. Furthermore, $\bar{c}$ is the average funding cost for the arbitrageurs. Note that the arbitrageurs can hold either positive or negative amount of swaps; we verify in our estimation that the net funding cost for the arbitrageurs are indeed positive.[25]

Finally, swaps of any given maturity are in zero-net supply. The market clearing condition is

$$X_t(\tau) + Q_t(\tau) = 0 \qquad \forall \tau > 0 \tag{10}$$

Equilibrium characterization. We first guess that the relative price for swaps with maturity τ takes the form

$$P_t(\tau) = \exp[-(A(\tau)^\top g_t + C(\tau))] \tag{11}$$

[25] It is without loss of generality to assume that the demand factor $\beta_{k,t}$'s have mean 0.

where $A(\tau)$ is a $(K+1)\times 1$ matrix, and $C(\tau)$ is simply a constant. The first element of $A(\tau)$ captures the price's sensitivity to the supply factor c_t, and the other elements of $A(\tau)$ capture the price's sensitivity to the K demand factors.

Using the arbitrageur's first order conditions and setting $K = 1$, we can characterize $A(\tau)$ and $C(\tau)$ in a set of differential equations, as presented below.

$$\Gamma^\top A(\tau) + A'(\tau) - \begin{pmatrix} 1 \\ 0 \end{pmatrix} - a\left[\int_0^\infty \left(\theta(\tilde{\tau})\begin{pmatrix} 0 \\ 1 \end{pmatrix} A(\tilde{\tau})^\top - \alpha(\tilde{\tau})A(\tilde{\tau})A(\tilde{\tau})^\top\right) d\tilde{\tau}\right]\Sigma\Sigma^\top A(\tau) = 0 \quad (12)$$

$$A(\tau)^\top\Gamma\begin{pmatrix} -\bar{c} \\ 0 \end{pmatrix} + \frac{1}{2}A(\tau)^\top\Sigma\Sigma^\top A(\tau) + C'(\tau) - aA(\tau)^\top\Sigma\Sigma'\int_0^\infty \left(-\alpha C(\tilde{\tau}) + \theta_0(\tilde{\tau})\right) A(\tilde{\tau})d\tilde{\tau} = 0 \quad (13)$$

The boundary conditions are

$$A(0) = 0 \qquad C(0) = 0 \quad (14)$$

We leave the details of derivations to Appendix B.

3.2. Calibration

To bring the model to data, we discretize the maturity space into M maturity buckets, separated by a sequence of break-points $m(0) \equiv 0 < m(1) < m(2) < ... < m(M-1) < m(M) \equiv \infty$. With a slight abuse of notation, we use τ to denote the maturity bucket, $\tau \in \{0, 1, ..., M-1\}$. A swap belongs to maturity bucket τ if its maturity is in $[m(\tau), m(\tau+1))$. We denote the average maturity of swaps in bucket τ by $\bar{m}(\tau)$.

We consider a discretized term structure for two reasons. First, it allows us to estimate investors' demand in each maturity bucket non-parametrically. We do not impose any parametric assumptions on demand side parameters $\theta_k(\tau)$, $\theta_0(\tau)$, and $\alpha(\tau)$. Hence, we are able to learn what different preferred-habitat investors' demand looks like from the data. Second, the preferred-habitat investor assumption is more likely to hold for a maturity bucket than for a specific maturity point.

Denote $s_t(\tau)$ as the average swap spread in maturity bucket τ, and $X_t(\tau)$ as the total swap holdings by the arbitrageurs in maturity bucket τ. Furthermore, the relative price of the swap can be written as $P_t(\tau) = \exp(-\bar{m}(\tau)s_t(\tau))$. Finally, we define $\delta(\tau) \equiv \frac{1}{\bar{m}(\tau)-\bar{m}(\tau-1)}$, which is the probability that a swap in maturity bucket τ transitions to maturity bucket $\tau-1$ in the next period.

The discrete versions of Equation 12 and Equation 13 become

$$\Gamma^\top A(\tau) + [A(\tau) - A(\tau-1)]\delta(\tau) - \begin{pmatrix} 1 \\ 0 \end{pmatrix} = a\left[\sum_{\tilde{\tau}} \left(\theta(\tilde{\tau})\begin{pmatrix} 0 \\ 1 \end{pmatrix} A(\tilde{\tau})^\top - \alpha(\tilde{\tau})A(\tilde{\tau})A(\tilde{\tau})^\top\right)\right]\Sigma\Sigma^\top A(\tau) \tag{15}$$

$$A(\tau)^\top\Gamma\begin{pmatrix} -\bar{c} \\ 0 \end{pmatrix} + \frac{1}{2}A(\tau)^\top\Sigma\Sigma^\top A(\tau) + [C(\tau) - C(\tau-1)]\delta(\tau) = aA(\tau)^\top\Sigma\Sigma'\sum_{\tilde{\tau}}\left(-\alpha C(\tilde{\tau}) + \theta_0(\tilde{\tau})\right)A(\tilde{\tau}) \tag{16}$$

for all $\tau \geq 1$. Furthermore, the boundary conditions translate to $A(0) = C(0) = 0$.

In our baseline calibration, we set $M = 5$, with $m(1) = 0.05$, $m(2) = 0.25$, $m(3) = 5$ and $m(4) = 10$.[26] Under this definition of maturity bucket, we find that the preferred-habitat assumption is satisfied for most of the end-user investors. As Table 3 shows, the majority of end-users concentrate their activities in a single maturity bucket under this partition. We find that the main preferred-habitat investors in maturity group 1 (below 3 months) are funds, while preferred-habitat investors in group 2 (maturity between 3 months and 5 years) include mainly banks, corporations, and funds. Moreover, in the longest maturity group (maturity 10 years & above), the dominant investors are PF&I.

For the first four maturity buckets, we set $\bar{m}(\tau)$ to be the mid-maturity in the interval. For the last maturity group, we set $\bar{m}(\tau)$ to be 25, which is the empirically observed notional-weighted average maturity of swaps in that group. The parameters for the maturity buckets are summarized in Table 5.

We consider one aggregate demand factor, i.e., $K = 1$. This implies that we have two aggregate shocks in total, one for the supply side and one for the demand side. We refer to the shocks to arbitrageurs' funding cost c_t as supply shocks, and shocks to the demand factor $\beta_{1,t}$ as demand shocks. We do not take a stance on exactly what the demand factor is. The reduced form evidence in Table 4 suggests the demand factor is related to the level of the interest rate. Furthermore, we do not impose any assumptions on Σ, which means that the contemporaneous supply and demand shocks can potentially be correlated.

We calibrate the model by matching a set of model-generated moments with the corresponding empirical moments. All the empirical moments are constructed using monthly observations from July 2019 to December 2022. To calculate swap spreads for each month and each maturity group,

[26] The swap spread at the ultra short-term should be 0. We take $m(1) = 0.05$ as an approximation for ultra short-term swap spreads.

we use the actual fixed rate observed in our data for new transactions between end-users and dealers in that month. We subtract from it the maturity-matched bond yield as on the trade date, and aggregate at month-maturity group level using notional-weighted averages across all transactions.[27] We use Q_t in Equation 1 as our definition of quantities.[28]

For each maturity bucket τ ($\tau = \{1, 2, 3, 4\}$),[29] we first target the volume-weighted average swap spreads and the average net notional held by end-users across our sample period. These moments are informative about the level of the hedging needs $\theta_0(\tau)$, as well as the demand elasticities $\alpha(\tau)$. Empirically, we find that the swap spread along the maturity curve features a hump-shaped pattern: it increases from 10 bps in the first maturity group to 21.5 bps in the third maturity group, and then decreases to negative 37 bps in the longest maturity group.[30] In terms of quantities, on average, end-users in groups 1 and 4 are receiving fixed, and end-users in group 2 and 3 are paying fixed.

Furthermore, we target a set of second moments including the variance and covariance of price and quantity changes. For scaling reasons, we consider the change in quantity as

$$\Delta q_t = \frac{Q_t - Q_{t-1}}{(|Q_t| + |Q_{t-1}|)/2}, \tag{17}$$

which enables comparison across sectors and is bounded between +2 and -2. This scaled measure is similar to the Davis and Haltiwanger (1992) growth rate measure that mitigates the effect of outliers. We target the variances of swap spreads changes ($\Delta s_t(\tau)$) and the variances of scaled quantity changes ($\Delta q_t(\tau)$) for maturity groups 1-4. We find that the volatility of quantity changes is lower for group 2 and 4, consistent with the fact that banks, corporations, and PF&I have lower volatility in their exposures compared with funds (see Figure 5). To capture the correlation between prices and quantities, we also target the uni-variate regression coefficients of scaled quantity changes on swap spread changes for each maturity bucket respectively. The joint dynamics of spreads and quantities are informative about the law of motion of the supply and demand factors, as well as different sectors' exposure to the demand shock. We summarize the empirical moments in Table 6. The exact expressions for the model counterparts are presented in Appendix B.[31]

[27] Some trades erroneously report the fixed rate in terms of basis points instead of percentage points. We benchmark the fixed rate in our data with the maturity-matched daily market overnight indexed swap (OIS) fixed rate sourced from the Bank of England yield curve database. We retain trades where the difference between our fixed rate and the market OIS rate falls within 2.5% to 97.5% of its distribution.

[28] We only include investors with more than half of their trading volume in their respective dominant maturity buckets. We include all the large pension funds, but we only include their positions in the maturity bucket 10 years & above.

[29] Since the first maturity group $(0, 0.05)$ is chosen just to satisfy $s_t(0) = 0$ and there are few preferred-habitat investors in the very short-end, we only target the prices and quantities in maturity groups 1-4.

[30] Figure A6 shows that the hump-shaped pattern exists when we look at finer maturity groups as well.

[31] To obtain closed form results in the model, we construct the model counterpart of Equation 17 as the change in quantity scaled by the absolute value of the average quantity. Since all the variables are stationary,

In terms of the parameter values, we have $3 \times (M-1) = 12$ demand side parameters (α, θ_0 and θ_1 for maturity groups 1-4). Since the demand side parameters for group 0 do not affect prices and quantities in any other maturity group, we set them to 0. We do not impose any assumptions on the demand parameters of the other groups. On the supply side, we need to calibrate the average funding cost $\bar{c}$ and the risk aversion coefficient a. Furthermore, we assume that Γ is a diagonal matrix, i.e., the predictable component of the change in the demand factor, $d\beta_{1,t}$, only depends on the lagged demand and not the arbitrageur's lagged funding cost. Similarly, the predictable component of the change in dealers' funding cost only depends on the lagged funding cost and not on the demand factor. In the end, there are six parameters that govern the law of motion of state variables, and in total, we have 20 parameters.

4. Results and Counterfactuals

4.1. Calibration Results

Figure 6 presents the model simulated moments compared with the corresponding empirical moments. The model can almost perfectly match the average swap spreads, the average quantities, and the regression coefficients of quantity changes on spread changes. Furthermore, the model captures the variance and covariance of changes in prices and quantities reasonably well.

We present the calibrated parameters in Table 7. First, the calibration confirms our reduced-form evidence that investors in the long-end of the market (10 years & above), who are mostly PF&Is, demand fixed payments, that is $\theta_0(4) < 0$. In contrast, investors in maturity group 2 (3 months to 5 years) demand floating rate payments $\theta_0(2) > 0$. Investors in this group include banks, corporations, and funds. Second, $\theta_1(2)$ and $\theta_1(4)$ have opposite signs, which means that investors in the short-end and long-end have opposite exposure to demand shocks. The estimates are qualitatively consistent with the interpretation that the demand factor approximates interest rate movements. When the interest rate increases, the demand for fixed-rate from long-end investors decreases; the demand for floating-rate from the short-end investors also decreases. The opposite signs of demand intercept and exposure to the demand factor confirm that the institutions trading at the short-end are natural hedging counterparties for the institutions trading at the long-end. However, market segmentation together with intermediary frictions prevent them from hedging with each other perfectly.

Furthermore, we find that preferred-habitat investors generally have very inelastic demand. In particular, investors at the long-end (PF&I) have more inelastic demand compared to investors at the short-end (banks, corporations, and funds). More specifically, investors in the first maturity

this approximation is close.

group, primarily funds, have the most elastic demand. As a result, their positions are more volatile compared to the other sectors, consistent with panel (a) of Figure 4 and Figure 5.

In equilibrium, swap spreads load positively on the supply side factor c_t, i.e. the first element of $A(\tau)$ is positive. This means that, everything else equal, when dealers' balance sheet cost is high, swap spreads tend to be larger for all maturities. On the other hand, swap spreads load negatively on the demand side factor β_t, i.e., the second element of $A(\tau)$ is negative. This implies that when β_t is large, spreads are low. Furthermore, spreads for longer maturity swaps are more sensitive to both supply and demand shocks. In other words, the absolute value of $A(\tau)$ increases with τ for both elements, implying that swap spreads are more volatile at the long-end. Finally, we find that the supply and the demand shocks are positively correlated in our calibration.

The role of supply vs. demand factors. Next, we examine the contribution of the different supply and demand side factors in determining the shape of the swap spread curve. In Figure 7 panel (a), we start with the swap spreads in the model using the calibrated parameter values, and we first remove the average dealer sector funding cost by setting $\bar{c} = 0$. During our sample period, on net, the dealer sector is holding positive amount of swaps across all maturity groups. Dealers therefore demand positive swap spreads to compensate for the funding cost incurred. Hence, setting the average funding cost $\bar{c}$ to 0 leads to an almost parallel downward shift in swap spreads for all maturities with a magnitude of about 7 bps. This change in the swap spreads is relatively small given the fact that the average swap spreads range from negative 40 bps to 20 bps empirically.

We then remove the demand side pressure by setting the intercepts of all the preferred-habitat investors' demand to 0, i.e., $\theta_0(\tau) = 0$ for all τ. As shown in Figure 7 panel (a), removing demand pressure essentially brings swap spreads to 0 for all maturity groups, suggesting that demand pressure from different investors indeed plays a quantitatively significant role in driving the shape of the swap spread curve. Next, we set the demand shocks to 0, i.e., $\beta_{1,t} = 0$, this reduces the swap spreads for all the maturities because it reduces the risks born by the dealer sector. Finally, removing the supply side risks brings all swap spreads to 0, which is the frictionless case.

We emphasize that the large effect of demand pressure on swap spreads relies on the dealer sector being risk averse. Indeed, the risk aversion coefficient of the dealer sector (a) is quite high in our calibration. Local demand imbalances expose the dealer sector to short-term swap spread fluctuations in each maturity bucket, and the impact on prices is larger when dealers are more risk averse. We find that when the dealer sector's risk aversion coefficient is smaller (close to 0), the demand pressure has a much smaller impact on swap spreads. In other words, it is the interaction between the demand pressure from the end-users and the dealer sector's risk aversion that generates large effects on swap spreads.

To further understand the relative importance of demand pressure from the different sectors, we set the demand intercept to 0 for maturity group 2 and the maturity group 4 one at a time. We ignore the other maturity groups because their demand intercepts are much smaller and are unlikely to play an important role quantitatively. Figure 7 panel (b) shows the re-calculated swap spreads compared with the baseline case. As investors in the long-end and short-end are natural counterparties, removing the demand intercept from either group results in more imbalance in net demand and the dealer sector needs to hold more inventories in equilibrium. This tilts the swap spread curve away from 0. In both cases, the impact is larger for the longer maturity swaps. Despite the fact that group 4 has smaller magnitude of demand ($|\theta_0(4)| < |\theta_0(2)|$) than group 2, their effects on swap spreads are similar in magnitudes. This is because demand at the longer maturity segments exposes the dealer sector to more risks, hence each unit of long-maturity demand has a larger impact on prices compared to the demand of short-maturity swaps.

In Appendix C, we recalibrate the model assuming that dealer sector's holding cost is dependent on the swap's maturity. Since the maturity-weighted net position of the dealer sector is negative, $\bar{c}$ is calibrated to be negative so that the dealer sector on average bears positive funding cost.[32] We again find that the demand pressure, interacted with dealers' risk aversion, plays a quantitatively more significant role compared to dealers' funding costs.

4.2. Counterfactual Analysis

We conduct a series of counterfactual analysis in this section, motivated by regulatory discussions and differences in the financial regulatory regimes across countries.

Demand pressure. We first examine how changes in end-users' demand affect the interest rate swap market across the maturity segments, and the spillover effects to other participants in this market. Such demand shifts could come from regulatory changes. For example, in light of the recent Silicon Valley Bank crisis in 2023, regulators are discussing measures to encourage banks to hedge their interest rate risks more, for example, including more comprehensive interest rate scenarios in stress tests or applying higher capital charges to interest rate risk in the banking book (Wilkes, 2024). Similarly, the UK pension funds crisis in 2022 also motivated various regulatory discussions on pension funds' interest rate hedging strategies. Alternatively, the demand shifts can be seen as a comparative static exercise to study cross-country differences and their effects on the swap spread curve. For example, banks' interest rate hedging needs are closely tied to the maturities and loan-rate fixation conventions of mortgages in the local region (Hoffmann et al., 2019). Variation

[32] Setting $\bar{c} = 0$ increases the swap spreads, but the magnitude is also quite small.

in mortgage market conventions induces cross-region variation in the banking sector's demand for interest rate swaps, and thus on equilibrium swap spreads.

We start by considering changes in the average level of demand, i.e., θ_0. We treat factors affecting the banking sector's hedging demand as changing the demand intercept of investors in group 2, which is the dominant maturity bucket for banks. Likewise, we model factors affecting pension funds' hedging demand as changing the demand intercept of investors in group 4, which is where the majority of pension funds' trades are. Furthermore, while higher hedging demand in the banking case means more negative demand in the second maturity bucket (i.e., smaller $\theta_0(2)$), higher hedging demand for PF&I means they demand more fixed-rate payment in the longest-tenor maturity bucket (i.e., larger $\theta_0(4)$). To make the two experiments comparable, we change the demand intercept by one unit in both cases but in the opposite directions.

The results are shown in Figure 8. As banks and PF&Is have opposite hedging needs, an increase in one sector's hedging demand reduces the average hedging cost for the other sector. When banks hedge more, this raises the swap spreads for all maturity groups, reducing the hedging cost for PF&I. Specifically, a one-unit increase in banks' hedging demand raises the swap spread for the longest maturity bucket by 60 bps. A back-of-the-envelope calculation suggests that this increase in swap spreads would save investors in the longest maturity group, i.e. primarily the PF&I sector, almost \$2 billion ($0.6\% \times 328 \approx 1.97$ billion) per year on average in hedging costs. Note that because investors' demands are inelastic, the net notional exposure barely changes. On the other hand, a one-unit increase in PF&I's hedging demand reduces the swap spread faced by the banking sector by about 75 bps, which would lead to an estimated ∼\$6 billion ($0.75\% \times 796 \approx 5.97$ billion) reduction in average hedging costs for the investors trading in group 2, i.e. primarily the end-user banks.

In Figure 8 panels (c) and panel (d), we plot the changes in the average swap spreads in the two experiments respectively. Comparing the two, we find that the effect on swap spreads is much larger when the demand shift happens in the PF&I sector, even though the magnitude of demand changes in the two experiments are the same. A one-unit change in banks' hedging demand leads to a 33 bps change in swap spreads on average across maturity buckets, while the same magnitude of demand change in the PF&I sector leads to an average change of 83 bps. This is because swaps with longer tenor are riskier, hence demand imbalances in the long-end have larger impact on equilibrium prices than those in the short-end. Furthermore, regardless of where the demand shift originates, its impact on spreads is monotonically increasing in swaps' maturities. In both cases, the change in swap spreads in the longest maturity bucket is twice the change in the second maturity bucket.

Finally, we repeat the experiment of demand shifts under more elastic demands. Investors' demand could become more elastic when either market power or concentration of the investor base changes or when it becomes easier to hedge interest rate risk using other instruments. Specifically, we increase the demand elasticities for all preferred-habitat investors by 10 fold. We then plot the change in swap spreads when banks' hedging demand increase by one unit (Figure 8 panel (e)) and when PF&I's hedging demand increase by one unit (Figure 8 panel (f)). We find that the same magnitude of demand changes lead to smaller effects on equilibrium prices, as a larger fraction of the shock is absorbed by adjustments in quantities.

Demand sensitivity. In addition to shifting the level of demand, regulation could also affect how hedging demand responds to aggregate conditions. Hence, we also evaluate the effect on swap spreads when demand in different sectors becomes more sensitive to the aggregate demand factor. Similar to before, we focus on the two main preferred-habitat investors: the banking sector in maturity bucket 2, and the PF&I sector in maturity bucket 4.

In the first experiment, we increase the sensitivity of banks' hedging demand to the aggregate factor by increasing the absolute value of $\theta_1(2)$ by 0.1 while maintaining the sign. In the second experiment, we increase the sensitivity of PF&I's demand by increasing the absolute value of $\theta_1(4)$ by the same magnitude. The equilibrium average swap spreads are re-calculated and shown in Figure 9 panels (a) and (b). Changes in demand sensitivity lead to two counter-acting forces. On the one hand, when banks' demand is more sensitive to the aggregate demand factor, swap spreads become more exposed to demand shocks for all maturities. Since the "duration-weighted" average holding of dealers is negative, an increase in risks from demand shocks leads to higher prices and lower spreads. This is captured in the last term of Equation 13. On the other hand, because of the correlation between supply and demand shocks, higher sensitivity to demand shocks actually leads to overall less volatile prices, i.e., $A(\tau)^\top \Sigma\Sigma^\top A(\tau)$ becomes smaller in Equation 13. This force increases average swap spreads because of the Jensen term in returns. We find that the latter force dominates when the change in sensitivity is small. When the change in $\theta_1(2)$ is large, we find that the first force becomes stronger for long-tenor swaps.

In Figure 9 panel (c) and (d) we plot the changes in swap spreads for each maturity group. Translating the spread changes into dollar amount saved, when the magnitude of $\theta(2)$ increases by 0.1, this saves the PF&I sector \$164 million ($0.05\% \times 328 \approx 0.164$ billion) in terms of hedging costs per year. In turn, if the magnitude of $\theta(4)$ is 0.1 larger, this reduces the banking sector's hedging costs by \$1.6 billion ($0.2\% \times 796 \approx 1.59$ billion) per year. As before, we find the same magnitude of changes in the long maturity group has much larger impact on all the swap spreads than those in the short maturity group. Finally, in Figure 9 panel (e) and (f), we repeat the counterfactual under more elastic demand. The spillover effect across different sectors is much smaller.

More integrated markets. A major friction in this market is that investors with opposite hedging needs trade in segmented markets, exposing the dealers to fluctuations in swap spreads of different sub-markets. To understand the quantitative implication of market segmentation, we consider a hypothetical scenario where some PF&Is trade in the same maturity group as banks. Since it is not realistic to move all the long-term demand to short-term maturity bucket, we consider the case where $\gamma = 10\%$ of the demand in group 4 is moved to group 2 in Figure 10. We scale the demand parameters, θ_0 and θ_1, by $\bar{m}(4)/\bar{m}(2)$ so that PF&I's demand in duration term stays approximately the same. Specifically, the new demand parameters $\theta_1'(\tau)$, $\theta_0'(\tau)$ and $\alpha'(\tau)$ are equal to the baseline estimates for $\tau = 0, 1, 3$. For $\tau = 2$ and $\tau = 4$,

$$\theta_0'(2) = \theta_0(2) + \gamma \times \theta_0(4) \times \frac{\bar{m}(4)}{\bar{m}(2)} \tag{18}$$

$$\theta_1'(2) = \theta_1(2) + \gamma \times \theta_1(4) \times \frac{\bar{m}(4)}{\bar{m}(2)} \tag{19}$$

$$\theta_0'(4) = (1-\gamma) \times \theta_0(4) \qquad \theta_1'(4) = (1-\gamma) \times \theta_1(4) \tag{20}$$

$$\alpha'(2) = \alpha(2) + \gamma \times \alpha(4) \qquad \alpha'(4) = (1-\gamma)\alpha(4) \tag{21}$$

We find that moving PF&Is to trade in the same maturity group as banks shifts down the swap spread curve, as shown in Figure 10 panel (a). This is mainly because merging sectors with opposite demand reduces the risks born by the dealer sector, leading to lower spreads. This leads to substantial saving in hedging costs for banks, but increases the hedging costs for PF&Is. On net, the hedging costs for the two sector combined is reduced by $30 million.

In Figure 10 panel (b), we plot the net positions in each maturity bucket. Moving part of the PF&I's demand to the same group as banks' demand facilitates more netting and reduces the outstanding positions in all maturity buckets. Specifically, it leads to a 36% reduction in net position in maturity group 2 and 10% reduction in maturity group 4.

Arbitrageurs' risk aversion. Lastly, certain dealer regulations may also induce dealers to behave as if they are more risk-averse. We find that an increase in arbitrageur's risk aversion coefficient leads to more positive swap spreads in the short-end and more negative swap spreads in the long-end. In Figure 11, we double the magnitude of the risk-aversion coefficient. We see that swap spreads are 40 bps higher in the short-term maturity group, but 20 bps lower in the long-term maturity group. Intuitively, equilibrium swap spreads reflect the local preferred-habitat demand more because dealers are now more worried about demand shocks (than in the baseline) and hence conduct less carry trade.

4.3. Future Extensions

In this section, we discuss potential future extensions, leveraging our detailed swaps holdings and transactions data and the model framework further. First, one can investigate demand heterogeneity *within* each maturity bucket using the granular quantity and pricing data at an investor level. Our current framework explores the heterogeneity *across* maturity groups. However, within each maturity group, different institution types may exhibit different trading patterns. For example, in maturity group 2, in addition to banks, various types of funds also trade large quantities, with potentially heterogeneous demand elasticities and exposure to aggregate shocks. Unpacking the heterogeneity within maturity groups can shed light on additional sources of local demand pressures, how they vary with market conditions and affect asset prices.

Second, it may also be interesting to consider multiple demand factors since different end-users may respond to different parts of the yield curve or other business cycle variables. For example, while all end-user sectors appear sensitive to parallel shifts in the yield curve, banks and funds may respond differently to steepening or flattening of the yield curve compared to PF&Is. Considering multiple demand factors could be particularly important for analyzing how demand and swap spreads change over the business cycle. Relatedly, given that we have shifted from a low to a high interest rate environment in 2022, it would be interesting to estimate the model on sub-samples to shed light on how financial institutions behave differently under different monetary policy regimes. Such an analysis will be possible once more data becomes available for the high interest rate period.

Finally, comparing the hedging behavior of a particular institution type (e.g., banks or insurers) across different countries could inform us on the factors motivating the demand for swaps in particular maturity segments in the first place. For example, a large fraction of UK insurers' liabilities are now in mutual fund like products that offer no investment guarantees (Sen and Humphry, 2018), which is very different from US insurers who provide long-term guaranteed return products. Similarly, banks in different countries have different loan fixation regimes and deposit market sensitivities. Regulations in different countries may also play a role. However, such geographical comparisons require more comprehensive data compiled from individual countries, which calls for greater coordination among regulatory bodies of different countries.

5. Conclusion

This paper provides the first large-scale empirical evidence on the extent of risk sharing in the interest rate swaps market, and quantifies how demand imbalances and frictions in the dealer sector affect swap spread dynamics. Using granular transaction-level data on both the stock and the flow of swap trades, we show that the PF&I sector emerges as a natural counterparty to banks and corporations. While PF&I mostly receive fixed, banks and corporations pay fixed. Furthermore, as rates fall, PF&I increase their net receive positions, while banks and corporations increase their net pay positions. Their trading behavior is consistent with them hedging interest rate risk from their underlying business models. The opposite positions of PF&I vis-a-vis banks and corporations imply that they are natural counterparties in the interest rate swap market, and this cross-sector netting reduces the aggregate net demand that has to be supplied by the dealers. However, the market is highly segmented across maturities: PF&I mostly hold long maturity swaps of 10 years & above, while banks and corporations mainly hold positions with maturities between 3 months to 5 years. This segmentation leaves large demand imbalances for dealers at different maturities.

We study the implications of demand imbalances on asset prices by calibrating a preferred-habitat investors model with risk-averse arbitrageurs, who face both funding cost shocks and demand side fluctuations. The richness of our data allows us to impose very little assumptions in our calibration. We find that the demand pressure, especially from the banking and PF&I sector, plays a relatively larger role than arbitrageurs' funding costs in explaining the shape of the swap spread curve. We also provide quantitative assessments of the spillover effects of sector-level demand shifts on the hedging costs of other sectors, which inform regulatory discussions on hedging requirements in light of recent events in the banking and PF&I sectors. Our results highlight the complex interactions and consequences of demand imbalances in one of the largest and most liquid financial markets in the world.

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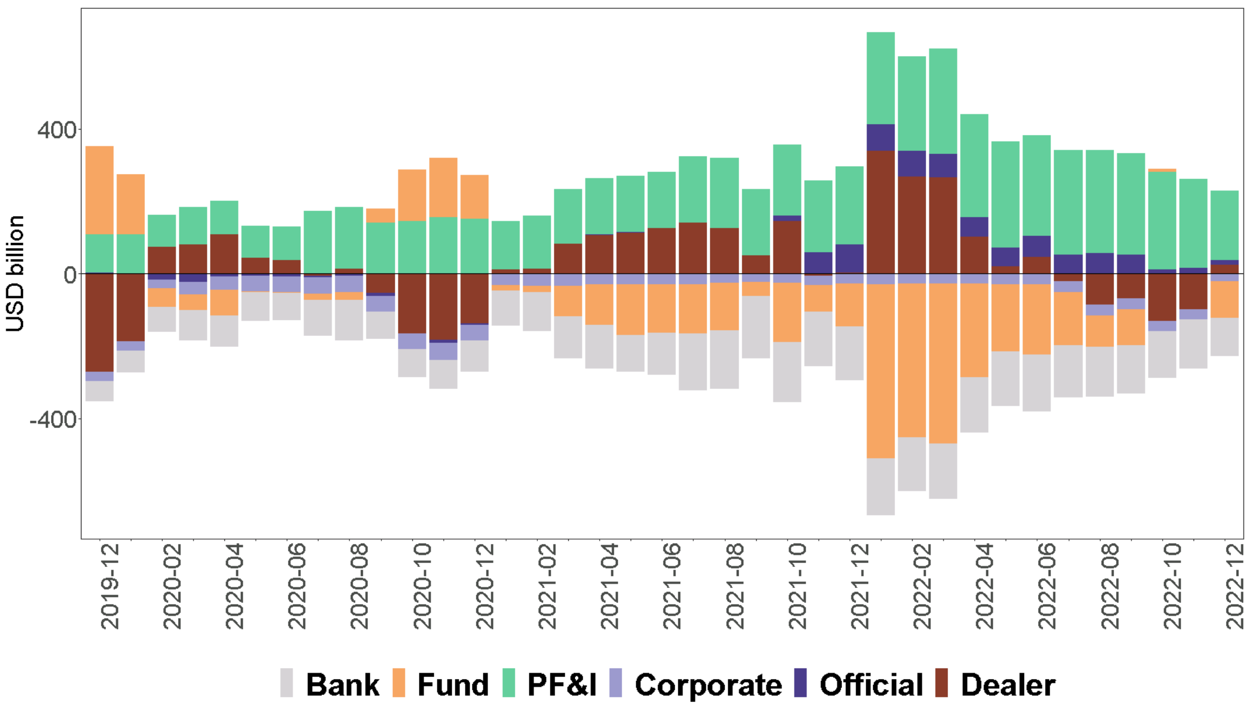
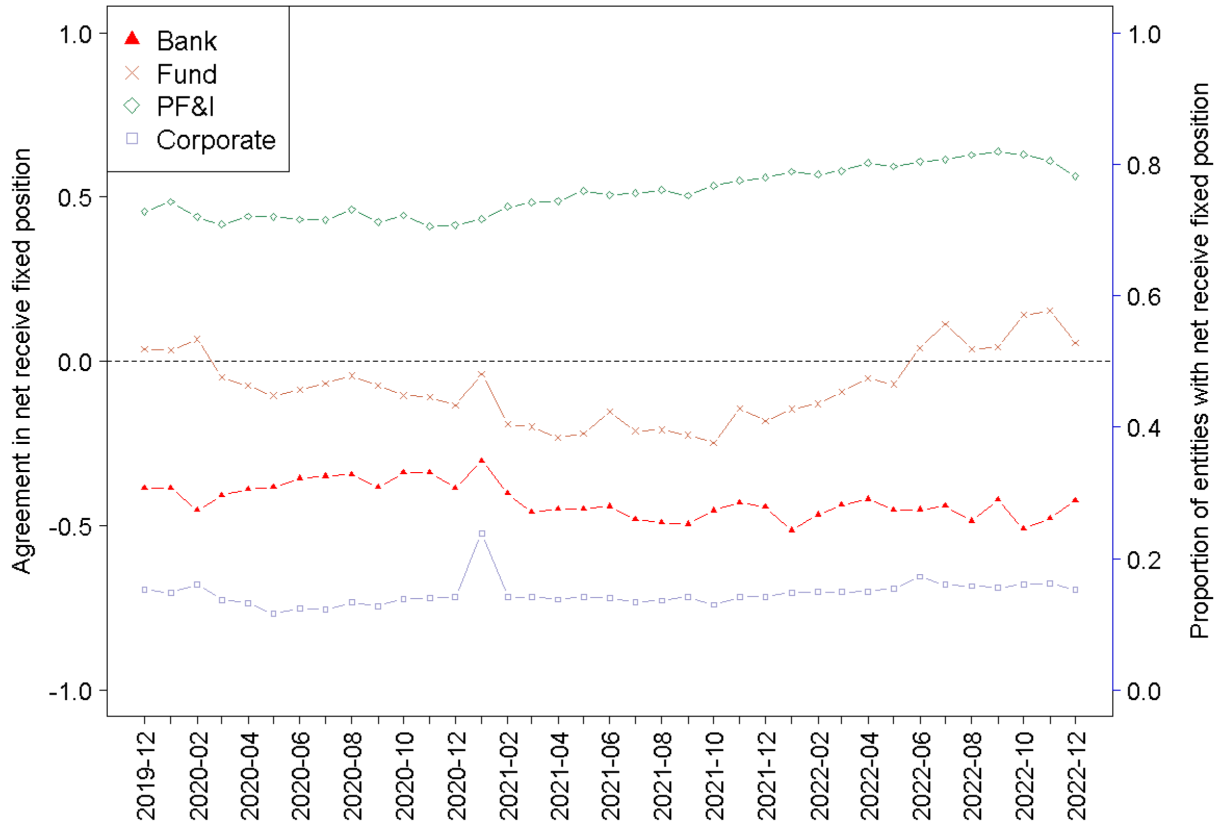
Figure 1: Net Outstanding Positions



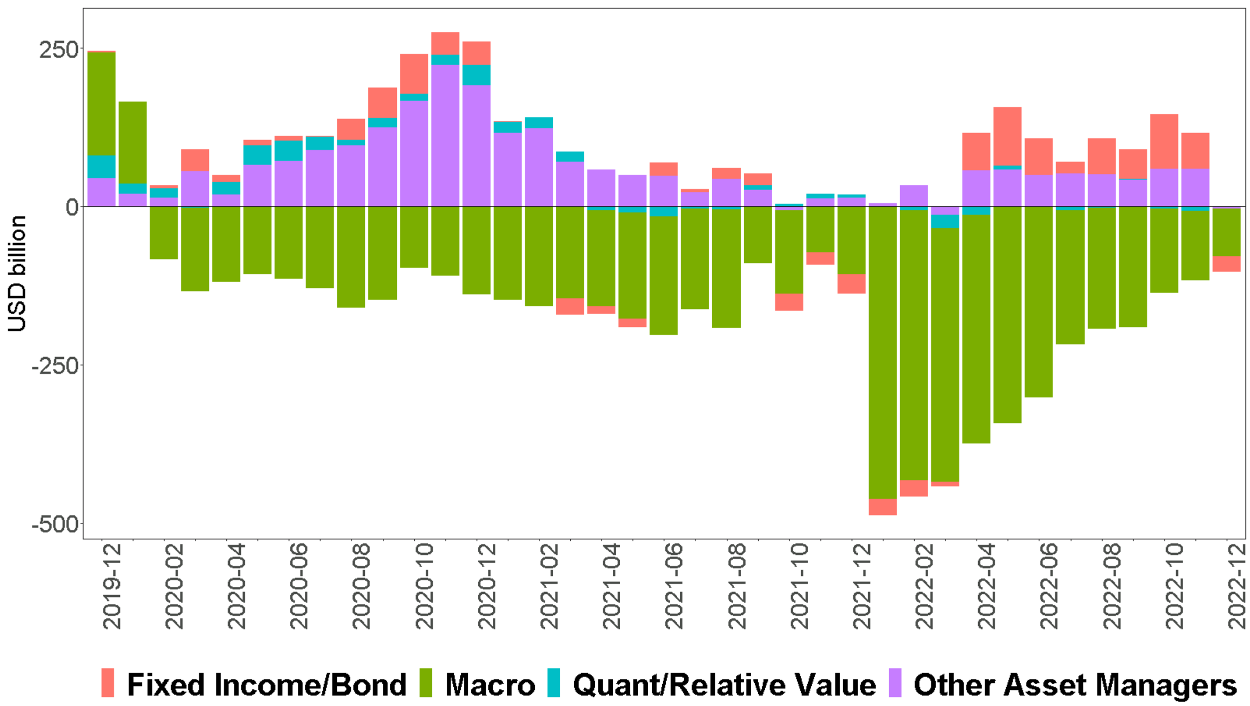
Notes: This figure shows net outstanding positions in $ billion at the start of every month for five end-user sectors and the dealer sector. A positive value on the y-axis indicates a net receive fixed position while a negative value indicates a net pay fixed position. Net outstanding position is calculated as the difference between the outstanding notional values of receive fixed rate and pay fixed rate swaps for each legal entity as per Equation 1, and then aggregated for five end-user sectors: Bank, Fund, PF&I (pensions, liability-driven investment funds, and insurance), Corporate, and Official (sovereign and supra-national institutions). The net outstanding position for the dealer sector is calculated as the opposite side of aggregate end-user positions such that the market clears. This figure considers swaps denominated in British pound sterling (GBP), while Figure A2 considers swaps denominated across currencies in our sample.

Figure 2: Exposure Heterogeneity within Sectors



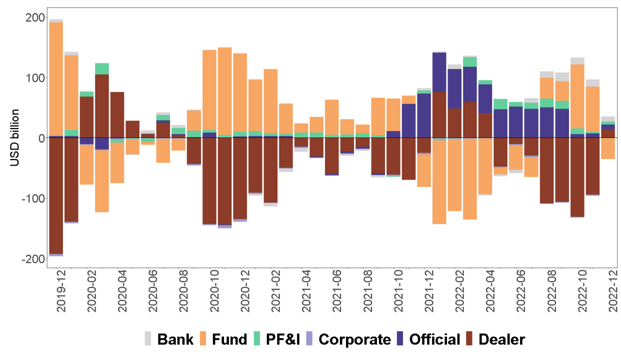
Notes: This figure depicts within-sector heterogeneity in exposures using entity-level net positions at the start of every month. We use two measures of exposure heterogeneity. The left axis represents an agreement score, where each entity gets a score of +1 if it has a net receive fixed outstanding position, or -1 if it has a net pay fixed outstanding position. We then plot the monthly time-series of an average score across all entities within each sector. A score closer to zero indicates large disagreement within the sector, a score closer to +1 (-1) indicates that most entities hold net receive (pay) fixed position. The second measure is depicted on the right axis which shows the proportion of entities within each sector that held a net receive fixed position. About 80% of PF&I (pensions, liability-driven investment funds, and insurance) held net receive fixed positions during the sample period, while 83% of corporations and 70% of banks held net pay fixed positions. Funds displayed the largest heterogeneity with a roughly equal split between net receive and net paid positions.

Figure 3: Net Outstanding Positions by Fund Type

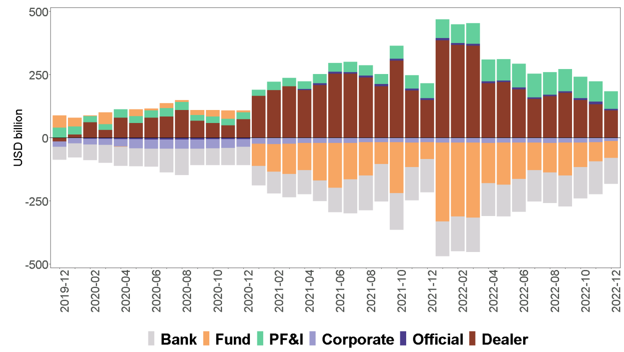


Notes: This figure shows net outstanding positions in $ billion at the start of every month for four fund types: Fixed Income/Bond, Macro, Quantitative/Relative Value, and Other Asset Managers. We identify fund types at a legal entity level using string matching on their names with common investment strategies. A positive value on the y-axis indicates a net receive fixed position while a negative value indicates a net pay fixed position. Net outstanding position is calculated as the difference between the outstanding notional values of receive fixed rate and pay fixed rate swaps for each legal entity as per Equation 1, and then aggregated for the four fund types.

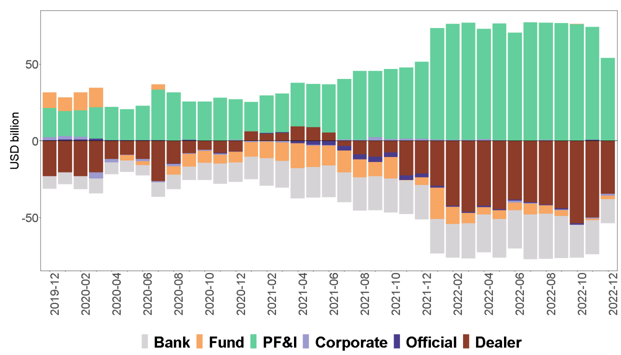
Figure 4: Net Outstanding Positions by Maturity Group



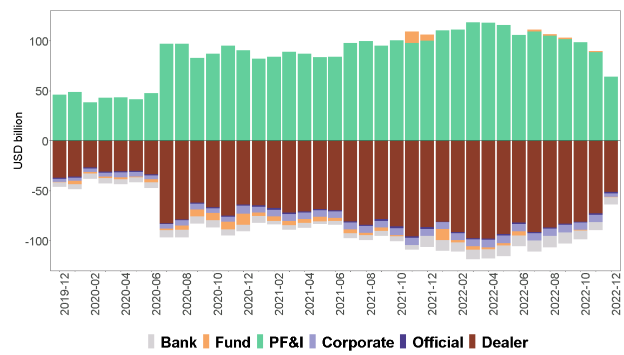
(a) Below 3 months



(b) 3 months to 5 years



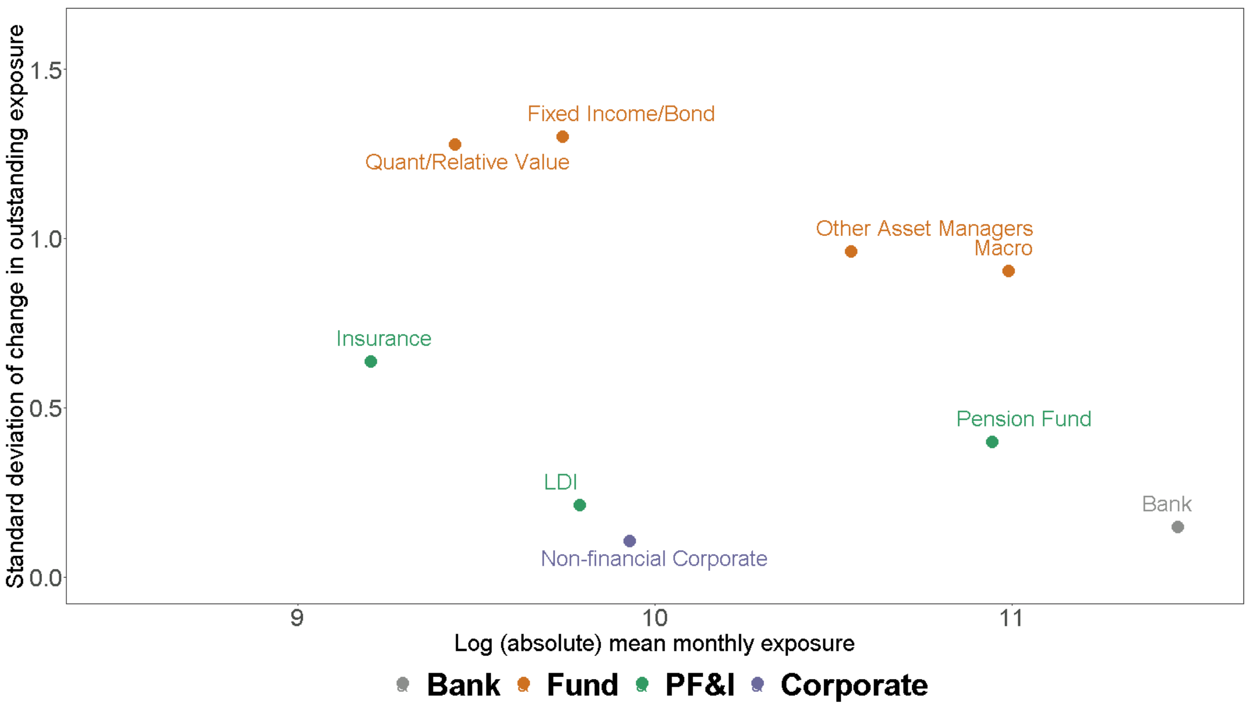
(c) 5 years to 10 years



(d) 10 years & above

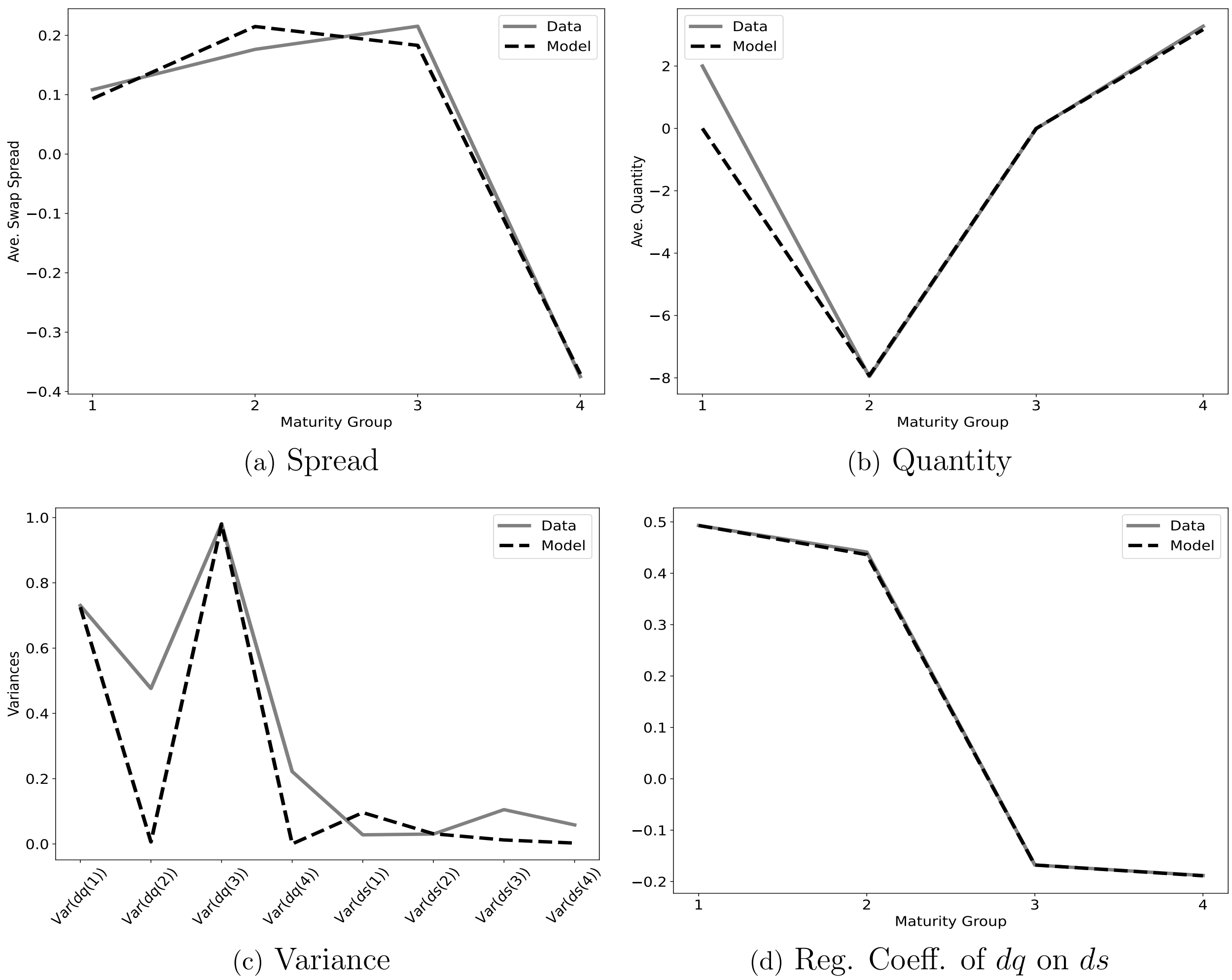
Notes: This figure shows net outstanding positions in $ billion at the start of every month for five end-user sectors and the dealer sector, split by four maturity groups: Below 3 months in panel (a), 3 months to 5 years in panel (b), 5 years to 10 years in panel (c), and 10 years & above in panel (d). A positive value on the y-axis indicates a net receive fixed position while a negative value indicates a net pay fixed position. Net outstanding position is calculated as the difference between the outstanding notional values of receive fixed rate and pay fixed rate swaps for each legal entity as per Equation 1, and then aggregated for five end-user sectors: Bank, Fund, PF&I (pensions, liability-driven investment funds, and insurance), Corporate, and Official (sovereign and supra-national institutions). The net outstanding position for the dealer sector in each maturity group is calculated as the opposite side of aggregate end-user positions such that the market clears.

Figure 5: Investor Size and Exposure Volatility



Notes: This figure plots the relationship between size of sub-sectors and volatility in their outstanding positions. Sub-sectors include the four types of funds and three types of PF&I, with a single representation each from Bank and Corporate. X-axis reports the size of each sub-sector, calculated as the log of average (absolute) net monthly exposure observed during our sample period. Y-axis represents the corresponding standard deviation of change in monthly outstanding positions within the dominant maturity group for that sector. Dominant maturity groups are: 3 months to 5 years for Bank and Corporate, Below 3 months for Fund, and 10 years & above for PF&I. Changes in monthly outstanding positions are scaled to enable comparison and mitigate the effect of outliers. This variable is defined in Equation 17 and is bounded between -2 and +2. All sub-sectors are represented on the plot using the color of the overall sector as reported in the legend.

Figure 6: Comparing Model Simulated Moments with Empirical Moments



(a) Spread

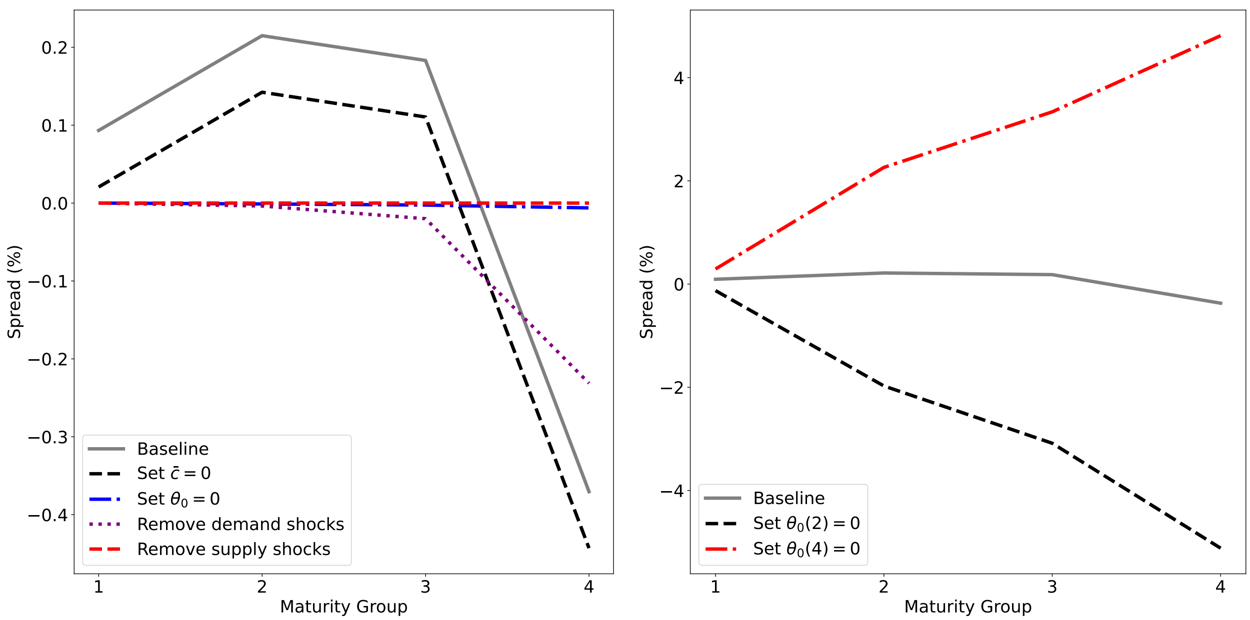
(b) Quantity

(c) Variance

(d) Reg. Coeff. of dq on ds

Notes: This figure compares the model simulated moments with the corresponding empirical moments from the data. All the spreads and yields are quoted in percentage terms. Quantities are in unit of $100 billion.

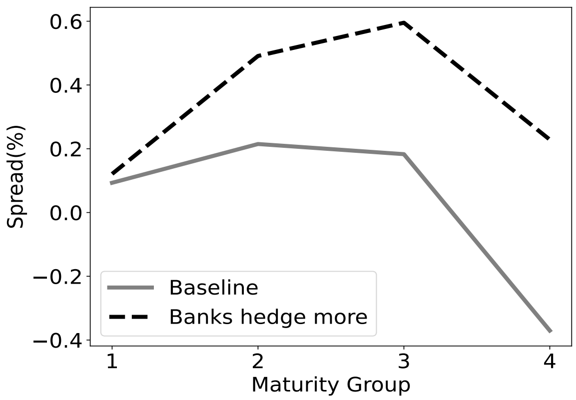
Figure 7: Decomposing Supply and Demand Factors



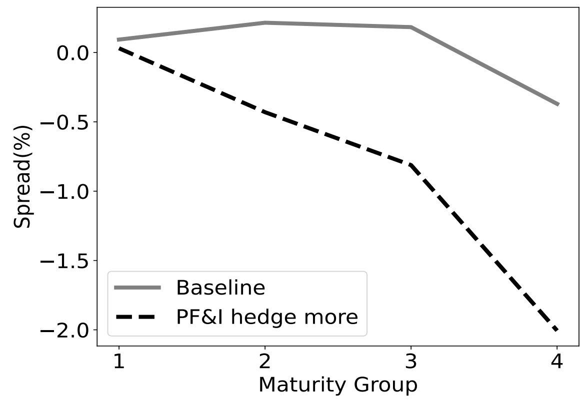
(a) (b)

Notes: This figure plots the average swap spreads for different scenarios. In panel (a), we start with the baseline swap spreads, then we set $\bar{c} = 0$ and recalculate the swap spreads in equilibrium. Next, we set $\theta_0(\tau) = 0$ for all τ. We then remove demand side shocks, i.e. $d\beta_{1,t} = 0$ and finally remove all supply side shocks $dc_t = 0$. In panel (b), we set $\theta_0 = 0$ for one group at a time and recalculate the equilibrium swap spreads. Spreads are quoted in percentage terms.

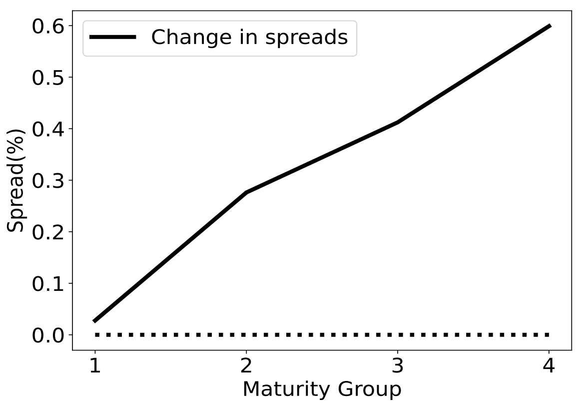
Figure 8: Counterfactual Analysis on Demand Pressure



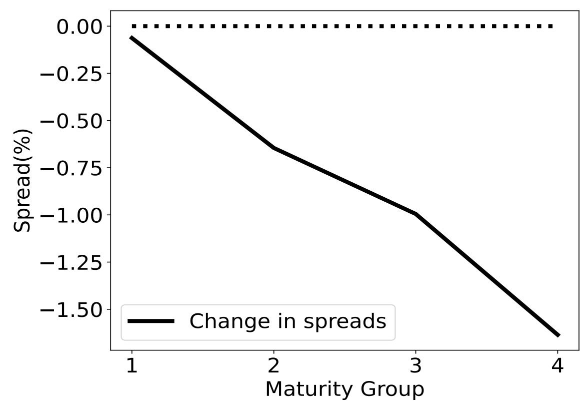
(a) Banks Hedge More



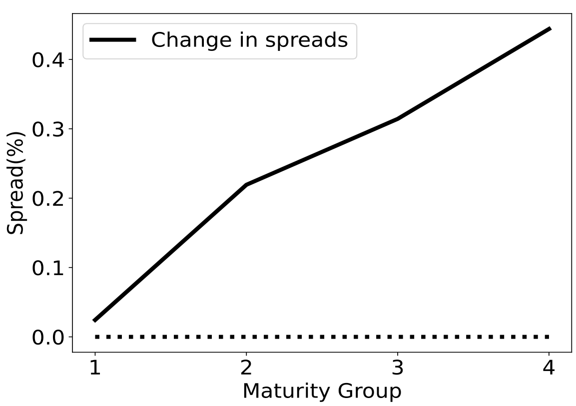
(b) PF&I Hedge More



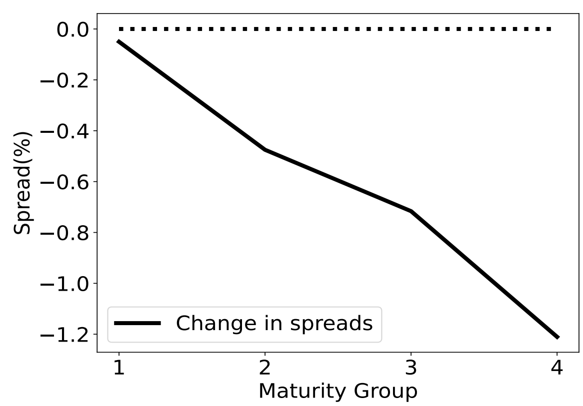
(c) Banks Hedge More



(d) PF&I Hedge More



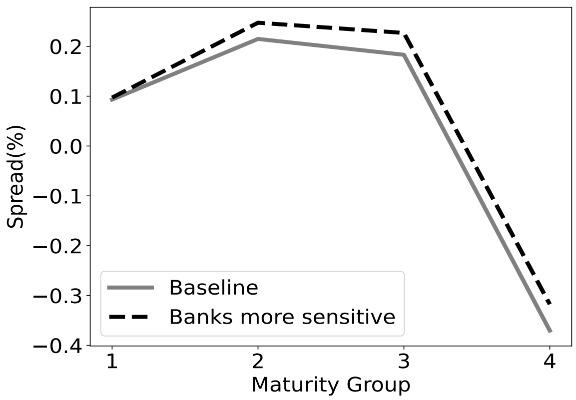
(e) Banks Hedge More (Elastic Demand)



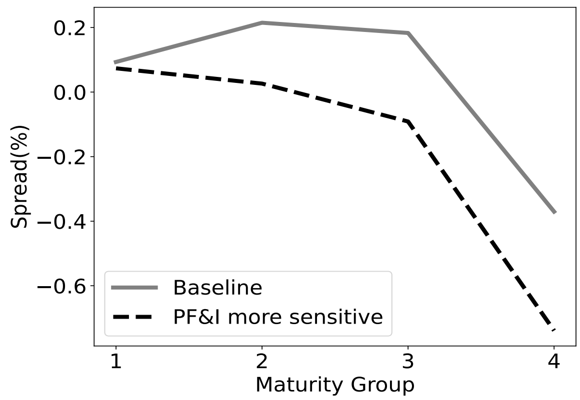
(f) PF&I Hedge More (Elastic Demand)

Notes: Panels (a) and (b) plot the counterfactual swap spreads when $\theta_0(2)$ is higher by one unit and $\theta_0(4)$ is lower by 1 unit respectively. Panels (c) and (d) plot the changes in spreads respectively. Panels (e) and (f) plot the changes in spreads for the two counterfactuals when demand for all sectors are 10 times more elastic.

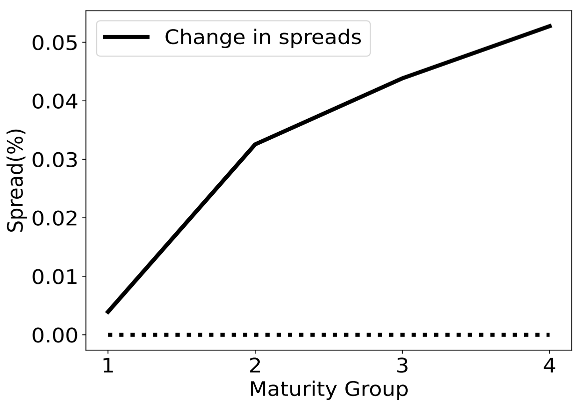
Figure 9: Counterfactual Analysis on Demand Sensitivity



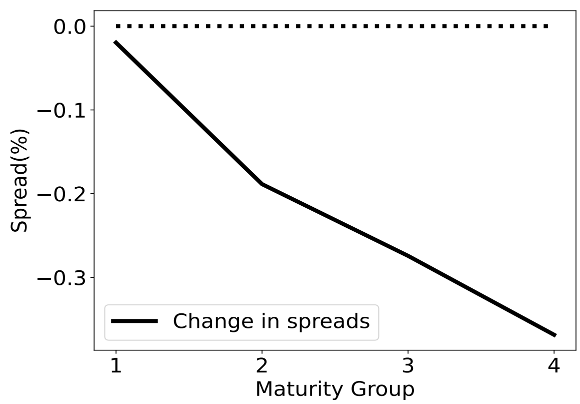
(a) Banks More Sensitive



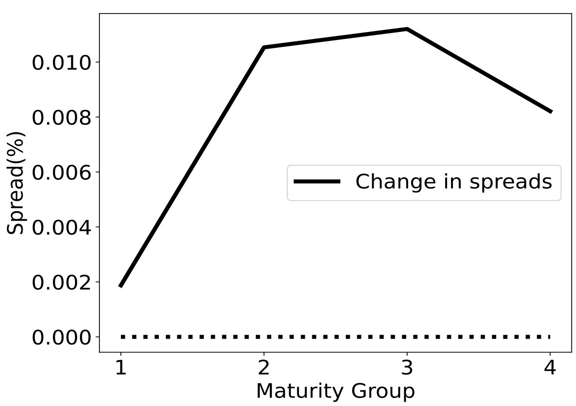
(b) PF&I More Sensitive



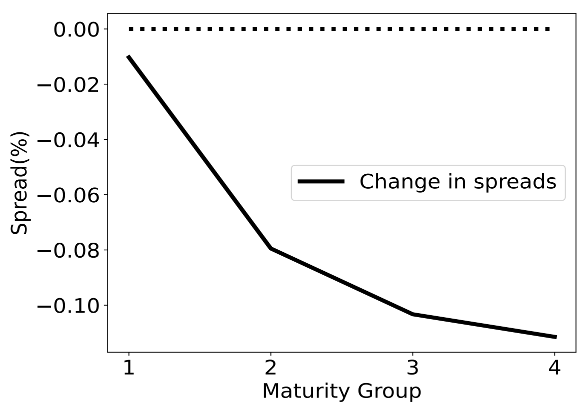
(c) Banks More Sensitive



(d) PF&I More Sensitive



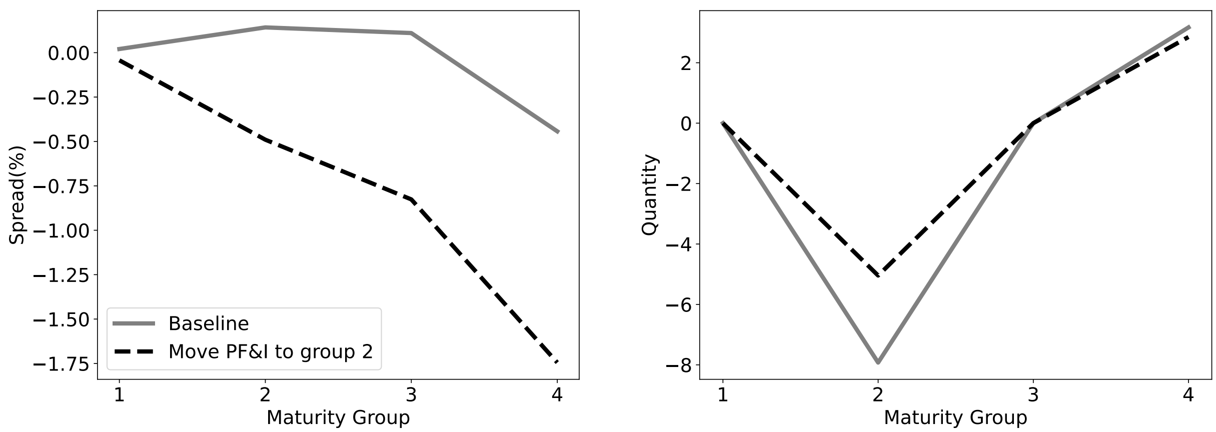
(e) Banks More Sensitive (Elastic Demand)



(f) PF&I More Sensitive (Elastic Demand)

Notes: Panels (a) and (b) plot the counterfactual swap spreads when $\theta(2)$ is lower by 0.1 and $\theta(4)$ is higher by 0.1 respectively. Panels (c) and (d) plot the changes in spreads respectively. Panels (e) and (f) plot the changes in spreads for the two counterfactuals when demand for all sectors are 10 times more elastic.

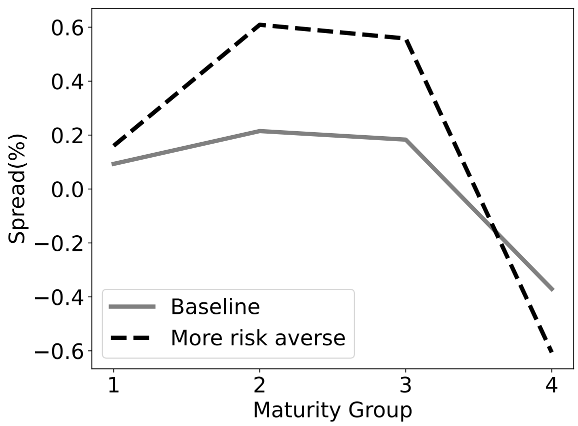
Figure 10: Counterfactual Analysis on Market Integration



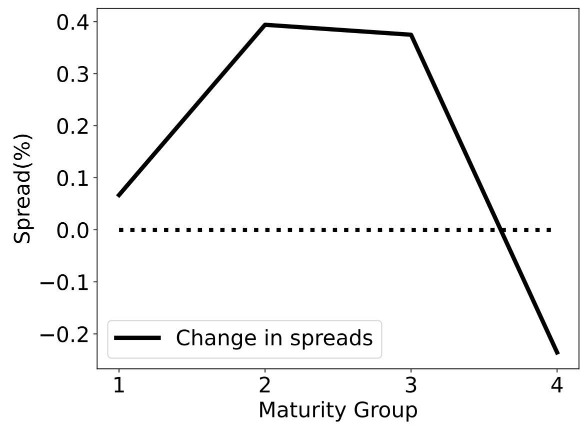
(a) Spread (b) Quantity

Notes: This figure considers the counterfactual in which we move 10% of the demand in group 4 to group 2. For group 1 and 3 we do not change the demand parameter. For group 2 and 4, we adjust the demand parameters according to Equation 18 through Equation 21.

Figure 11: Counterfactual Analysis on Risk Aversion Coefficient



(a) Spreads



(b) Change in Spreads

Notes: This figure considers the counterfactual in which the arbitrageurs become twice as risk averse as in the baseline case. We recalculate the equilibrium swap spreads. All spreads are quoted in percentage terms.

Table 1: Outstanding Positions and Transaction Volume

	Outstanding Positions ($ billion, as on Feb 1, 2022)		Transaction Volume ($ billion, monthly average)	
	Gross notional (1)	Net notional (2)	Gross notional (3)	Net notional (4)
Bank	472	-161	47	-5
Fund	1,600	-425	1,847	15
PF&I	1,339	261	110	17
Corporate	89	-28	4	-2
Official	98	71	22	-1

Notes: This table reports the outstanding positions and new transaction volumes in $ billion for five end-user sectors: Bank, Fund, PF&I (pensions, liability-driven investment funds, and insurance), Corporate, and Official (sovereign and supra-national institutions). Column (1) reports the gross outstanding notional as on February 1, 2022, and column (2) reports the net outstanding notional. A positive value indicates a net receive fixed position while a negative value indicates a net pay fixed position. Column (3) reports the average monthly gross notional traded by each sector throughout our sample period, and column (4) reports the average monthly net notional traded. All values are for swaps denominated in British pound sterling (GBP).

Table 2: Descriptive Statistics for Investor-level Outstanding Positions

	Investor-level net position ($ million, absolute)					
	N	Mean	SD	p25	p50	p75
Bank	210	1,871	5,458	44	214	1,006
Fund	730	1,786	23,711	7	40	184
PF&I	1,152	577	2,078	27	80	287
Corporate	516	218	528	19	53	141
Official	32	4,659	17,079	37	212	552

Notes: This table reports the distribution of net (absolute) outstanding positions for investors within each end-user sector as on February 1, 2022. Units are in $ million. We calculate the net exposure at the investor level as the difference between the notional values of receive fixed and pay fixed swaps outstanding on a date, and report the distribution of its absolute value within the sector. "N" refers to the number of unique investors that had any outstanding exposure in GBP swaps as on February 1, 2022 in our sample. All sectors in general and funds in particular display the presence of a few large investors as evidenced by the large difference in the mean and median positions.

Table 3: Investor Maturity Preference

Panel A	Fraction of investors trading in one maturity group	
	Equally-weighted	Notional-weighted
Bank	0.94	0.91
Fund	0.93	0.97
PF&I	0.88	0.70
Corporate	0.96	0.95

Panel B	Share of trades in dominant maturity group					
	N	Mean	SD	p25	p50	p75
Bank	160	0.81	0.18	0.69	0.85	1
Fund	1,045	0.81	0.20	0.63	0.87	1
PF&I	747	0.73	0.19	0.57	0.70	0.90
Corporate	272	0.90	0.18	0.85	1	1

Notes: This table shows that end-users in the interest rate swaps market exhibit preferred habitat behavior. Panel A reports the equally-weighted and notional-weighted fraction of investors within each sector that trade at least 50% of their total transaction volume of swaps in a single maturity group. Maturity groups are defined as: below 3 months, 3 months to 5 years, 5 years to 10 years, and 10 years & above. Panel B reports the distribution of the proportion of notional-weighted trades that fall under each investor's own dominant maturity group. Investor-level shares are calculated at legal entity identifier (LEI) level and the distribution is constructed at the sector level. In panel B, "N" refers to the number of unique investors within a sector that traded GBP swaps during our sample period.

Table 4: Changes in Interest Rates and Quantity of Exposures

	Δ Quantity ($ million)			
Panel A: PC1 (3M, 5Y, 10Y, 30Y)	Bank	Fund	PF&I	Corporate
Δ Bond Yield (PC1, t-1)	55.5**	-112.3*	-14.9***	4.15
	(25.4)	(58.2)	(5.21)	(2.65)
Adj. R^2	0.02	0.00	0.01	0.01
Panel B: 30Y yield	Bank	Fund	PF&I	Corporate
Δ Bond Yield (30Y, t-1)	102.9**	-169.1	-24.3***	7.43
	(50.1)	(107.3)	(9.15)	(4.58)
Adj. R^2	0.02	0.00	0.01	0.01
Panel C: 10Y yield	Bank	Fund	PF&I	Corporate
Δ Bond Yield (10Y, t-1)	96.2**	-221.8**	-23.7***	6.11
	(44.3)	(109.9)	(8.66)	(3.97)
Adj. R^2	0.02	0.00	0.01	0.01
Panel D: 5Y yield	Bank	Fund	PF&I	Corporate
Δ Bond Yield (5Y, t-1)	87.3**	-210.7**	-25.4***	6.10
	(39.1)	(98.2)	(8.70)	(4.04)
Adj. R^2	0.02	0.00	0.01	0.01
Panel E: 3M yield	Bank	Fund	PF&I	Corporate
Δ Bond Yield (3M, t-1)	97.8**	-101.0	-32.7***	12.1
	(46.6)	(121.2)	(10.6)	(8.24)
Adj. R^2	0.02	0.00	0.01	0.01
Observations	6,200	9,520	28,400	12,600
Dominant maturity group	3M-5Y	Below 3M	10Y & above	3M-5Y
Investor FE	Yes	Yes	Yes	Yes

Notes: This table reports estimates of a fixed-effects panel regression for the model of the form in Equation 2. The dependent variable is the change in monthly outstanding net position (in $ million) held by an investor within the dominant maturity group of the sector to which it belongs. Dominant maturity groups are: 3 months to 5 years for Bank and Corporate, below 3 months for Fund, and 10 years & above for PF&I. Panel A considers the change in first principal component of 3 month, 5 year, 10 year, and 30 year GBP bond (gilt) yields as the regressor, while panels B, C, D and E individually consider changes in these yields. Regressors are lagged by one month. All columns include investor fixed effects. Standard errors clustered by investor are reported in parentheses. $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.

Table 5: Maturity Groups and Relevant Parameters

	Values
Maturity groups $\tau = 0, 1, ..., 4$	$\{(0, 0.05), [0.05, 0.25), [0.25, 5), [5, 10), [10, \infty)\}$
Ave. maturity $\bar{m}(\tau)$	$\{0.025, 0.15, 2.75, 7.5, 25\}$
Transition prob. $\delta(\tau)$	$\{20, 6.67, 0.38, 0.21, 0.06\}$

Notes: This table summarizes the maturity groups, and the average maturity we use for each maturity group in the calibration.

Table 6: Targeted Moments

Moments	Data
Ave. swap spreads in group 1-4 (spread quoted in %)	[0.108, 0.176, 0.215, -0.375]
Ave. quantity in group 1-4 (100 Billion $)	[2, -7.959, -0.009, 3.278]
Variances of swap spread changes in group 1-4	[0.028, 0.03, 0.105 , 0.058]
Variances of scaled quantity changes in group 1-4	[0.73, 0.476, 0.980, 0.222]
Regression coefficients of scaled quantity changes on the corresponding swap spread changes for group 1-4	[0.493, 0.441, -0.168, -0.188]

Notes: This table summarizes the empirical moments that we target in our calibration. We use monthly data from July 2019 to November 2022. The swap spreads are the volume weighted average swap spreads for a given maturity group. The changes in quantities are calculated according to Equation 17.

Table 7: Calibrated Parameters

Parameters	Values
Arbitrageur risk aversion coeff. a	123.05
Arbitrageur avg. cost $\bar{c}$	7.26×10^{-4}
Demand elasticities α	$[1.51 \times 10^{-2}, 4.55 \times 10^{-5}, 1.14 \times 10^{-8}, 2.73 \times 10^{-7}]$
Demand intercepts θ_0	$[1.23 \times 10^{-6}, 7.925, 0, -3.17]$
Demand sensitivities to aggregate demand factor θ_1	$[1.93 \times 10^{-5}, -1.741, 0, 1.12 \times 10^{-1}]$
Speed of mean reversion Γ	$\begin{pmatrix} 7.16 \times 10^{-4} & 0 \\ 0 & 7.96 \times 10^{-3} \end{pmatrix}$
Variances of supply and demand shocks Σ	$\begin{pmatrix} 3.03 \times 10^{-3} & 1.19 \times 10^{-3} \\ 3.196 \times 10^{-1} & 1.585 \times 10^{-1} \end{pmatrix}$

Notes: This table summarizes the calibrated parameter values in the model.

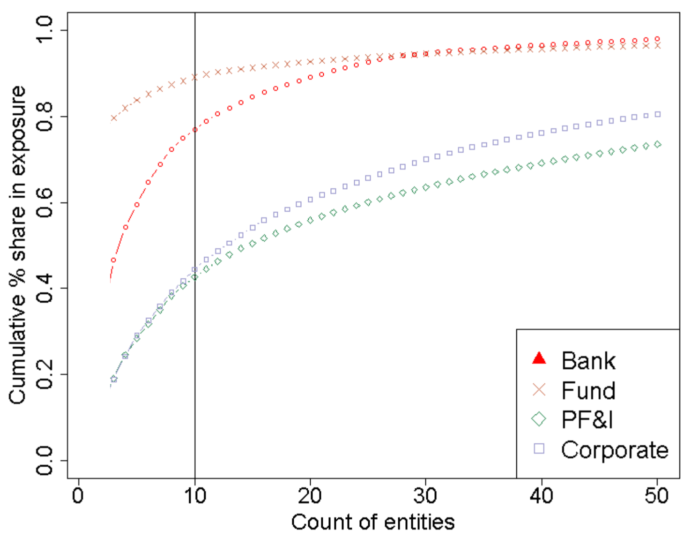
Internet Appendix

“The Market for Sharing Interest Rate Risk: Quantities and Asset Prices”

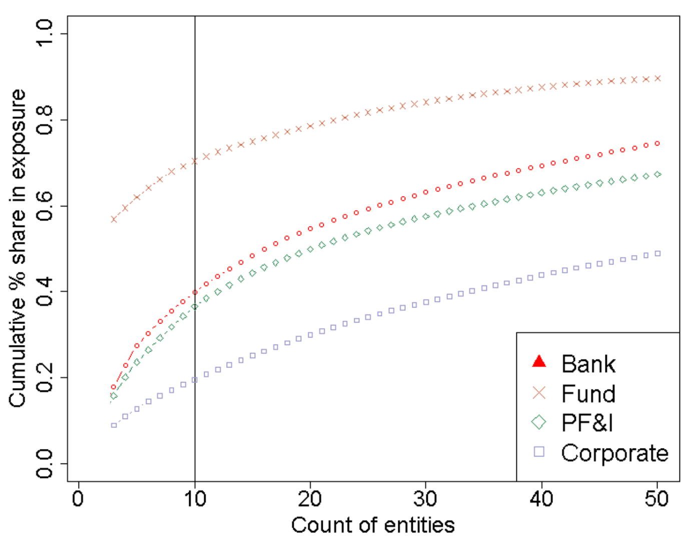
Umang Khetan Jian Li Ioana Neamțu Ishita Sen

March 2024

Figure A1: Concentration in Exposures



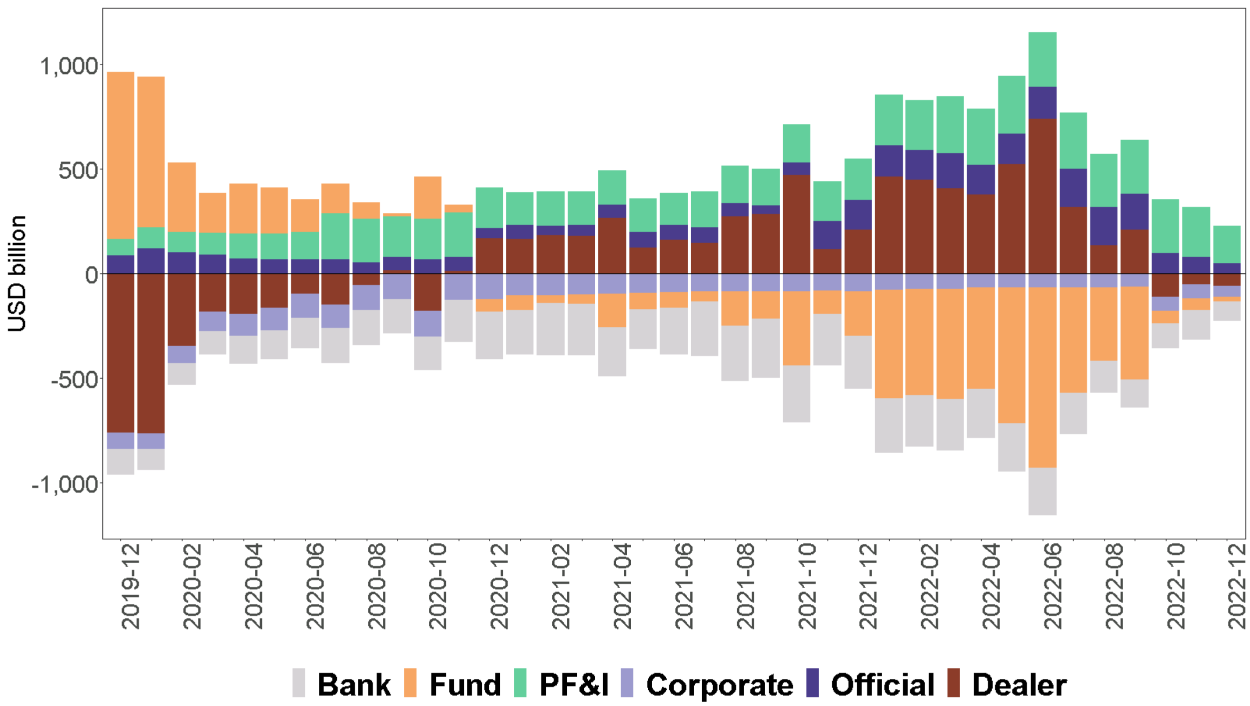
(a) GBP



(b) All currencies

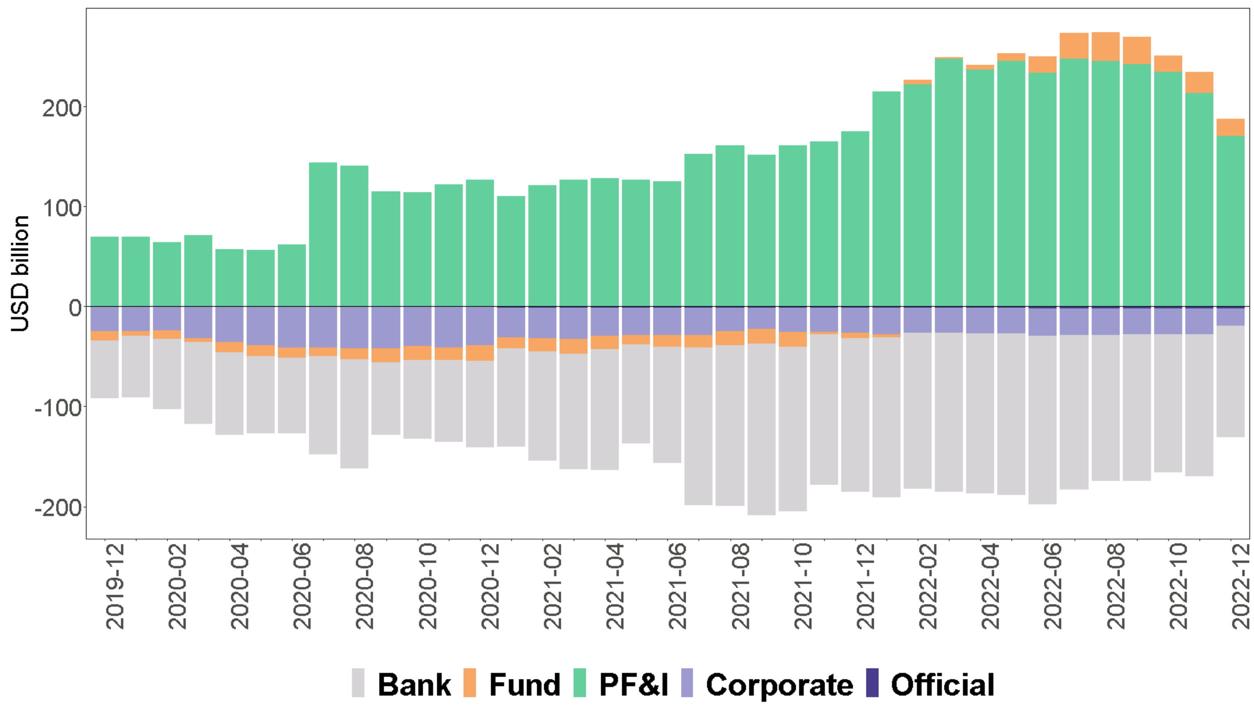
Notes: This figure shows that net exposures are concentrated within a few entities, particularly in the fund sector. The figure plots the cumulative share of net (absolute) position held by top 50 investors within each sector as on February 1, 2022, for GBP swaps in panel (a) and swaps across all currencies in panel (b). Vertical line in black traces the top 10 investors in each sector with their corresponding cumulative share on the y-axis. The first point in both plots shows the share of top 3 entities put together in each sector.

Figure A2: Net Outstanding Positions (All Currencies)



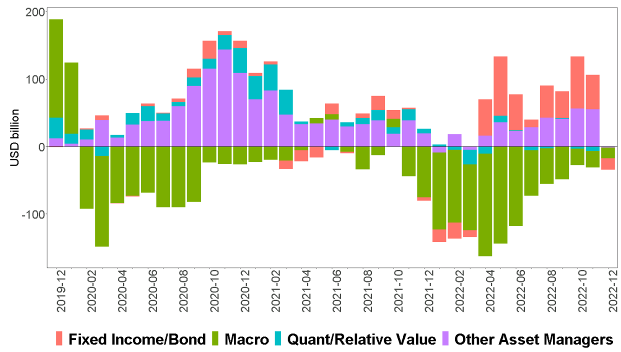
Notes: This figure shows net outstanding positions in $ billion at the start of every month for five end-user sectors and the dealer sector. A positive value on the y-axis indicates a net receive fixed position while a negative value indicates a net pay fixed position. Net outstanding position is calculated as the difference between the outstanding notional values of receive fixed rate and pay fixed rate swaps for each legal entity as per Equation 1, and then aggregated for five end-user sectors: Bank, Fund, PF&I (pensions, liability-driven investment funds, and insurance), Corporate, and Official (sovereign and supra-national institutions). The net outstanding position for the dealer sector is calculated as the opposite side of aggregate end-user positions such that the market clears. This figure considers swaps denominated across all currencies in our sample, while Figure 1 considers GBP swaps.

Figure A3: Net Outstanding Positions (UK entities)

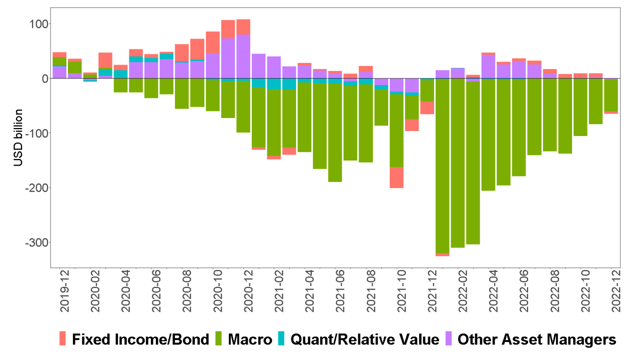


Notes: This figure shows net outstanding positions in $ billion at the start of every month for five end-user sectors, where each entity is located in the United Kingdom (UK). A positive value on the y-axis indicates a net receive fixed position while a negative value indicates a net pay fixed position. Net outstanding position is calculated as the difference between the outstanding notional values of receive fixed rate and pay fixed rate swaps for each legal entity as per Equation 1, and then aggregated for five end-user sectors: Bank, Fund, PF&I (pensions, liability-driven investment funds, and insurance), Corporate, and Official (sovereign and supra-national institutions). This figure considers swaps denominated in British pound sterling (GBP).

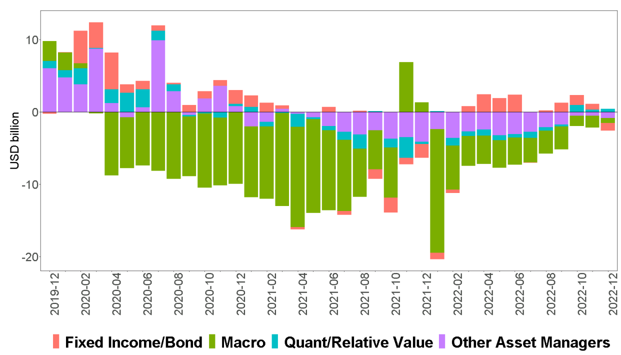
Figure A4: Net Outstanding Positions by Maturity Group and Fund Type



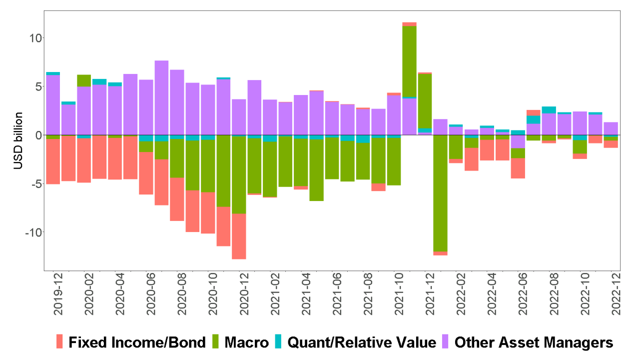
(a) Below 3 months



(b) 3 months to 5 years



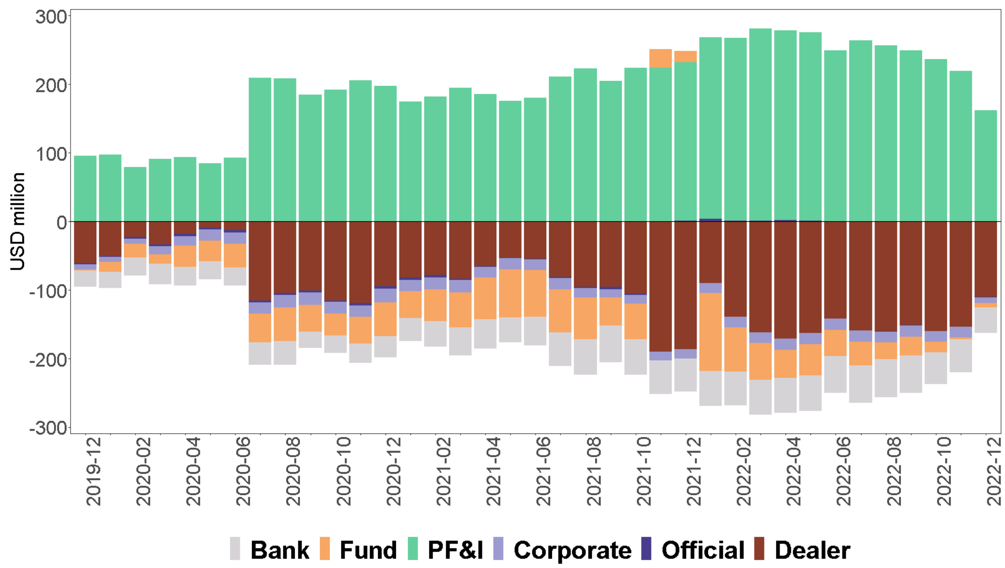
(c) 5 years to 10 years



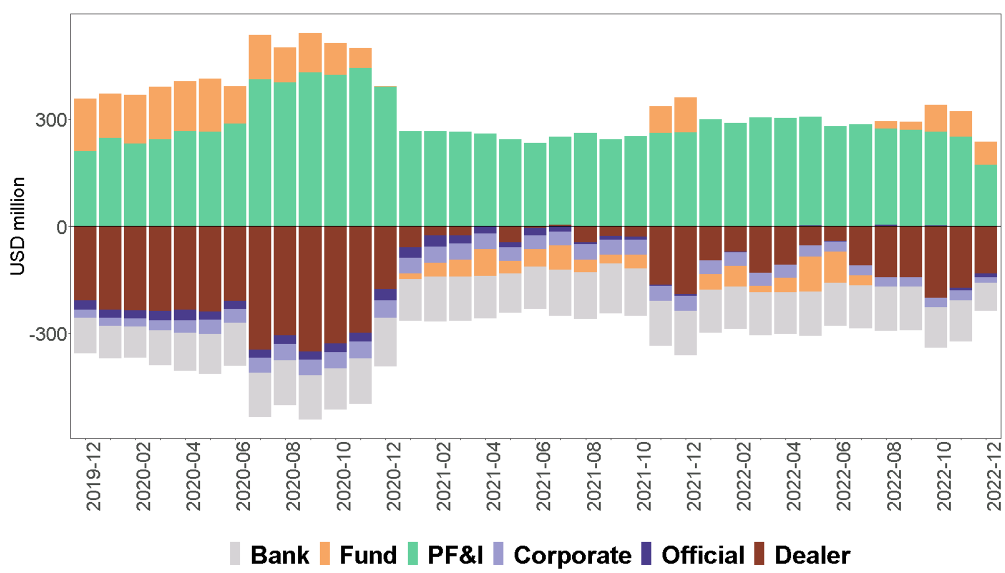
(d) 10 years & above

Notes: This figure shows net outstanding positions in $ billion at the start of every month for four fund types, split by four maturity groups: below 3 months in panel (a), 3 months to 5 years in panel (b), 5 years to 10 years in panel (c), and 10 years & above in panel (d). A positive value on the y-axis indicates a net receive fixed position while a negative value indicates a net pay fixed position. Net outstanding position is calculated as the difference between the outstanding notional values of receive fixed rate and pay fixed rate swaps for each legal entity as per Equation 1, and then aggregated for the four fund types: Fixed Income/Bond, Macro, Quantitative/Relative Value, and Other Asset Managers. We identify fund types at a legal entity level using string matching on their names with common investment strategies.

Figure A5: Net Outstanding DV01



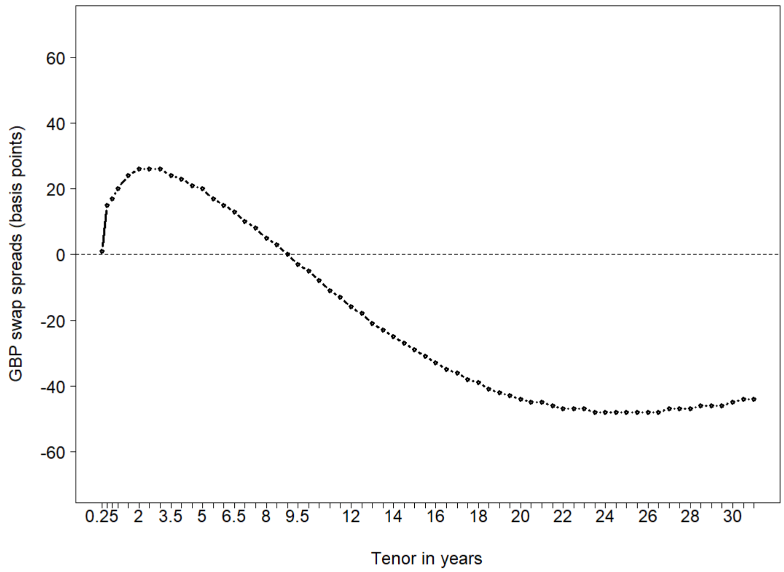
(a) GBP



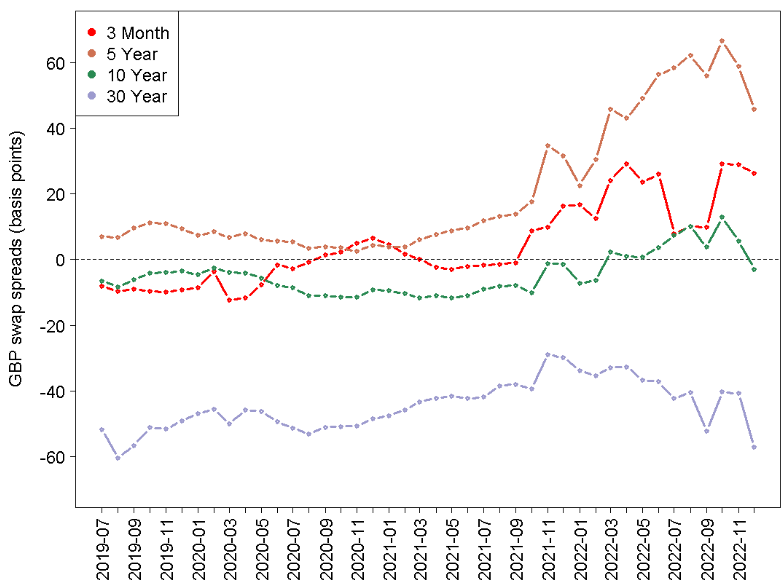
(b) All currencies

Notes: This figure shows net outstanding DV01 in $ million at the start of every month for five end-user sectors and the dealer sector. DV01 refers to the change in dollar value of swaps for one basis point parallel shift in the interest rate curve. A positive value on the y-axis indicates a net positive DV01 (i.e., the value of swap increases with a downward shift in the interest rate curve) while a negative value indicates a net negative DV01. The net outstanding DV01 for the dealer sector is calculated as the opposite side of aggregate end-user positions such that the market clears. Panel (a) represents the net outstanding DV01 for GBP swaps only, while panel (b) considers all currencies in our sample.

Figure A6: Swap Spreads



(a) Average term structure



(b) Time-series

Notes: This figure plots the hump-shaped term structure of GBP swap spreads in panel (a) and the time-series of 3 month, 5 year, 10 year, and 30 year swap spreads in panel (b). Swap spread is defined as the difference between swap fixed rate and the maturity matched bond (gilt) yield. Panel (a) shows the average term structure using 3-monthly maturity intervals up to one year, and 6-monthly thereafter. The underlying data for these plots is sourced from the Bank of England's bond and overnight indexed swap (OIS) database.

Table A1: Estimated Coverage of Transactions Activity

	Average daily turnover in April 2022		
	Our data ($ billion)	BIS benchmark ($ billion)	Coverage
All currencies	3,425	4,987	69%
Pound sterling (GBP)	287	341	84%
Euro (EUR)	1,328	1,688	79%
US dollar (USD)	1,460	2,209	66%
Australian dollar (AUD)	141	279	51%
Other currencies	209	470	44%

Notes: This table reports the estimated coverage of interest rate swap transactions observed in our data using the April 2022 Bank for International Settlements (BIS) over-the-counter interest rate derivatives turnover survey as the benchmark. BIS data can be accessed here. Our sample includes all trades where at least one of the counterparties is a UK entity. We adjust for double counting arising out of the dual reporting of trades with same unique identifier, as well as duplication on account of centralized clearing of trades with different unique trade identifiers. We calculate the adjusted turnover in the month of April 2022 and divide it by 19, the number of trading days in that month. We compare our average daily turnover to the BIS benchmark that includes all interest rate derivatives except options and complex derivatives, and report the estimated share for all currencies put together and for some of the major currency pairs separately.

Table A2: Gross and Net Outstanding Positions by Maturity Group and Fund Type

Panel A	Gross position ($ billion)					
	Below 3M	3M to 5Y	5Y to 10Y	10Y & above	Total	Share
Fixed Income/Bond	164	105	15	6	290	0.18
Macro	343	358	9	4	714	0.45
Quant/Relative Value	146	37	8	4	195	0.12
Other Asset Managers	200	147	23	31	401	0.25
Panel B	**Net receive fixed position ($ billion)**					
	Below 3M	3M to 5Y	5Y to 10Y	10Y & above	Net-to-gross	Share
Fixed Income/Bond	-24	-1	0	0	0.09	0.05
Macro	-108	-310	-6	-3	0.60	0.87
Quant/Relative Value	-5	0	-1	0	0.03	0.01
Other Asset Managers	18	19	-3	1	0.09	0.07

Notes: This table reports the outstanding gross positions (panel A) and net receive fixed positions (panel B) as on February 1, 2022, held within each of the four maturity groups by four fund types: Fixed Income/Bond, Macro, Quantitative/Relative Value, and Other Asset Managers. We identify fund types at a legal entity level using string matching on their names with common investment strategies. The second-to-last column in panel A reports the total position of the fund type across all maturities, and the last column reports the share of each fund type in the overall outstanding gross positions. The second-to-last column in panel B reports the ratio of net position to gross notional for each fund type using positions aggregated across maturity groups, and indicates the extent of two-sided exposures held by each fund type. The last column in panel B reports the share of each fund type in the net (absolute) positions in aggregate across all maturity groups.

Table A3: Share of Transactions by Maturity Group

	Below 3M	3M to 5Y	5Y to 10Y	10Y & above
Bank	8%	70%	18%	4%
Fund	60%	32%	5%	3%
PF&I	5%	24%	18%	53%
Corporate	4%	63%	14%	19%

Notes: This table shows that investors have strong preferred habitats when trading new interest rate swaps. The table reports the share of transaction volume in each of the four maturity groups by four end-user sectors: Bank, Fund, PF&I (pensions, liability-driven investment funds, and insurance), and Corporate. Transaction volume refers to the gross notional of all new GBP swaps executed by entities in these sectors across our sample period.

B. Equilibrium Derivation

To solve the equilibrium, apply Ito's lemma to the equilibrium price Equation 11 and plug in the expression of dg_t in Equation 17, we get the expected return,

$$
\begin{aligned}
dP_t(\tau) =& - A(\tau)^\top P_t(\tau)\left(-\Gamma(g_t - \bar{g})dt + \Sigma dB_t\right) + \frac{1}{2}A(\tau)^\top \Sigma\Sigma^\top A(\tau)P_t(\tau)dt \\
& (A'(\tau)g_t + C'(\tau))P_t(\tau)dt \\
\frac{dP_t(\tau)}{P_t(\tau)} =& - A(\tau)^\top \left(-\Gamma(g_t - \bar{g})dt + \Sigma dB_t\right) + \frac{1}{2}A(\tau)^\top \Sigma\Sigma^\top A(\tau)dt \\
& A'(\tau)g_t dt + C'(\tau)dt
\end{aligned}
$$

Collecting the terms in front of dt, we get

$$
\mu_t(\tau) = A(\tau)^\top \Gamma(g_t - \bar{g}) + \frac{1}{2}A(\tau)^\top \Sigma\Sigma^\top A(\tau) + A'(\tau)g_t + C'(\tau) \tag{22}
$$

Dealer's problem is

$$
\max_{X_t(\tau)} \left[\int_0^\infty X_t(\tau)(\mu_t(\tau) - c_t)d\tau - \frac{a}{2}Var\left(\int_0^\infty X_t(\tau)A(\tau)^\top \Sigma d\tau dB_t\right) \right]
$$

Take first order condition with respect to $X_t(\tau)$, we get

$$
\mu_t(\tau) - c_t = aA(\tau)^\top \Sigma\Sigma' \left[\int_0^\infty X_t(\tau)A(\tau)d\tau \right] \tag{23}
$$

Plug in the expression for $X_t(\tau)$ from the market clearing condition (assuming $K = 1$)

$$
\begin{aligned}
X_t(\tau) = -Q_t(\tau) &= \alpha(\tau)log(P_t(\tau)) + \beta_t(\tau) \\
&= -\alpha(\tau)[A(\tau)g_t + C(\tau)] + \theta_0(\tau) + \theta_1(\tau)\beta_{1,t}
\end{aligned}
$$

Furthermore, plug in the expression for $\mu_t(\tau)$ from Equation 22 into Equation 23. Matching the coefficients in front of g_t, we get Equation 12. Matching the coefficients in front of the constant terms, we get Equation 13.

To get the moments, the average spread for maturity bucket τ is

$$
E[s_t(\tau)] = \left[A(\tau)^\top \begin{pmatrix} \bar{c} \\ 0 \end{pmatrix} + C(\tau) \right] / \tau \tag{24}
$$

The average quantity from the client's perspective for maturity bucket τ is

$$E[Q_t(\tau)] = \alpha(\tau)[A(\tau)^\top \begin{pmatrix} \bar{c} \\ 0 \end{pmatrix} + C(\tau)] - \theta_0(\tau) \tag{25}$$

The change in spread is

$$ds_t(\tau) = \frac{A(\tau)}{\tau} dg_t \tag{26}$$

Hence the variance is

$$Var(ds_t(\tau)) = \frac{A(\tau)^\top}{\tau} Var(dg_t) \frac{A(\tau)}{\tau} \tag{27}$$

We define $\tilde{A}$ to be a $T \times 2$ matrix, where the τth row is $\frac{A(\tau)}{\tau}$.

Plug in

$$dg_t = -\Gamma g_t + \Sigma dB_t \tag{28}$$

$$Var(dg_t) = \Gamma Var(g_t) \Gamma^\top + \Sigma\Sigma^\top \tag{29}$$

$$Var(g_t) = \rho \tag{30}$$

where ρ is the solution to

$$-\Gamma\rho - \rho^\top \Gamma^\top + \Sigma\Sigma^\top = 0 \tag{31}$$

we get the formula for variance of spread changes.

Furthermore, to match the empirical counterpart, we define the change in quantities as the change in Q_t scaled by the absolute average quantity, i.e.,

$$\frac{dQ_t(\tau)}{|E[Q_t(\tau)]|} = \frac{\alpha(\tau)A(\tau)^\top dg_t - (0, \theta(\tau))dg_t}{|E[Q_t(\tau)]|} = \frac{[\alpha(\tau)A(\tau)^\top - (0, \theta(\tau))]dg_t}{|E[Q_t(\tau)]|} \tag{32}$$

The variance of this object is

$$Var\left(\frac{dQ_t(\tau)}{|E[Q_t(\tau)]|}\right) = \frac{[\alpha(\tau)A(\tau)^\top - (0, \theta(\tau))] Var(dg_t) [\alpha(\tau)A(\tau)^\top - (0, \theta(\tau))]^\top}{|E[Q_t(\tau)]|^2} \tag{33}$$

We define $\tilde{M}$ to be a $T \times 2$ matrix, where the τth row is $[\alpha(\tau)A(\tau)^\top - (0, \theta(\tau))]/|E[Q_t(\tau)]|$.

Furthermore, define

$$\Lambda = \begin{pmatrix} \tilde{A} \\ \tilde{M} \end{pmatrix} \tag{34}$$

Hence, the variance-covariance matrix of spread changes and quantity changes is

$$Var\left(\begin{pmatrix} ds_t \\ \frac{dQ_t}{|E[Q_t]|} \end{pmatrix}\right) = \Lambda Var(dg_t)\Lambda^\top = \Lambda \left(\Gamma Var(g_t)\Gamma^\top + \Sigma\Sigma^\top\right)\Lambda^\top \tag{35}$$

C. Maturity Weighted Dealer Funding Cost

Given dealers face higher capital charges for holding securities with larger market risks and long-term swaps are riskier compared to short-term swaps, a reasonable extension is to let arbitrageurs' funding cost c_t vary across maturity buckets. In this section, we allow the funding cost to be different depending on the bucket's average maturity and verify that our main conclusions in the paper do not change.

More specifically, we assume arbitrageur's funding cost is linear in the swap's maturity, i.e. $c_t\tau$, where c_t follows an AR(1) process, and can be correlated with demand side shocks. c_t still characterize the balance sheet condition of the dealer sector at time t. But the cost incurred from taking on swap positions scale linearly with the swap's maturity.

The arbitrageur's change in wealth becomes,

$$dW_t = \int_0^\infty X_t(\tau)\left(\frac{dP_t(\tau)}{P_t(\tau)} - \tau c_t\right) \tag{36}$$

The differential equations characterizing $A(\tau)$ and $C(\tau)$ become

$$\Gamma^\top A(\tau) + A'(\tau) - \begin{pmatrix} \tau \\ 0 \end{pmatrix} - a\left[\int_0^\infty \left(\theta(\tilde{\tau})\begin{pmatrix} 0 \\ 1 \end{pmatrix} A(\tilde{\tau})^\top - \alpha(\tilde{\tau})A(\tilde{\tau})A(\tilde{\tau})^\top\right) d\tilde{\tau}\right]\Sigma\Sigma^\top A(\tau) = 0 \tag{37}$$

$$A(\tau)^\top\Gamma\begin{pmatrix} -\bar{c} \\ 0 \end{pmatrix} + \frac{1}{2}A(\tau)^\top\Sigma\Sigma^\top A(\tau) + C'(\tau) - aA(\tau)^\top\Sigma\Sigma'\int_0^\infty \left(-\alpha C(\tilde{\tau}) + \theta_0(\tilde{\tau})\right)A(\tilde{\tau})d\tilde{\tau} = 0 \tag{38}$$

Table C1: Calibrated Parameters (Maturity Dependent Funding Cost)

Parameters	Values
Arbitrageur risk aversion coeff. a	614.50
Arbitrageur avg. cost $\bar{c}$	-7.72×10^{-5}
Demand elasticities α	$[6.81 \times 10^{-2}, 1.21 \times 10^{-3}, 2.95 \times 10^{-7}, 3.29 \times 10^{-7}]$
Demand intercepts θ_0	$[8.58 \times 10^{-7}, 8.18, 0, -0.975]$
Demand sensitivities to aggregate demand factor θ_1	$[1.17 \times 10^{-5}, -1.665, 0, 3.34 \times 10^{-1}]$
Speed of mean reversion Γ	$\begin{pmatrix} 7.87 \times 10^{-2} & 0 \\ 0 & 3.44 \times 10^{-2} \end{pmatrix}$
Variances of supply and demand shocks Σ	$\begin{pmatrix} 2.71 \times 10^{-3} & 1.4 \times 10^{-3} \\ 2.59 \times 10^{-1} & 1.381 \times 10^{-1} \end{pmatrix}$

Notes: This table summarizes the calibrated parameter values in the model extension, where the dealers face maturity weighted funding costs.

Discretizing the above equations, we get the corresponding equation of Equation 15 and Equation 16

$$\Gamma^\top A(\tau) + [A(\tau) - A(\tau-1)]\delta(\tau) - \begin{pmatrix} \bar{m}(\tau) \\ 0 \end{pmatrix} = a\left[\sum_{\tilde{\tau}} \left(\theta(\tilde{\tau}) \begin{pmatrix} 0 \\ 1 \end{pmatrix} A(\tilde{\tau})^\top - \alpha(\tilde{\tau}) A(\tilde{\tau}) A(\tilde{\tau})^\top \right)\right] \Sigma\Sigma^\top A(\tau) \quad (39)$$

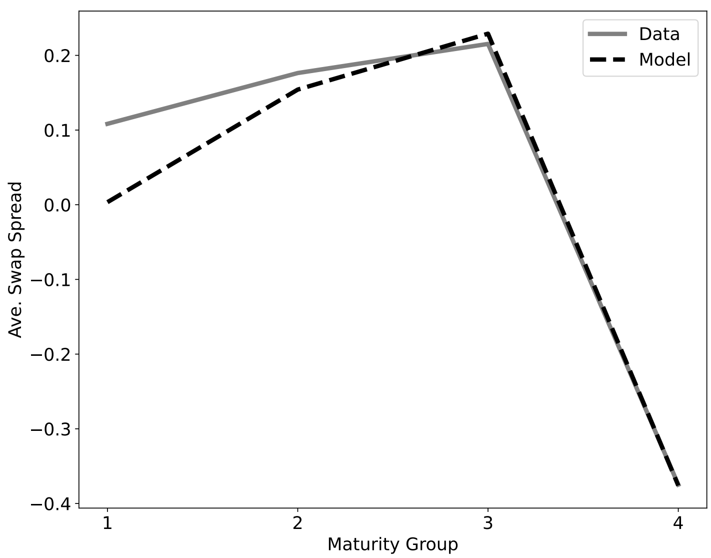
$$A(\tau)^\top \Gamma \begin{pmatrix} -\bar{c} \\ 0 \end{pmatrix} + \frac{1}{2} A(\tau)^\top \Sigma\Sigma^\top A(\tau) + [C(\tau) - C(\tau-1)]\delta(\tau) = aA(\tau)^\top \Sigma\Sigma' \sum_{\tilde{\tau}} \left(-\alpha C(\tilde{\tau}) + \theta_0(\tilde{\tau})\right) A(\tilde{\tau}) \quad (40)$$

where $\bar{m}(\tau)$ is the median maturity in group τ.

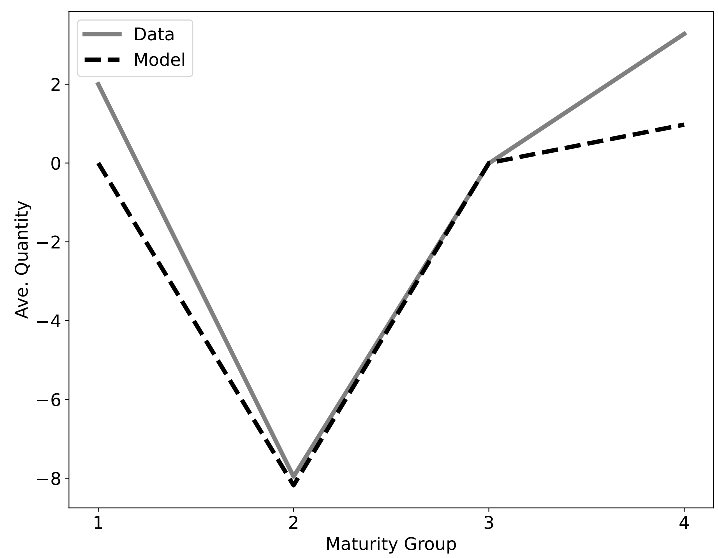
We target the same set of moments as in the main text. The calibrated parameter values are shown in Table Table C1, and comparison between model moments and empirical moments is shown in Figure C1. The match is reasonable on all dimensions but is slightly worse than our baseline calibration.

Same as in the baseline calibration, investors in the 10 year & above bucket demand fixed payments, while investors in the 3-month-to-5-year maturity bucket has a demand for paying fixed rate. The two groups of investors also have the opposite exposure to the aggregate demand factor, same as in the baseline case. The pattern of investor demand elasticity is also similar to before: investors at the long-end have less elastic demand compared to investors at the short-end. Since the maturity-weighted net holding of the dealer sector is negative, the average holding cost $\bar{c}$ is calibrated to be negative, so that the dealer sector bears a positive holding cost on average.

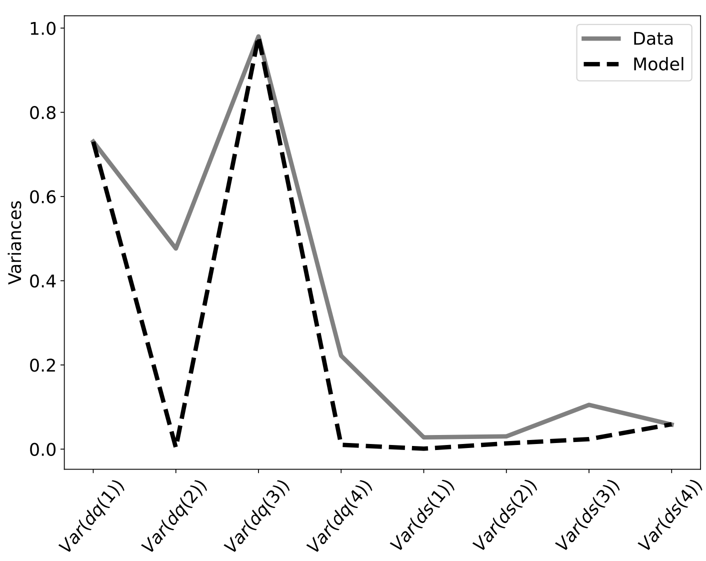
Figure C1: Comparing Model Simulated Moments with Empirical Moments (Maturity Dependent Funding Cost)



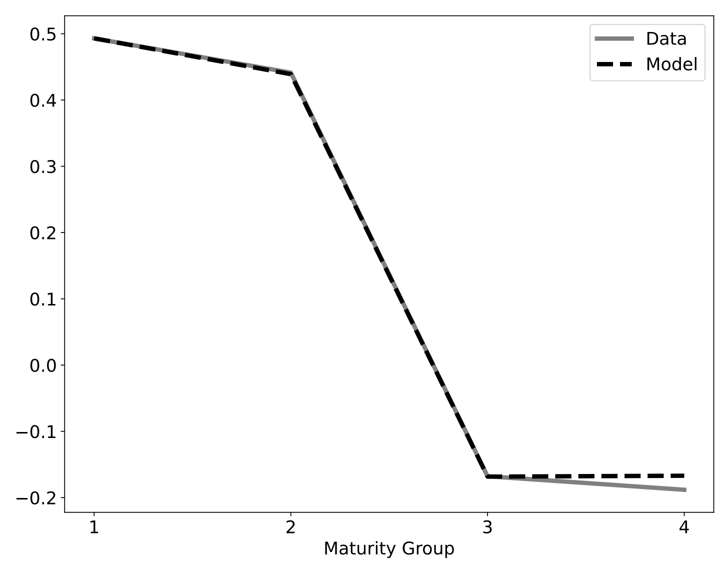
(a) Spread



(b) Quantity



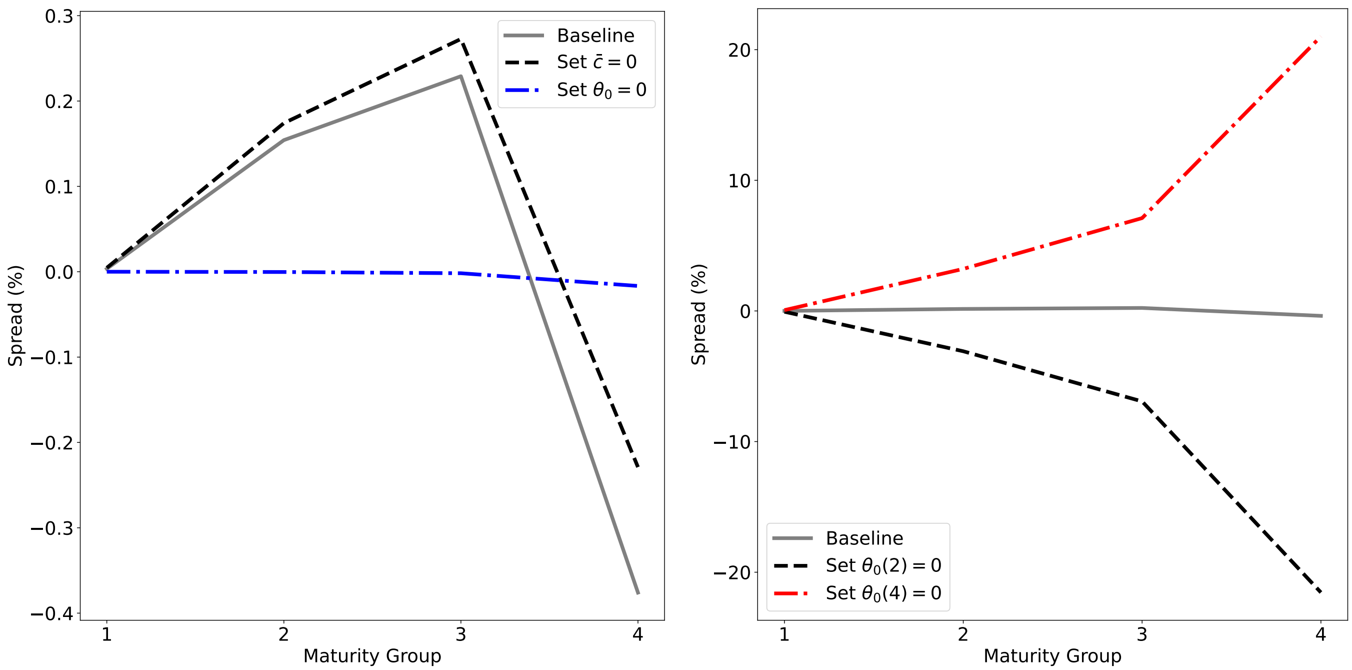
(c) Variance



(d) Reg. Coeff. of dq on ds

Notes: This figure compares the model simulated moments with the corresponding empirical moments from the data. All the spreads and yields are quoted in percentage terms. Quantities are in unit of $100 billion.

Figure C2: Decomposing Supply and Demand Factors (Maturity Dependent Funding Cost)



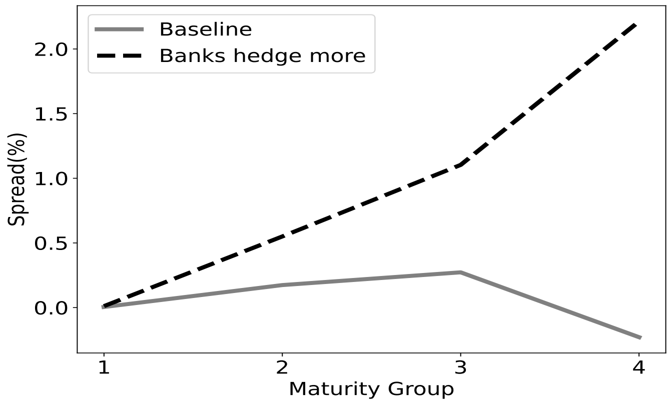
(a) (b)

Notes: This figure plots the average swap spreads for different scenarios. In panel (a), we start with the baseline swap spreads, then we set $\bar{c} = 0$ and recalculate the swap spreads in equilibrium. Next, we set $\theta_0(\tau) = 0$ for all τ. In panel (b), we set $\theta_0 = 0$ for one group at a time and recalculate the equilibrium swap spreads. Spreads are quoted in percentage terms.

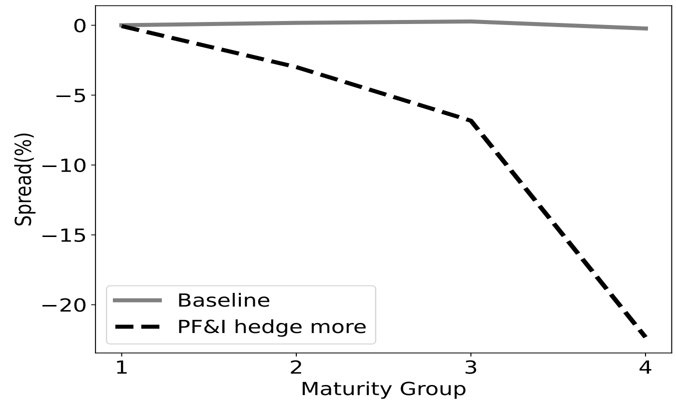
We find that demand imbalances interacted with high degree of dealer risk aversion still plays a quantitatively more important role than dealers' holding cost c_t. In Figure C2, we perform an analysis similar to that in the main text. We first set $\bar{c} = 0$, and see what is the counterfactual swap spread curve, and then set $\theta_0 = 0$ for all the maturity buckets. Since $\bar{c}$ is negative in this calibration, setting it to 0 brings the swap spread curve upward, and the average effect is only 5 bps. However, once we set θ_0 to 0 for all the maturity buckets, the swap spread curve almost become flat and close to 0, suggesting that the demand pressure affects the equilibrium swap spreads significantly. We also verify that switching off the demand pressure group by group also generates large changes in the swap spread curve.

To highlight the opposite demand from the banking sector and the PF&I sector, we repeat the two counterfactual analysis related to demand imbalances. First, we increase the average demand pressure from banks and PF&I respectively as in the main text. The results are shown in Figure C3 and are qualitatively similar to Figure 8. An increase in hedging demand from the banking sector (PF&I) reduces the hedging cost for the PF&I (banking sector). Quantitatively, the effects are larger than in the baseline calibration. As in the main

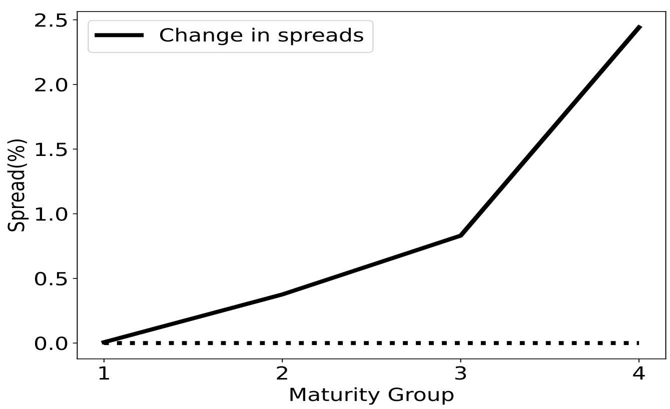
Figure C3: Counterfactual Analysis on Demand Pressure (Maturity Dependent Funding Cost)



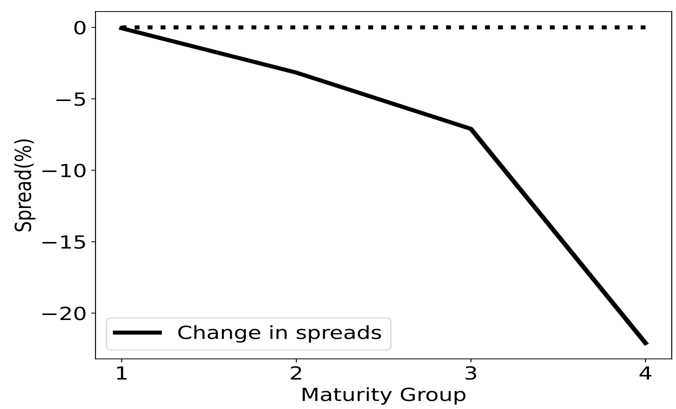
(a) Banks Hedge More



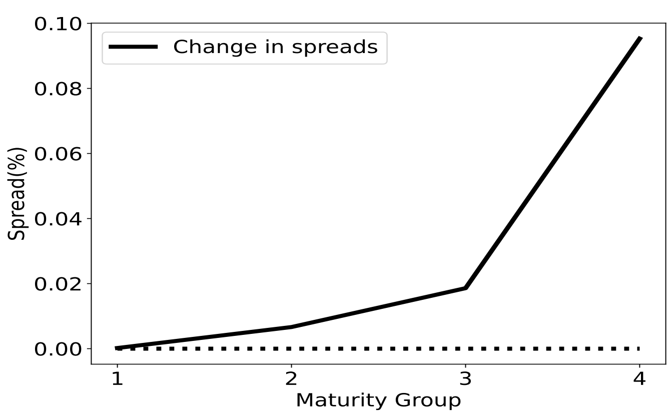
(b) PF&I Hedge More



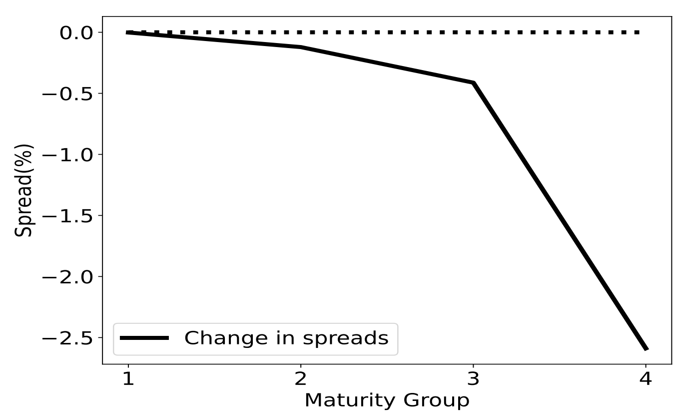
(c) Banks Hedge More



(d) PF&I Hedge More



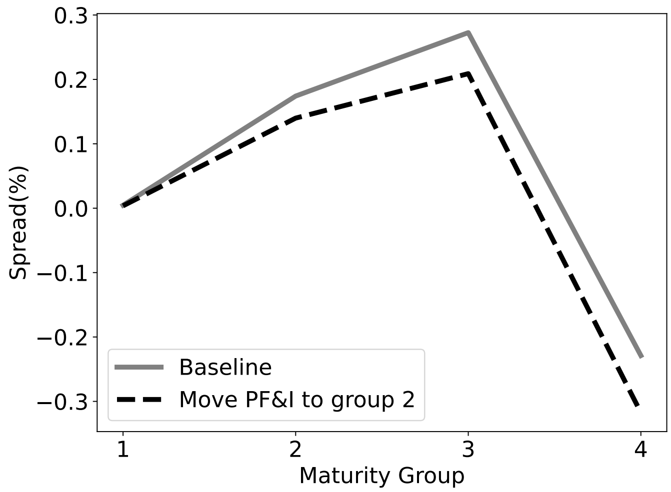
(e) Banks Hedge More (Elastic Demand)



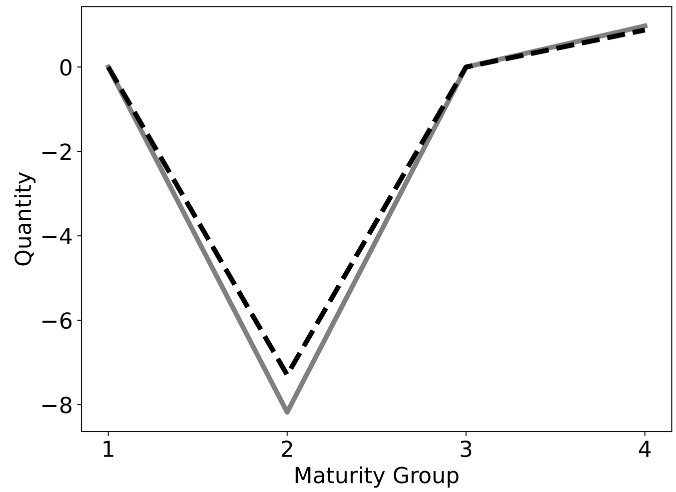
(f) PF&I Hedge More (Elastic Demand)

Notes: Panels (a) and (b) plot the counterfactual swap spreads when $\theta_0(2)$ is higher by one unit and $\theta_0(4)$ is lower by 1 unit respectively. Panels (c) and (d) plot the changes in spreads respectively. Panels (e) and (f) plot the changes in spreads for the two counterfactuals when demand for all sectors are 10 times more elastic.

Figure C4: Counterfactual Analysis on Market Integration (Maturity Dependent Funding Cost)



(a) Spread



(b) Quantity

Notes: This figure considers the counterfactual in which we move 10% of the demand in group 4 to group 2. For group 1 and 3 we do not change the demand parameter. For group 2 and 4, we adjust the demand parameters according to Equation 18 through Equation 21.

text, changes in demand from the PF&I sector leads to larger changes in the swap spreads compared to changes in demand from the banking sector. Regardless of where the demand change occurs, the effect on the equilibrium swap spread monotonically increases with maturity. Finally, if investors have more elastic demand, the effects on swap spreads will be smaller. Second, we consider a more integrated market. We move 10% of demand in group 4, the maturity group of PF&I, to group 2, the maturity group of banks. We adjust the demand parameters according to Equation 18 through Equation 21 in the main text. As before, allocating part of PF&I's demand to the same maturity bucket as banks improves netting, reduces swap spreads as well as dealer sector's net position in all maturity buckets.