A Danish Fix for U.S. Mortgage Lock-in?*

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Abstract

We study Danish fixed-rate mortgage contracts, which are similar to those in the United States except that borrowers may repurchase their mortgages at market value. Using Danish administrative data, we show that households actively buy back debt when mortgage prices fall below par and that household mobility is largely insensitive when existing mortgage rates are below prevailing market rates — unlike in the United States, where moving rates fall sharply as rates rise. We develop an equilibrium model that explains these patterns and show that introducing a repurchase-at-market option into U.S. mortgages substantially reduces interest-rate-induced lock-in with limited effects on equilibrium mortgage rates.

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1 Introduction

Recent increases in interest rates have exposed a central friction in fixed-rate mortgage markets. In the United States, borrowers holding mortgages with coupons below market interest rates face strong incentives to remain in their homes, even when moving would otherwise be optimal. Because fixed-rate mortgages ("FRMs") must be prepaid at par, households that move or refinance after rates rise forfeit the embedded value of their low-rate debt. This mechanism generates a pronounced "lock-in" effect (Quigley, 1987; Fonseca and Liu, 2024): household mobility and refinancing activity decline sharply in high-rate environments, with important implications for labor mobility, housing allocation, and monetary transmission. Despite its macroeconomic relevance, there is limited empirical evidence on how alternative mortgage contract designs might mitigate rate-induced lock-in while preserving the benefits of fixed-rate borrowing.

We address this question using the Danish fixed-rate mortgage market. Danish FRMs are similar to U.S. contracts — thirty-year, fully amortizing, freely prepayable at par — but differ in one crucial respect: borrowers may also repurchase their outstanding mortgage at market value at any time. This buyback right allows households to realize capital gains when mortgage prices fall, rather than forfeiting them upon moving or refinancing. Using comprehensive Danish administrative data, we study how this contractual feature shapes refinancing and moving decisions over the interest-rate cycle. To interpret the empirical patterns, we develop an equilibrium model of household mortgage choice that incorporates buyback rights, refinancing frictions, and the tax treatment of mortgage interest and capital gains. This framework allows us to isolate the mechanisms through which contract design affects household refinancing and moving behavior and to conduct counterfactual experiments for the U.S. mortgage market.

We document three main findings. First, Danish households actively repurchase their mortgages when market prices fall below par, monetizing the embedded value of their debt and refinancing at higher interest rates. Second, household mobility in Denmark is largely insensitive to the fact that existing mortgage rates are below prevailing market rates, in stark contrast to the United States, where moving rates decline sharply as rates rise above outstanding coupons. Third, our model shows that these patterns arise from the interaction of buyback rights with refinancing frictions and tax incentives. Counterfactual experiments indicate that introducing a Danish-style buyback option into U.S. fixed-rate mortgages would substantially reduce interest-rate-induced lock-in, preserving household mobility with only modest effects on equilibrium mortgage rates. Our results suggest that contract design plays a central role in shaping household responses to interest-rate shocks.

Our empirical analysis uses comprehensive administrative microdata covering the universe of Danish households from early 2010 to early 2024. We define a prepayment as any event in which a household fully retires its outstanding mortgage balance, whether at par or at market value; we sometimes refer to such events as buybacks. Prepayments arise mainly through two distinct channels: (i) moves, in which the household sells its property and relocates, and (ii) refinancings, in which the household remains in the same property but replaces the existing mortgage with a new loan.

The data reveal three core facts. First, consistent with standard refinancing incentives and with U.S. evidence (Berger et al., 2021), refinancing hazards increase sharply when the market yield prevalent at the time of mortgage origination exceeds the current market yield by 50-100 basis points ("bps"). Danish borrowers actively exercise their par prepayment option, refinancing into lower rates with minimal delay. Second, refinancing hazards also rise markedly when yield gaps[1] — defined as the difference between the mortgage market yield prevailing when a household originated its mortgage and the contemporaneous mortgage market yield — fall below -150 bps. This increase reflects widespread discounted buybacks, whereby households repurchase mortgages below par to realize embedded capital gains and refinance into higher rates. Such behavior is largely absent in the United States, where refinancing activity almost entirely disappears once market rates exceed existing coupons. This contrast raises a central question: why do Danish households optimally replace low-coupon, discounted debt with higher-coupon debt issued near par? Third, and most strikingly, Danish moving hazards are nearly flat across negative yield gaps: households move at similar rates regardless of how far market yields exceed those prevalent at the time mortgages were originated. In the United States, Fonseca and Liu (2024) estimate that a 100 bps decrease in the coupon gap (a close analog to our yield gap measure) reduces annual moving rates by 57-120 bps; in Denmark, the corresponding effect is economically negligible. The buyback right allows Danish households to move without forfeiting embedded capital gains, effectively eliminating the mortgage lock-in channel. All results are robust across both nonparametric and parametric specifications and to alternative sets of controls. Moreover, to facilitate comparisons with the existing mortgage lock-in literature, we replicate our analysis using the conventional household-specific coupon gap instead of our yield-gap measure. The resulting estimates are quantitatively and qualitatively

[1] As Section 3.3 will make clear, our yield gap measure is a close, but distinct, analog to the coupon gap measure frequently used in the mortgage lock-in literature, and defined as the difference between a mortgage's coupon and the current market interest rate.

similar, indicating that our conclusions are not driven by the choice of mortgage incentive measure.

These findings carry immediate macroeconomic relevance. In the U.S., the sharp rate increases of 2022-2023 have frozen housing market activity, with mobility and refinancing at multi-decade lows. Our Danish evidence demonstrates that an alternative institutional design — one that allows borrowers to repurchase their debt at market value — can sustain mobility even in a rising-rate environment, effectively delinking household decisions from the vintage of their existing mortgage.

To rationalize these patterns, we develop an equilibrium model of the Danish FRM market. Households hold prepayable mortgages and periodically receive opportunities to refinance or move, subject to fixed costs. When given an opportunity, a household may (i) prepay at par and refinance or move at the prevailing market rate, (ii) repurchase its mortgage at market price and refinance or move, or (iii) remain inactive. The key institutional distinction from the U.S. is the ability to repurchase debt at market value. Mortgage interest is tax-deductible, creating an incentive to refinance into higher-coupon, par-priced mortgages when rates rise: the larger coupon increases future tax deductions. The resulting trade-off — between prepayment costs and enhanced tax shields — resembles the classic trade-off theory of corporate capital structure (Leland, 1994), applied to household debt. The model predicts refinancing hazards that are "U"-shaped in yield gap, decreasing for negative gaps and increasing for positive ones, and moving hazards that are nearly flat across negative gaps, consistent with our empirical findings.

While our theory emphasizes the role of mortgage interest deductibility, the empirical patterns admit an alternative interpretation. Discounted buybacks may also reflect heterogeneity in households' beliefs about the persistence of interest rate shocks. To explore this possibility, we extend the model to allow households to hold subjective expectations that deviate from market-implied beliefs. When households expect interest rates to decline sooner than the market anticipates, they repurchase discounted mortgage debt more aggressively, intending to refinance again at lower rates in the future. Empirically, both channels may be operative, and discounted buybacks in Denmark are likely shaped jointly by tax incentives and households' rate expectations.

We use the model to evaluate the implications of introducing Danish-style buyback rights into U.S. mortgages. Under the current U.S. system, both moving and refinancing rates decline sharply when market rates rise above outstanding coupons. Allowing borrowers to repurchase at market value largely eliminates the moving distortion, preserving household mobility throughout the rate cycle. Refinancing at negative yield gaps remains muted, however, because U.S. tax law offers weaker mortgage interest deductibility and taxes capital gains from debt forgiveness. Strengthening refinancing rates in that case would require modifications to the U.S. tax code. Despite these institutional differences, the equilibrium mortgage rate in the U.S. with a repurchase-at-market option is on average only 18 bps higher than under the current system. The intuition is simple: under the current U.S. system, the only prepayments when yield gaps are negative come from movers, who must prepay at par — a windfall to investors holding mortgages trading at a discount, thereby lowering mortgage rates when mortgage markets are competitive. Repurchase-at-market rights eliminate this windfall, but because such moves are infrequent, the effect on equilibrium rates is modest. Importantly, the pricing effect is state dependent and operates in a direction that mitigates affordability concerns. The cost of the repurchase-at-market option is highest when mortgage rates are low and lowest when rates are high—precisely when affordability pressures are greatest. As a result, the Danish system would enhance borrower flexibility and mobility while having only limited effects on equilibrium mortgage rates and housing affordability.

Introducing a repurchase-at-market option in the U.S. would require institutional adaptation. In the agency market, it would involve either (i) a modification of the prepayment terms embedded in agency MBS so as to allow borrowers to prepay the lesser of par or market value (and a corresponding adjustment to the GSE guarantee terms), or (ii) the ability for borrowers to repurchase, via brokers, the exact MBS in which their mortgage resides and the subsequent cancellation of such mortgage, alongside the principal reduction of the MBS pool. In the jumbo market, it would require accounting and regulatory adjustments that align banks' balance sheet valuations with market prices, removing disincentives to accept discounted repayments. These changes compare favorably to the main alternatives: assumability and portability rely on discretionary lender approval and complex coordination, and have seen negligible take-up in both U.S. government-backed programs and Denmark despite being formally available — revealed preference evidence that these mechanisms face severe practical frictions. Buyback rights, by contrast, are contractually self-executing at observable market prices and operate through existing refinancing infrastructure. We discuss implementation in detail in Section 5.

Related literature. Our paper contributes to work on mortgage lock-in and household mobility (Quigley, 1987, 2002; Ferreira, Gyourko and Tracy, 2010; Fonseca and Liu, 2024; Liebersohn and Rothstein, 2025; Batzer et al., 2024; Aladangady, Krimmel and Scharlemann, 2025). These studies document that U.S. FRM borrowers face constraints when market rates rise, with implications for geographic mobility, monetary transmission and house price dynamics. We show that such frictions stem from specific prepayment rules — the requirement that prepayments occur at par — rather than from fixed-rate contracts per se. We also contribute to the literature on mortgage contract design (Campbell, Clara and Cocco, 2021; Guren, Krishnamurthy and McQuade, 2021; Fonseca, Liu and Mabille, 2024) by highlighting transactional flexibility as a distinct dimension with first-order implications for household responses to interest rate shocks.

Our theoretical contribution connects household finance to the trade-off theory of corporate capital structure (Miller, 1977; Leland, 1994). Households in our model face an analogous decision to firms choosing leverage: whether to retain low-coupon debt or refinance into higher-coupon debt that increases the tax shield. This parallel provides a foundation for understanding when discounted mortgage repurchases arise as optimal. We also draw on the literature on heterogeneous beliefs (Harrison and Kreps, 1978; Scheinkman and Xiong, 2003): households who view high rates as temporary repurchase discounted debt more aggressively, even absent tax incentives.

The paper most closely related to ours is Svenstrup and Willemann (2006), who study the introduction of a Danish-style buyback option in the U.S. mortgage market. Using a two-factor pricing model with stochastic interest rates and house prices, they conclude that the option would reduce the credit premium charged by the GSEs by about 5 bps while increasing borrower coupon rates by roughly 50 bps per year. Their analysis highlights two key channels through which the buyback option creates value: it reduces credit risk by providing underwater borrowers an alternative to default and mitigates rate-induced lock-in.

Our paper differs in several important respects. First, we bring data to bear on the question. Using Danish administrative microdata, we document how buyback rights are used in practice and how they affect household mobility — providing empirical discipline absent from earlier work. Second, our model features households that optimally choose when to move, refinance, or repurchase their mortgage, rather than relying on reduced-form prepayment and default hazards. This distinction is quantitatively important because the cost of the buyback option depends on how frequently borrowers move when rates are high and how moving rates vary with coupon gaps. In contrast to the constant moving intensity assumed in the PSA-style specification of Svenstrup and Willemann (2006), we estimate lower and state-dependent moving rates, which leads them to obtain a larger option cost than we do. Third, while their analysis evaluates the option value at a single point in the interest-rate state space, we compute equilibrium mortgage rates across the ergodic distribution of interest rates and show that the option cost is strongly state dependent — highest when rates are low and negligible when rates are high. Finally, because our framework is an equilibrium model with endogenous household behavior, it allows us to conduct counterfactual policy experiments that lie beyond the scope of a pricing model.

The remainder of the paper proceeds as follows. Section 2 describes the Danish mortgage market. Section 3 presents our empirical analysis. Section 4 develops the equilibrium model and counterfactual calculations. Section 5 discusses U.S. implementation and alternative mechanisms. Section 6 concludes.

2 Institutional details

The Danish mortgage market is one of the most sophisticated and stable capital-market-based housing finance systems in the world. It combines features familiar to U.S. observers — most notably, the widespread use of long-term fixed-rate prepayable mortgages — with several important institutional differences that we describe below. Greater details can be found in Frankel et al. (2004) and Berg, Nielsen and Vickery (2018).

2.1 Balance principle

Danish mortgage lending is conducted almost exclusively by specialized mortgage banks, which finance their loans by issuing covered bonds under a "balance principle." Each mortgage loan is matched by the issuance of a corresponding bond with identical cash flows, ensuring that the mortgage bank bears no interest rate or prepayment risk. Payments from borrowers are passed through directly to bond investors. The mortgage bank retains ownership of the loans and bears credit risk, but these risks are mitigated by conservative regulation — loan-to-value limits (80% for owner-occupied homes), full recourse against borrowers, and efficient foreclosure procedures. The mortgage bank also charges a separate credit fee to bear such risk. This institutional design has historically produced very low credit losses, even during housing downturns.

2.2 Fixed-rate mortgages and par prepayment

In Denmark, approximately half of all mortgages are 30-year fixed-rate, fully amortizing loans with a par prepayment option.[2] In contrast to the U.S., where mortgage rates are

[2] Figure A-1 reports, year by year in our microdata, the number of fixed-rate and adjustable-rate mortgages. Over our sample period, approximately 48% of all mortgages are fixed-rate. The remaining loans are classified as adjustable-rate mortgages ("ARMs"). In the Danish context, this category includes mortgages with an initial fixed-rate period ranging from 1 to 5 years, after which the interest rate resets at

quoted on a nearly continuous scale, Danish FRM borrowers choose among a discrete set of coupon rates, typically spaced 50 bps apart. At origination, borrowers generally select the highest coupon for which the corresponding covered bond trades slightly below par, so that mortgage proceeds are received at a small discount relative to the mortgage's face value. Mortgage loans originated by the same mortgage institution with the same coupon and maturity are pooled into common covered-bond series, allowing prepayment risk to be shared across a large number of borrowers and creating deep and liquid secondary markets for Danish mortgage bonds. Borrowers can refinance at any time without penalty, and capital-market investors in Danish covered bonds — much like investors in U.S. agency mortgage-backed securities (thereafter, "MBS") — bear prepayment and interest rate risk but not credit risk. Both systems rely on deep secondary markets that distribute these risks to a broad investor base. This shared funding model helps explain why Denmark and the U.S. belong to a very small set of countries where long-term, freely prepayable fixed-rate mortgages (thereafter, "FRMs") are widely available.

2.3 The distinctive Danish innovation: repurchase at market value

The key institutional difference between the Danish and U.S. systems lies in how mortgages can be extinguished when interest rates rise. In Denmark, a borrower may repurchase the outstanding mortgage by buying the corresponding covered bonds in the secondary market and delivering them to the lender. Because bond prices fall when rates rise, this allows the borrower to retire the debt below par — effectively realizing a capital gain. U.S. borrowers, by contrast, can only prepay at par and are subject to "due-on-sale" clauses that require repayment upon property transfer.[3][4] As we will show in our paper, this "repurchase-at-market-value" feature has far-reaching implications. It prevents borrowers from being trapped in below-market-rate loans when interest rates increase, facilitating housing mobility and reducing allocative inefficiencies. Conversely, in the U.S. system, rising rates reduce housing turnover, mortgage refinancing, and moving rates (Fonseca and Liu, 2024).

prevailing market rates (so-called "flex" loans). A subset of these ARMs also feature interest-only repayment during the initial period.

[3] As with FHA mortgages in the U.S., the Danish mortgage system permits loan assumption by a homebuyer, potentially reducing lock-in effects (Berg, Nielsen and Vickery, 2018). We show in Section 5.2, however, that assumptions occur at negligible frequency relative to discounted mortgage repurchases.

[4] Another difference is that Danish households can generally refinance irrespective of home equity or credit conditions, whereas U.S. refinancing typically remains subject to underwriting requirements.

2.4 Taxation

The tax treatment of mortgage interest and of capital gains realized by Danish households upon discount repurchases are the last institutional elements discussed in this section. These features are essential, as they help rationalize why Danish households may find it optimal to repurchase low-coupon, discount mortgages and refinance them with higher-coupon, par-priced mortgages when interest rates rise. In both the U.S. and Denmark, mortgage interest is tax-deductible, subject to specific limitations. In Denmark, mortgage interest is classified as "negative capital income" and, since 2002, has been subject to an effective flat tax rate of 33% (Gruber, Jensen and Kleven, 2021). In the U.S., following the Tax Cuts and Jobs Act of 2017 (hereafter "TCJA"), mortgage interest remains deductible for households that itemize, but only for interest payments on mortgage principal up to USD 750,000 (Ambrose et al., 2022; Scharlemann and Van Straelen, 2024).[5] Finally, while gains realized by Danish households from repurchasing mortgages at a discount are not taxable, the corresponding tax treatment in the U.S. — if such discount repurchases were feasible for fixed-rate mortgage borrowers — is less clear. Such gains could be treated as cancellation-of-indebtedness income and therefore taxed as ordinary income,[6] or alternatively as capital gains, analogous to the profits earned by investors who short fixed-income securities and subsequently close these positions at lower prices. In either case, gains generated by discount repurchases would likely be taxable under current U.S. tax law.

3 Empirical analysis

3.1 Data sources and sample selection

The microdata used in this paper comes from various governmental institutions, but is made available to us by Statistics Denmark.[7] We observe the entire Danish population

[5]Households may deduct mortgage interest, charitable contributions, and state and local taxes (up to a statutory cap). When these itemized deductions exceed the "standard deduction," households benefit from itemizing rather than claiming the standard deduction, which amounts to USD 31,500 for married couples filing jointly in 2025.

[6]Exceptions include debt discharged in bankruptcy, which is generally excluded from taxable income, and mortgage debt canceled in connection with foreclosure, which may generate either ordinary income or capital gains depending on whether the debt is recourse or non-recourse.

[7]Mortgage data from 2012 and onward is collected from mortgage institutions by the Danish Central Bank. We are grateful to FinansDanmark for providing us with mortgage data from 2009 to 2011. Income and wealth data is from the Danish tax authorities and demographic data are from the central Danish population register (CPR). Mortgage bond prices are from Værdipapircentralen, but provided to us by the Danish Central Bank, and yield data is from FinansDanmark's public database.

at the beginning of each year, from early 2010 until early 2024.[8] Since we have data on the exact date of various events,[9] for some of our analysis we are able to convert our yearly panel data into a monthly panel data. The unit of observation for our analysis is thus either a household-year or a household-month. While we present most of our main results for household's *primary mortgage* — defined as the largest mortgage per household, measured by its face value at the beginning of that year — our results are robust to including all mortgages for each household in our sample.[10]

In our data, we identify a mortgage prepayment as the disappearance of a loan from a household's balance sheet. We measure refinancing activity when a household prepays an existing mortgage and originates a new mortgage within the same or the next calendar year. Household moving is identified using changes in registered residential addresses.[11]

The data cover nearly 3 million Danish households per year, corresponding to slightly more than 7 million unique households across the entire sample period. With an average homeownership rate of about 50%, we identify close to 1.5 million homeowners per year and almost 3 million unique homeowners across the full period.[12]

Conditional on being a homeowner, Table 1 reports descriptive statistics for our sample in 2010, in 2023, and for the pooled household-year observations. Over the sample period, 23% of homeowners own their house free and clear of any debt, while 37% have an FRM, and 40% have an ARM. The average maturity of FRMs (resp. ARMs) at origination is 27 years (resp. 29 years), and the average fixed coupon for FRM borrowers is 3% while the average mortgage yield at origination is 3.31%. The fact that the average mortgage yield at origination slightly exceeds the average mortgage coupon reflects the

[8] The data is originally recorded at year-end; however, we restructure it so that the end-of-year values serve as the beginning-of-year data for the subsequent year.

[9] Specifically, we have the date at which a household takes on a new mortgage, buys a new property and changes address.

[10] 70-80% of mortgage borrowers have only 1 mortgage outstanding at a point in time, while 15-20% of mortgage borrowers have 2 mortgages outstanding at a point in time. See Figure A-2 for the distribution of "number of mortgages" for households with an outstanding mortgage at the beginning of each year, from 2010 to 2024.

[11] Our analysis focuses on the households' primary mortgage, defined as its largest outstanding loan. As a result we can have that households move without prepaying their primary mortgage. This would be the case if the primary mortgages is linked to a secondary home, while the household moves primary residence. Accordingly, prepayment, refinancing, and moving are related but distinct decisions in the data.

[12] Our estimate of home ownership (50%) is lower than the 60% reported by Eurostat and in the publicly available tables from Statistics Denmark (Statistikbanken.dk). This discrepancy can be attributed to differences in measurement: Eurostat relies primarily on survey data, whereas the Statistics Denmark figures are derived from individuals rather than households. When home ownership is instead calculated as the proportion of dwellings occupied by their owners, using publicly available Statistics Denmark data (BOL104), the resulting estimates are closely aligned with ours.

institutional convention that Danish FRMs are originated with coupons chosen from a discrete set of rates, typically spaced 50 bps apart, and with the corresponding mortgage bonds issued at a small discount to par (see Section 2.2). Consequently, the par prepayment option is initially slightly out of the money.

In our data over our sample period, unweighted average refinancing rate for FRM (resp. ARM) borrowers is equal to 14% per year (resp. 6% per year), while these statistics are equal to 18% and 6% respectively when we weight by mortgage face value, suggesting that FRM borrowers who refinance are typically those with larger mortgage face values. Unweighted average moving rate for FRM (resp. ARM) borrowers is equal to 3.3% per year (resp. 4.4% per year), and those statistics are broadly similar when we weight by mortgage face value.

3.2 Macroeconomic evidence

3.2.1 Prevailing mortgage rates

Figure 1 plots the evolution of long-term Danish mortgage yields since 2010.[13] This measure corresponds to the yield-to-maturity on newly issued long-term mortgage bonds, taking into account both the coupon and issuance price of the underlying bond and computed under standard prepayment assumptions. Because of the balance principle (see Section 2.1), mortgage borrowers ultimately bear these financing costs. Consequently, this measure provides a comprehensive summary of the cost of obtaining a new long-term mortgage, incorporating not only the contractual mortgage coupon but also the fact that newly issued mortgage bonds typically trade at a small discount to par. The figure reveals a pronounced secular decline in mortgage rates from 2010 through 2021, followed by a historically unprecedented surge beginning in 2022.

The decline from 2010 to 2021 mirrors the broader fall in European long-term yields over the same period, reflecting persistently low inflation, subdued growth, and a prolonged phase of monetary accommodation by the European Central Bank (thereafter, "ECB"). The downward trend culminated in 2020-2021, when the yield on newly issued long-term FRMs reached an all-time low just below 1%. These historically low rates coincided with the ECB's extraordinary policy easing during the COVID-19 crisis, which transmitted directly to Danish financial conditions. Because Denmark maintains a fixed exchange rate between the Danish krone (thereafter, "DKK") and the euro, Danmarks Nationalbank's monetary policy focuses on defending this peg rather than targeting inflation. To preserve the DKK/EUR parity, the central bank adjusts its policy rates in

[13] The data are publicly available at this link, courtesy of FinansDanmark.

line with ECB decisions and intervenes in foreign exchange markets by buying or selling euros as needed. As a result, Danish short-term (and to a large extent, long-term) rates closely shadow the euro-area term structure.

Starting in early 2022, this long phase of low rates abruptly reversed. As inflation accelerated across Europe, the ECB shifted towards aggressive monetary tightening, raising its deposit rate from -0.50% (maintained until July 2022) to 4.00% by September 2023. Danish sovereign yields and the broader DKK fixed-income complex adjusted in lockstep, and 30-year mortgage market yields surged from slightly below 2% in early 2022 to a peak of 5.5% by mid-2023. This sharp increase in mortgage rates, following more than a decade of declining rates, generates a unique empirical environment. During the 2010-2021 period, most outstanding FRMs carried coupons that were above prevailing mortgage market rates, making refinancing and par prepayment attractive. By contrast, the recent period of rising rates features a large share of mortgages with coupons well below prevailing market rates, rendering the par prepayment option far out of the money. These contrasting episodes provide rich variation for evaluating households' prepayment, refinancing, and mobility behavior under dramatically different interest-rate environments.

3.2.2 Price of outstanding mortgage bonds

The evolution of Danish mortgage bond prices since 2010 mirrors the long-term interest rate cycle documented above. During the prolonged period of declining mortgage market yields from 2010 through 2021, most outstanding FRM bonds traded close to par. As interest rates gradually declined and new mortgage bonds were issued with ever-lower coupons, the market value of existing higher-coupon bonds tended to remain near 100, reflecting the frequent prepayment of above-market loans and the continual refinancing activity of households. In this low-rate environment, the par prepayment option embedded in Danish FRMs was persistently at or in the money, and the price distribution of outstanding mortgage bonds remained tightly concentrated around par.

This pattern changed abruptly in 2022, when the sharp rise in mortgage market interest rates caused a broad repricing of outstanding mortgage bonds. As shown in Figure 1, which plots the time series of market prices for mortgage bonds maturing in 2050 by coupon rate, the increase in rates triggered large and heterogeneous price declines across coupon cohorts. Bonds issued during the preceding low-rate period — many carrying coupons of 0.5% to 1.5% — began trading at substantial discounts to par as investors demanded higher yields. These price adjustments directly mirror the mark-to-market gains realized by Danish households on the liability side of their balance sheets, since the mortgage contracts they hold can be repurchased at the current market price of the underlying bonds. For example, a household with a 0.5% coupon mortgage maturing in 2050 experienced a gain of nearly 30% of the mortgage's face value between January and October 2022.

This episode illustrates the asymmetry in household incentives across interest-rate environments. During periods of declining rates, borrowers with outstanding mortgages carrying coupons above prevailing market rates have strong incentives to refinance and prepay at par, preventing mortgage bond prices from rising substantially above 100. In contrast, when rates rise sharply — as in 2022-2023 — many outstanding mortgages carry coupons well below prevailing market rates, causing mortgage bond prices to fall below par. In these circumstances, borrowers can exploit the institutional feature unique to Denmark: the ability to repurchase their mortgage debt at a discount. This structural feature implies that mortgage bond prices not only determine the funding cost of newly originated loans, but also directly affect household balance sheets and refinancing incentives over the interest-rate cycle. Later, we study the time-series and cross-sectional variation in these refinancing incentives and how they affect households' prepayment, refinancing, and moving decisions.

3.2.3 Aggregate prepayment, refinancing, and moving rates

Using our microdata, we compute aggregate mortgage prepayment, refinancing and moving rates for FRMs and ARMs, and plot the resulting series at the annual frequency in Figure 2 and Figure 3.[14] We begin by documenting average differences across contract types, then relate refinancing activity to movements in interest rates, and finally examine the time-series behavior of moving rates. Several patterns emerge from this preliminary analysis.

First, refinancing rates are consistently higher for FRM borrowers than for ARM borrowers throughout the sample, while ARM borrowers exhibit higher moving rates than FRM borrowers over the entire period, with time-series averages of approximately 4.1% and 3.1% per year, respectively. In addition, refinancing activity among FRM borrowers displays substantially greater time-series variation than that of ARM borrowers, whereas moving rates for the two groups evolve in broadly similar ways.

Turning to refinancing behavior, periods of elevated FRM refinancing activity closely coincide with episodes of declining long-term interest rates. Refinancing rates rise sharply during 2012–2015 and again in 2019, corresponding to periods of substantial

[14] We use the terms "buyback" and "prepayment" interchangeably to denote households' exercise of their option to repurchase their mortgage at the lower of (i) par or (ii) market value.

declines in Danish mortgage market rates. These episodes are consistent with the exercise of the par prepayment option embedded in FRMs, as households refinance to lock in lower borrowing costs and reduce future debt service. Conversely, refinancing activity temporarily slows in 2011, when mortgage rates increase briefly and the par prepayment option moves out of the money.

In 2022, however, a qualitatively different refinancing regime emerges. As interest rates rise sharply and mortgage bond prices fall, FRM refinancing rates increase once again — this time driven not by declining rates, but by widespread discount buybacks. In this environment, households holding low-coupon FRMs repurchase their outstanding mortgages below par, realize the embedded mark-to-market gains on their liabilities, and subsequently refinance at the higher prevailing market rate. This behavior is absent among ARM borrowers, whose funding costs adjust mechanically to market conditions and who therefore lack a comparable embedded prepayment or repurchase option.

We next consider housing mobility. Moving rates for FRM and ARM borrowers follow similar dynamics: they slowly trend upward over the 2010s, spike sharply in 2021 amid elevated household relocation during the first year of the COVID-19 pandemic, and subsequently revert toward their long-run trajectories. Outside of this pandemic-related episode, moving activity among both FRM and ARM borrowers exhibits relatively limited time-series variation. Importantly, as mortgage rates increase sharply beginning in 2022, FRM moving rates return to their pre-pandemic levels and do not exhibit the pronounced decline observed in the U.S. and commonly attributed to the mortgage rate lock-in effect. This stability suggests that the Danish mortgage system's institutional features prevent rising interest rates from generating substantial mobility frictions.

Overall, the time-series behavior of aggregate refinancing and moving activity is consistent with the core mechanisms that we will emphasize throughout the paper. When long-term interest rates fall, FRM borrowers exercise their par prepayment option to lock in lower rates; when rates rise, they instead exploit the Danish system's repurchase-at-market-value feature to crystallize mark-to-market gains and re-establish (near) par-priced, higher-coupon mortgages. By contrast, moving rates remain largely insensitive to mortgage rate fluctuations, with the pandemic-induced spike representing a one-off deviation that affects FRM and ARM borrowers similarly. These aggregate patterns provide macro-level validation for the micro-level behavioral responses analyzed in the subsequent sections.

3.3 Microdata evidence

For this analysis, our unit of observation is a household-month, where i denotes the household identifier and t the month. We restrict our focus to households whose primary mortgage is an FRM.

3.3.1 Initial mortgage yield and the yield gap

Let y_t denote the market yield on newly issued long-term mortgage bonds at time t, and let $\tau(i)$ denote the origination date of household i's primary mortgage. The quantity $y_{\tau(i)}$ therefore corresponds to the mortgage market yield prevailing when household i originated its mortgage.

Our microdata contain the coupon of each household's mortgage, but not the discount to par at which the mortgage was originated. This limitation is analogous to that faced by researchers studying U.S. FRMs, who typically observe mortgage coupons but not the points paid or received at origination.[15] Because Danish mortgages are generally originated at a small discount to par, the coupon alone does not fully capture the financing cost incurred by the borrower. We therefore use the contemporaneous market yield $y_{\tau(i)}$ as a proxy for the borrower's origination financing cost. This measure incorporates both the mortgage coupon and the issuance discount and is thus more closely aligned with the economic incentives underlying prepayment and refinancing decisions.

A potential concern is that borrowers originating mortgages at the same point in time may nonetheless face different financing costs depending on the mortgage institution through which the loan is originated. To assess the importance of this issue, the top panel of Figure A-3 plots the price of 2% long-term mortgage bonds issued by the four largest Danish mortgage institutions, while the bottom panel of Figure A-3 reports the cross-sectional standard deviation of bond prices across issuers. The figure shows that bonds with the same 2% coupon and maturity track one another very closely over time. The average cross-sectional standard deviation of prices is approximately 40 bps, corresponding to differences in financing yields of less than 10 bps under standard duration assumptions.[16] Table A-1 shows that similar conclusions hold across coupon categories. Taken together, these results suggest that the market yield on newly issued long-term mortgage bonds provides a good approximation of the financing cost faced by borrowers originating FRMs at a given point in time.

[15]"Points" are upfront fees or rebates paid at mortgage origination. Borrowers can pay points to obtain a lower coupon rate or receive lender credits in exchange for a higher coupon, so the coupon does not uniquely determine the loan's effective financing cost.

[16]This back-of-the-envelope calculation assumes a duration of 5 years at origination.

Motivated by these observations, we define the yield gap for household i at time t as

$$z_{it} := y_{\tau(i)} - y_t, \tag{1}$$

that is, the difference between the mortgage market yield prevailing when the household originated its mortgage and the contemporaneous mortgage market yield.

Figure 4 plots the average yield gap in our sample over time. Throughout most of the 2010s, the average yield gap fluctuates between 0 and +200 bps as mortgage rates trend downward and FRM borrowers repeatedly refinance into lower-rate mortgages, thereby resetting their yield gap toward zero. By contrast, the sharp increase in mortgage rates during 2022 and 2023 causes the average yield gap to decline abruptly and become substantially negative. In the remainder of the paper, we examine how households' prepayment, refinancing, and moving decisions vary with the yield gap.

3.3.2 Mobility and refinancing responses to the yield gap

We estimate the relationship between mortgage prepayment behavior and household i's lagged yield gap using both nonparametric and parametric specifications. Our baseline approach estimates the following nonparametric regression:

$$\mathbb{1}\left(\text{prepay}_{it}\right) = \sum_k \beta_k \mathbb{1}\left(z_{it-1} \in \text{bin}_k\right) + \gamma X_{it} + \epsilon_{it}, \tag{2}$$

where $\mathbb{1}(\cdot)$ denotes the indicator function and lagged yield gaps z_{it-1} are discretized into 50 bps bins. The vector X_{it} contains controls. Specifically, we estimate the model (i) without controls, (ii) with a control set closely mirroring Fonseca and Liu (2024), and (iii) with households' fixed effects.[17]

In addition to the nonparametric specification in equation (2), we estimate a piecewise-linear model that allows the sensitivity of prepayment hazards to differ across positive and negative yield gaps:

$$\mathbb{1}\left(\text{prepay}_{it}\right) = \alpha_0 + \beta_0 z_{it-1} + \alpha_1 \mathbb{1}\left(z_{it-1} \geq 0\right) + \beta_1 \mathbb{1}\left(z_{it-1} \geq 0\right) z_{it-1} + \gamma X_{it} + \epsilon_{it}, \tag{3}$$

thereby allowing for distinct slopes on either side of the zero yield-gap threshold, in contrast to the single-slope specification used in Fonseca and Liu (2024).

[17]When replicating the control vector of Fonseca and Liu (2024), X_{it} includes remaining mortgage maturity, month, and locality-by-year fixed effects, as well as log mortgage balance, log mortgage payment, age, age squared, and household size. Results are robust to additionally including controls for highest achieved level of education, household income, net wealth, and children in the household.

Figure 5 (resp. Figure 6) reports the estimated nonparametric relationships between yield gaps and refinancing (resp. moving) probabilities implied by equation (2), while Table 2 presents the coefficient estimates from the piecewise-linear specification in equation (3) for moves.

Several findings emerge from this analysis. First, refinancing hazards increase sharply once the yield gap exceeds approximately 50 bps. This pattern reflects the financial incentive for borrowers to refinance into lower-coupon mortgages, a flexibility that is readily available to Danish households. The increase in refinancing activity occurs only once the yield gap becomes sufficiently positive because Danish mortgages are typically originated at a small discount to par. Consequently, a yield gap of zero corresponds to a mortgage that still trades slightly below par, implying that the par prepayment option remains marginally out of the money. Once the yield gap reaches roughly 50 bps, the prepayment option becomes meaningfully in the money, leading to a pronounced increase in refinancing propensities. A broadly similar pattern has been documented in the U.S., where refinancing activity also rises with the financial gains from refinancing. However, the sensitivity of refinancing hazards appears considerably stronger in Denmark. For example, Berger et al. (2021) estimate that U.S. refinancing hazards increase by approximately 200 bps/month in response to comparable refinancing incentives, compared with nearly 400 bps/month in our Danish sample for our fixed-effect specification. This difference is consistent with Danish borrowers facing fewer refinancing frictions—whether behavioral, informational, or institutional—than their U.S. counterparts (Andersen et al., 2020; Berger et al., 2025).

Second, refinancing hazards rise when the yield gap falls below -150 bps, reflecting the incentive for Danish borrowers to repurchase their mortgages at a discount and realize the mark-to-market gains embedded in their fixed-rate contracts. This behavior stands in sharp contrast to that of U.S. borrowers, whose refinancing rates remain extremely low when yield gaps are negative, indicating a limited response to below-par mortgage pricing (Berger et al., 2021). As we argue in Section 4, the pronounced increase in refinancing hazards for negative yield gaps in Denmark is driven — at least partly — by the tax deductibility of mortgage interest. Although low-coupon discount mortgages and high-coupon par-priced mortgages might have equivalent pre-tax present values, the tax shield on interest payments makes high-coupon, par-priced mortgages more attractive on an after-tax basis.

Third, conditional on a positive yield gap, the moving hazard is modestly upward sloping across specifications. For instance, the estimated slope of 0.046 in Column 2 in Table 2 implies that, when the yield gap is positive, a 100 bps increase in the yield gap raises monthly moving rates by 4.6 bps, or approximately 55 bps per year relative to an unconditional mean of 331 bps per year.[18] A qualitatively similar pattern is documented in Fonseca and Liu (2024), although the estimated gradient in that study is larger than in Denmark. We interpret this relationship as reflecting the increasing value of mortgage prepayment as the yield gap widens: when refinancing at par is attractive, moving — and thereby prepaying the outstanding FRM — becomes more valuable, generating a positive association between yield gaps and mobility for positive gaps.

By contrast, conditional on a negative yield gap, the moving hazard is essentially flat, providing little evidence of a mortgage lock-in effect in Denmark. The precise slope depends on the specification: absent controls, the relationship is mildly downward sloping (slope of approximately -0.012 when expressed using monthly hazard, or -0.138 using yearly hazard), implying that a 100 bps decrease in the yield gap increases annual moving rates by about 14 bps; when using the control set of Fonseca and Liu (2024), the slope becomes mildly positive (slope of approximately 0.016 when expressed using monthly hazard, or $+0.19$ using yearly hazard), implying that a 100 bps decrease in the yield gap decreases annual moving rates by about 19 bps; finally, our fixed-effect specification leads to results somewhere in-between our specification without and with controls. These effects are economically small and stand in sharp contrast to the U.S. evidence, where the estimated slope ranges from 0.57 to 1.20 depending on the specification — i.e. substantially larger than in Denmark. Put differently, Danish households continue to relocate at nearly constant rates even when prevailing market rates substantially exceed their existing mortgage coupons, consistent with their ability to move without forfeiting the embedded capital gains in their FRMs.

Finally, Figure 5 and Figure 6 both display evidence of "burnout" at high positive yield gaps in Panels (a) and (b), where refinancing and moving hazards decline for large yield gaps. This pattern is consistent with a selection effect in which households that are most responsive to incentives act early, leaving behind borrowers who are persistently less responsive to interest-rate incentives. Consistent with this interpretation, the burnout pattern largely disappears once household fixed effects are included in Panel (c) of both figures, indicating that the decline at high yield gaps primarily reflects persistent heterogeneity across households rather than diminishing within-household responsiveness. Importantly, however, incorporating household fixed effects does not materially alter the main conclusions from Table 2: moving hazards remain approximately flat for negative yield gaps and upward sloping for positive yield gaps.

[18] 0.046 is the sum of the baseline slope 0.0158 and the positive gap add-on 0.0303.

3.3.3 Yield gaps vs. coupon gaps

The recent literature on mortgage lock-in typically measures refinancing incentives using the household-specific coupon gap, defined as the difference between the coupon rate on the borrower's outstanding mortgage and the prevailing market mortgage rate (e.g., Fonseca and Liu, 2024; Liebersohn and Rothstein, 2025; Aladangady, Krimmel and Scharlemann, 2025). Our analysis instead focuses on the yield gap introduced in Section 3.3.1, defined as the difference between the mortgage market yield prevailing when the household originated its mortgage and the contemporaneous mortgage market yield.

This choice has an important econometric advantage. When coupon gaps are used as explanatory variables, cross-sectional variation in coupon gaps may reflect not only differences in mortgage origination dates, but also borrower-specific characteristics that affect the mortgage rate obtained at origination. For example, more financially sophisticated households may obtain lower mortgage rates and may also refinance or move more aggressively. As a result, estimates based on household-specific coupon gaps may be affected by omitted-variable bias. To address this concern, the existing literature typically instruments the household-specific coupon gap with an aggregate coupon gap, defined as the difference between the prevailing mortgage market coupon and the mortgage market coupon available when the household originated its mortgage.

In contrast, all cross-sectional variation in our yield-gap measure is driven by the timing of mortgage origination rather than borrower-specific mortgage pricing. Consequently, our baseline specification is closely related to the reduced-form specifications estimated in the existing literature when aggregate coupon gaps are used as instruments for household-specific coupon gaps. Put differently, the identifying variation in our regressions originates from differences in mortgage vintages rather than from cross-sectional differences in borrowers' mortgage rates.

Because all cross-sectional variation in the yield gap stems from origination timing rather than borrower-specific pricing, our baseline yield-gap regressions require no instrument: the yield gap is, by construction, free of the omitted-variable bias that motivates instrumenting household-specific coupon gaps in the existing literature. To make the connection to that literature concrete, we replicate all results from Section 3.3.2 using household-specific coupon gaps in place of yield gaps. We define the coupon gap as the difference between the borrower's mortgage coupon and the contemporaneous market coupon, the latter measured as the coupon on newly originated long-term FRMs whose covered bonds trade closest to, but below, par. The nonparametric relationships (equation 2) estimated on coupon gaps appear in Figure A-4 (refinancing) and Figure A-5 (moves), and the piecewise-affine moving estimates (equation 3) in Table A-2, columns

(1)-(3). Because the household-specific coupon gap is potentially endogenous, column (4) implements the IV strategy of Fonseca and Liu (2024): we instrument the coupon gap with the aggregate coupon gap — the difference between the market coupon prevailing at the household's origination date and the contemporaneous market coupon — and, in the piecewise specification, instrument the positive-gap indicator and its interaction using the corresponding functions of the aggregate coupon gap. Figure A-6 plots realized coupon gaps against the aggregate instrument and shows a near-45-degree relationship, confirming instrument relevance. Reassuringly, the refinancing and moving relationships estimated on coupon gaps — by OLS or IV — are quantitatively and qualitatively similar to those obtained using yield gaps, and the IV estimates line up closely with the yield gap baseline. This is exactly what the vintage-only interpretation of the yield gap predicts: instrumenting the coupon gap isolates the same origination-timing variation that the yield gap captures directly.

3.4 Takeaways from the empirical analysis

Our empirical analysis highlights important differences between refinancing and moving behavior in the U.S. and Denmark, as well as in how these behaviors respond to yield gaps. These differences have potentially meaningful implications for monetary transmission and housing market dynamics.

The finding that refinancing rates in Denmark are elevated for both positive and negative yield gaps suggests that the transmission mechanism linking monetary policy, mortgage refinancing, and household consumption may differ substantially from that in the U.S. While a systematic and quantitative analysis of these differences lies beyond the scope of the present paper, we investigate them in detail in a companion paper.

Moreover, the relative insensitivity of moving rates to the yield gap (when such gap is negative) in Denmark indicates that household mobility is largely unaffected by the mortgage contract structure, especially amid the recent rise in interest rates. If mortgage-induced lock-in meaningfully impedes geographic mobility — as suggested by evidence from the U.S. — and generates welfare costs through, for example, labor–housing mismatches or inefficient utilization of the housing stock, then policy interventions aimed at mitigating such frictions warrant consideration.

One potential reform would be to incorporate features of the Danish mortgage system that allow borrowers to repurchase their mortgages at market value, thereby preserving mobility when interest rates rise. Section 5 examines the institutional adjustments required to implement such a buyback option in the U.S. context, with particular attention to differences between the agency and jumbo markets. We also discuss alternative mechanisms proposed in the literature — most notably mortgage assumptions and mortgage portability — and assess their effectiveness relative to the Danish framework.

4 Model

In this section, we develop an equilibrium model of the Danish fixed-rate mortgage market and analyze borrowers' refinancing and moving decisions. The model rationalizes two salient empirical features of this market: (i) the propensity of Danish FRM borrowers to repurchase their mortgages at a discount when market prices fall sufficiently below par, and (ii) the relative insensitivity of moving rates to the yield gap when the gap is negative. We then use the model to study a counterfactual policy experiment in which a buyback option is introduced into U.S. FRM contracts, and assess how household behavior and mortgage rates would respond under alternative implementation regimes, with particular attention to the role of mortgage interest deductibility and the taxation of capital gains.

4.1 Setup

We model the driving process as a (univariate) state variable x_t that summarizes the term structure of interest rates at time t. We assume that x_t follows a diffusion with drift $\mu(x)$, diffusion $\sigma(x)$, and infinitesimal generator $\mathcal{L}$.[19] The instantaneous short rate is given by a monotone function of the state, $r_t = r(x_t)$.

Mortgages are fixed-rate and exponentially amortizing at rate α.[20] The remaining face value at time t is therefore $\phi_t = \phi_0 \exp(-\alpha t)$. We assume that mortgages are always issued at a price of par, which means that the yield at issuance is equal to the mortgage coupon. Danish mortgages can be prepaid at any time at the lower of (a) par and (b) market value.

We consider risk-neutral households with subjective discount rate ρ. Let c_t denote the fixed coupon rate on the household's outstanding mortgage at time t. Households face two types of decision opportunities that arrive stochastically over time:

[19]For any twice continuously differentiable function f, $\mathcal{L}f(x) = \mu(x)f'(x) + \frac{1}{2}\sigma^2(x)f''(x)$.

[20]The assumption that mortgages are exponentially amortizing is a modeling device that allows us to save on state variables. In practice, the amortization profile of Danish FRMs is identical to that of U.S. FRMs — i.e. the mortgage is an annuity, and each payment of the annuity represents a varying amount of interest and principal; early on, the majority of the payment consists of interest, and at the end of the mortgage contractual life, the majority of the payment consists of principal.

- *refinancing opportunities* arrive according to a Poisson process with intensity λ; and
- *moving opportunities* arrive according to a Poisson process with intensity ψ.

These assumptions capture the idea that refinancing and moving decisions are subject to behavioral, informational, and institutional frictions that preclude continuous adjustment. Instead, households periodically receive discrete opportunities to reassess their housing and financing choices.

Exercising a refinancing (respectively, moving) opportunity entails a net proportional cost, denoted $\tilde{\kappa}_\lambda$ (respectively, $\tilde{\kappa}_\psi$), expressed as a fraction of the outstanding mortgage balance. We allow these costs to be stochastic, with cumulative distribution functions F_λ and F_ψ. Refinancing costs $\tilde{\kappa}_\lambda$ capture lender fees and transaction costs associated with repurchasing outstanding mortgage debt and issuing new covered bonds. In contrast, net moving costs $\tilde{\kappa}_\psi$ reflect both direct relocation expenses and indirect benefits — such as improved labor market opportunities or a better housing match — so that $\tilde{\kappa}_\psi$ may be positive or negative depending on circumstances.

When a household refinances or moves at time τ, it takes out a new par-priced mortgage with a coupon equal to the prevailing market mortgage rate m_τ and with an unchanged face value relative to the outstanding balance. If the original mortgage trades below par, the household repurchases it at its equilibrium market price, realizes the associated discount as a cash gain, and immediately issues (or relocates with) a new mortgage of identical face value.

Mortgage interest payments are tax-deductible at rate θ, a feature that plays a central role in the model. Tax deductibility creates incentives to refinance even when prevailing market rates exceed the outstanding coupon, provided the market value of the existing mortgage is sufficiently below par. In such cases, households face a trade-off between incurring a fixed prepayment cost today and increasing future interest deductions through a higher-coupon mortgage. This mechanism closely parallels the trade-off theory of corporate capital structure, in which firms balance the tax benefits of debt against expected future distress costs.

Finally, we abstract from household default risk. In Denmark, credit risk is borne by mortgage institutions rather than covered bond investors, and is priced separately through an institution-specific contribution fee that is distinct from the mortgage coupon. In the event of borrower default, the mortgage institution repurchases the loan from the covered bond pool at the lower of par or market value, so that from the perspective of bond investors, default is economically equivalent to prepayment. Moreover, default rates in Denmark are an order of magnitude smaller than prepayment rates,[21] implying that default plays a quantitatively negligible role in shaping mortgage pricing and household refinancing incentives in the environment we study. Accordingly, we treat mortgages as free of idiosyncratic credit risk and focus exclusively on interest-rate risk and prepayment behavior.

4.2 Household problem

The household's objective is to minimize the present value (at the subjective discount rate ρ) of all future mortgage-related cashflows. Its value function is equal to $V_t = \phi_t v(x_t, c_t)$, where the (normalized) value function v is defined via

$$v(x,c) := \inf_{a \in \mathcal{A}} \mathbb{E}_{x,c} \left[\int_0^{+\infty} e^{-(\rho+\alpha)t} \left(\left((1-\theta) c_t^{(a)} + \alpha \right) dt + a_t \sum_{\beta=\lambda,\psi} \left(\tilde{\kappa}_{\beta,t} - \max\left(0, 1 - p\left(x_{t-}, c_{t-}^{(a)}\right)\right) \right) dN_t^{(\beta)} \right) \right], \quad (4)$$

$$\text{s.t.} \quad dc_t^{(a)} = \left(m(x_t) - c_{t-}^{(a)} \right) a_t \left(\sum_{\beta=\lambda,\psi} dN_t^{(\beta)} \right) \quad (5)$$

In the above, $N_t^{(\lambda)}$ (resp. $N_t^{(\psi)}$) is a counting process with jump intensity λ (resp. ψ) representing opportunities to refinance (resp. move), $\mathcal{A}$ is the set of progressively measurable binary actions $a = \{a_t\}_{t \geq 0}$ such that $a_t \in \{0, 1\}$ for all t, $\tilde{\kappa}_{\beta,t}$ is the random net cost (associated with moving opportunities, when $\beta = \psi$, or refinancing opportunities, when $\beta = \lambda$) drawn at time t, $p(x, c)$ is the (equilibrium) market price of a mortgage with coupon c when the term structure state variable is x, and $m(x)$ is the (equilibrium) par coupon on mortgage debt, i.e. it is the fixed rate the household can lock-in when taking on a new, par-priced, mortgage at a time when the term structure state variable is equal to x.[22]

Equation (4) can be interpreted as follows: household's (normalized) value function is the present value (at the subjective discount rate ρ) of after-tax mortgage interest payments $(1-\theta)c_t$, mortgage principal repayments α, refinancing costs $\tilde{\kappa}_{\lambda,\tau}$ any time

[21] Figure 10 in Bäckman and Lutz (2025) reports a time-series average of approximately 1,000–2,000 annual repossessions in Denmark over 1995–2015. Given an outstanding mortgage stock of roughly one million loans during this period, and treating repossessions as a proxy for defaults, the implied annual default rate is below 0.20%. This rate is at least an order of magnitude lower than the corresponding prepayment rate.

[22] The progressively measurable binary process a_t is such that the exercise decision is taken at an arrival time *after* observing whether the opportunity is refinancing or moving and after observing the realized cost draw $\tilde{\kappa}_{\beta,t}$.

τ at which a refinancing takes place, moving costs $\tilde{\kappa}_{\psi,\tau}$ any time τ at which a moving event takes place, minus the realized market value gains $(1 - p(x_{\tau-}, c_{\tau-}))$ whenever the household buys back its mortgage at a discount at time τ (at the time of a refinancing or a move). If the refinancing or move occurs at a time when the mortgage trades at a premium (which is when the mortgage market interest rate $m(x_t)$ is below the mortgage coupon c_t), the household prepays its existing mortgage at par and does not realize any market value gain. v satisfies the HJB equation

$$
\begin{aligned}
(\rho + \alpha)v(x, c) &= \alpha + (1 - \theta)c + \mathcal{L}v(x, c) \\
&\quad + \sum_{\beta=\psi,\lambda} \beta \mathbb{E}\left[\min\left[0, v\left(x, m(x)\right) + \tilde{\kappa}_\beta - \max\left(0, 1 - p\left(x, c\right)\right) - v(x, c)\right]\right], \quad (6)
\end{aligned}
$$

where the expectation is taken w.r.t. the random variable $\tilde{\kappa}_\beta$. The term $\mathcal{L}v(x, c)$ captures expected changes in the value function due to changes in the state variable x. The term $\beta \mathbb{E}\left[\min\left[0, v\left(x, m(x)\right) + \tilde{\kappa}_\beta - \max\left(0, 1 - p\left(x, c\right)\right) - v(x, c)\right]\right]$ captures the refinancing (when $\beta = \lambda$) or moving (when $\beta = \psi$) options, which give the borrower the ability to:

- stay put, with continuation value $v(x, c)$;
- prepay at par (whenever $m(x) < c$ and $p(x, c) > 1$) and refinance (or move), with continuation value $v\left(x, m(x)\right) + \tilde{\kappa}_\beta$ post-prepayment;
- prepay at a discount (whenever $m(x) > c$ and $p(x, c) < 1$) and refinance (or move), with continuation value $v\left(x, m(x)\right) + \tilde{\kappa}_\beta - 1 + p\left(x, c\right)$ post-buyback.

4.3 Mortgage pricing

The mortgage market is competitive. Consider a mortgage with unit face value and coupon c when the term structure state variable is x. Its price satisfies

$$
p(x, c) := \mathbb{E}_x\left[\int_0^\tau e^{-\int_0^t (r(x_s)+\alpha)ds}(c + \alpha)dt + e^{-\int_0^\tau (r(x_s)+\alpha)ds}\right],
$$

where τ is the equilibrium par prepayment time. The martingale condition for mortgage prices is then given by

$$
\begin{aligned}
(r(x) + \alpha)p(x, c) &= c + \alpha + \mathcal{L}p(x, c) \\
&\quad + \sum_{\beta=\lambda,\psi} \beta \min\left[0, 1 - p(x, c)\right] \mathbb{P}\left(v(x, c) > v(x, m(x)) + \tilde{\kappa}_\beta - \max\left[0, 1 - p(x, c)\right]\right), \quad (7)
\end{aligned}
$$

where $\mathbb{P}(\cdot)$ denotes the probability operator. The term $\mathcal{L}p(x,c)$ captures the expected change in mortgage prices arising from movements in the state variable x. The final term reflects the borrower's prepayment option, which investors are short. In particular, when the mortgage trades at a premium ($p(x,c) > 1$), prepayment at par generates a capital loss for investors, whereas when the mortgage trades at a discount, borrower repurchases at market value do not impose any capital loss on investors.

The mortgage market interest rate $m(x)$ is defined implicitly, via the condition

$$p\left(x, m(x)\right) = 1. \tag{8}$$

The environment we analyze can be viewed as a dynamic game involving four sets of agents.

- households, who pay after-tax mortgage interest and principal $(1-\theta)c_t + \alpha$, incur refinancing costs κ_λ, and pay (or receive, if negative) net moving costs κ_ψ;
- mortgage investors, who receive contractual cash-flows equal to $c_t + \alpha$;
- mortgage banks, who collect refinancing fees κ_λ and capture a share of net moving costs κ_ψ;
- the Danish government, whose tax revenues are reduced through mortgage interest deductibility at rate θ.

When a household repurchases its mortgage at a discount and refinances — or moves into — a higher-coupon loan, the present value of future tax revenues declines, generating a fiscal loss for the government.[23]

4.4 Equilibrium

A Markov Perfect Equilibrium ("MPE") is defined as a value function v, optimal refinancing and moving strategy a, a price function p and a mortgage market interest rate $m(x)$ such that:

- given the price function p and mortgage market interest rates m, the refinancing and moving strategy a solves equation (6);

[23]This discussion abstracts from the tax treatment of capital gains or losses realized by mortgage investors following discounted buybacks. The incidence of such taxes depends on investor characteristics, tax status, and country of domicile. As is standard in the trade-off literature, and because our focus is on household incentives and behavior, we abstract from investor-level taxation in the analysis.

- given the refinancing and moving strategy a followed by households, mortgage prices satisfy the martingale condition (7);
- the mortgage market interest rate satisfies equation (8).

While the existence and uniqueness of an MPE are beyond the scope of our paper, there are certain properties of an MPE that are straightforward to establish. For instance, in any MPE, the mortgage pricing function p will be monotone increasing in c, and the value function v will be monotone increasing in c.

These observations allow us to characterize the optimal borrower behavior, conditional on receiving an opportunity to refinance or move. There are two cases to consider. First, assume the realization κ_β of the random prepayment cost $\tilde{\kappa}_\beta$ is strictly positive. In this case, the optimal prepayment strategy of a borrower can be characterized by an inaction region, defined via $\mathcal{I}_\beta(x;\kappa_\beta) := \left[\underline{C}_\beta(x;\kappa_\beta);\bar{C}_\beta(x;\kappa_\beta)\right]$, with $\underline{C}_\beta(x;\kappa_\beta) < m(x) < \bar{C}_\beta(x;\kappa_\beta)$. If $c \in \mathcal{I}_\beta(x;\kappa_\beta)$ at the time the borrower has an opportunity to prepay (in order to refinance, when $\beta = \lambda$, or in order to move, when $\beta = \psi$), the borrower stays put. Otherwise the borrower prepays and refinances (or moves):

- if $c \leq \underline{C}_\beta(x;\kappa_\beta)$, the household refinances or moves, prepays its mortgage and realizes a mark-to-market gain $1 - p\,(x, c)$;
- if $c \geq \bar{C}_\beta(x;\kappa_\beta)$, the household refinances or moves and prepays its mortgage at a price of par.

The bounds of the inaction region $\mathcal{I}_\beta(x;\kappa_\beta)$ satisfy, for all x:

$$v\left(x, \bar{C}_\beta(x;\kappa_\beta)\right) = v\,(x, m(x)) + \kappa_\beta \tag{9}$$

$$v\left(x, \underline{C}_\beta(x;\kappa_\beta)\right) = v\,(x, m(x)) + \kappa_\beta - 1 + p\left(x, \underline{C}_\beta(x;\kappa_\beta)\right) \tag{10}$$

The above reasoning will be relevant for all refinancing decisions since we impose $\tilde{\kappa}_\lambda > 0$, and for moving decision whenever the random net moving cost $\tilde{\kappa}_\psi$ is strictly positive. Instead, when a moving opportunity arises, if the realization κ_ψ of the random net moving cost $\tilde{\kappa}_\psi$ is negative, equations (9) and (10) cannot be satisfied; in that case, the inaction region for moving decisions is empty, $\mathcal{I}_\psi(x;\kappa_\psi) = \emptyset$, and it is optimal for the borrower to move irrespective of the value of the mortgage coupon.

4.5 Long run distribution, refinancing and moving hazard rates

In our model, the yield gap is $z_t = z\,(x_t, c_t) := c_t - m\,(x_t)$. The mortgage trades at a premium (resp. discount) whenever $z_t > 0$ (resp. $z_t < 0$). Imagine that we track an economy with a continuum of Danish households, all financing their house via FRMs. One can characterize the long-run distribution over interest rates and coupons $f(x,c)$, defined via:

$$f(x,c)dcdx := \lim_{t\to+\infty} \frac{1}{t}\int_0^t \mathbb{1}\left(x_t \in [x, x+dx]; c_t \in [c, c+dc]\right) dt. \tag{11}$$

This ergodic density satisfies the KF equation, for $c \neq m(x)$

$$0 = \mathcal{L}^* f(x,c) - \sum_{\beta=\lambda,\psi} \beta F_\beta \left(v(x,c) - v\left(x, m(x)\right) + \max\left(0, 1 - p(x,c)\right)\right) f(x,c), \tag{12}$$

where $\mathcal{L}^*$ is the adjoint of the operator $\mathcal{L}$[24] and F_β is the cumulative distribution function for the random net cost $\tilde{\kappa}_\beta$. In equation (12), the term $\mathcal{L}^* f(x,c)$ encodes changes in the household distribution related to changes in the state x_t, while the second term is an exit term associated with prepayments, either due to refinancings ($\beta = \lambda$) or moves ($\beta = \psi$), occurring at intensity β times the probability $F_\beta\left(v(x,c) - v\left(x, m(x)\right) + \max\left(0, 1 - p(x,c)\right)\right)$ that the net cost $\tilde{\kappa}_\beta$ is sufficiently low for the option to be exercised.

Let $h(z), h_\lambda(z), h_\psi(z)$ be the model-implied prepayment, refinancing and moving hazards, as a function of the yield gap, that an econometrician would estimate, if she had an infinite time-series data available. One can characterize such hazard rates using the ergodic density f of our dynamic system:

$$h_\beta(z) = \beta \frac{\int F_\beta\left(v\left(x, z+m(x)\right) - v(x, m(x)) + \max\left(0, 1 - p\left(x, z+m(x)\right)\right)\right) f\left(x, z+m(x)\right) dx}{\int f\left(x, z+m(x)\right) dx}$$

$$h(z) = h_\lambda(z) + h_\psi(z).$$

4.6 Calibration

We compute the equilibrium of our model using a recursive method that leverages a finite difference scheme for both the value function and mortgage prices and that is described in Section A.2. x_t is the driving process in this model, and it summarizes the term structure of interest rates at time t. Since we focus on the recent time period, during which interest rates (across maturities) reached historical lows in both Denmark and the U.S., we find it convenient to assume that x_t follows an Ornstein-Uhlenbeck process and that the short rate satisfies $r(x) = \max(0, x)$, so as to ensure that the term structure of

[24] For any twice continuously differentiable function f, the adjoint is defined via $\mathcal{L}^* f(x) := -\frac{d}{dx}\left[\mu(x) f(x)\right] + \frac{d^2}{dx^2}\left[\frac{\sigma^2(x)}{2} f(x)\right]$.

interest rates remains positive but that model-implied long term rates can attain levels arbitrarily close to zero. In other words, we assume that

$$dx_t = -\eta(x_t - \bar{x})dt + \sigma dZ_t, \tag{13}$$

where $\bar{x}$ is the long-term mean of x_t, η the speed of mean reversion, and σ the volatility. x_t is sometimes called the "shadow rate".

Table 3 summarizes the parameter values used in the model, while Table 4 reports the parameter estimates from the shadow-rate term structure model. We set the effective tax rate on mortgage interest to $\theta = 33\%$, consistent with the marginal rate applicable to mortgage interest deductions in Denmark (Gruber, Jensen and Kleven, 2021). Following Agarwal, Driscoll and Laibson (2013) and Berger et al. (2025), we assume a subjective discount rate of $\rho = 5\%$.

The term structure model is estimated by maximum likelihood using monthly Danish 10-year government bond yields from January 1987 to December 2019. For any parameter triplet $(\eta, \bar{x}, \sigma)$ and observed 10-year Danish government bond yield at time t, we invert the model to recover the unique shadow rate x_t such that the model-implied 10-year yield exactly matches the observed yield. Because the yield curve is driven by a single factor, this inversion is exact. The resulting shadow-rate series is then used as input in the maximum likelihood estimation. The estimation yields a relatively low average shadow rate, with an ergodic mean of 0.51%, and a high degree of persistence, corresponding to a half-life of 7.6 years.

We next turn to the parameters governing refinancing behavior. Refinancing costs are always positive, so we assume they are log-normally distributed, with mean $\bar{\kappa}_\lambda$ and standard deviation σ_λ. To calibrate these parameters, we follow Andersen et al. (2020), who document that refinancing costs in Denmark are well approximated by a piecewise affine function of the outstanding mortgage balance.[25] For the average fixed-rate mortgage in our sample (approximately DKK 1,000,000 in face value), this specification implies refinancing costs of roughly DKK 8,000, corresponding to 0.80% of the outstanding balance. Accordingly, we set the mean of F_λ to $\bar{\kappa}_\lambda = 0.80\%$, and $\sigma_\lambda = 0.50\%$. In the model, refinancing opportunities arrive according to a Poisson process, which can be interpreted as capturing some form of inattention. In their baseline time- and state-dependent inaction specification, Andersen et al. (2020) estimate a quarterly probability of inattention of 92%.[26] This estimate implies a refinancing opportunity arrival rate of

[25] Andersen et al. (2020) model refinancing costs as $\kappa(\phi) = 3{,}000 + \max(0.002\phi, 4{,}000) + 0.001\phi$, where ϕ denotes the mortgage principal.

[26] See Andersen et al. (2020), Model 3, which incorporates inattention through an "asleep" probability

$\lambda = -\ln(0.92)/0.25 \approx 33\%$ per year.

We finally turn to the parameters governing moving behavior. Calibrating the distribution of moving costs, F_ψ, is inherently more challenging, as relocation decisions reflect heterogeneous and often non-financial motives, including household formation and dissolution, labor market transitions, and lifecycle-driven housing adjustments. We adopt a conservative benchmark of $\bar{\kappa}_\psi = 0$, corresponding to the assumption that, on average, the benefits of moving — such as improved housing matches or enhanced labor market opportunities — offset the associated financial and non-financial costs.

We calibrate the standard deviation of moving costs, σ_ψ, and the arrival rate of moving opportunities, ψ, jointly, exploiting a key implication of the model. When the yield gap is positive, households benefit from moving even in the absence of net moving benefits, since the embedded par prepayment option is in the money; moreover, these gains increase with the size of the yield gap. Thus, consistent with our empirical results, for positive yield gaps, the probability of exercising the moving option conditional on a moving opportunity is increasing in the yield gap, implying that the moving hazard itself is increasing in the yield gap over this region. We therefore choose σ_ψ and ψ to jointly match (i) the unconditional average moving rate among Danish FRM borrowers (3.2% per year) and (ii) the slope of the moving hazard with respect to the yield gap for positive gaps (approximately equal to $0.046 \times 12 \approx 0.55$, i.e. the moving rate increases by approximately 55 bps/year for each 100 bps increase in the yield gap, see Table 2, column 2). This calibration yields $\psi = 5.5\%$ and $\sigma_\psi = 10\%$.

4.7 Model results

4.7.1 Model vs. data: refinancing and moving hazard rates

Figure 7 (left panel) plots the equilibrium mortgage rate $m(x)$ together with the refinancing inaction region $\mathcal{I}_\lambda(x; \bar{\kappa}_\lambda) = [\underline{C}_\lambda(x; \bar{\kappa}_\lambda), \bar{C}_\lambda(x; \bar{\kappa}_\lambda)]$ as a function of the 10-year government yield — the yield to maturity on risk-free bullet bonds trading at par and a standard benchmark for mortgage rates (see Section A.3 for more details). The inaction region is depicted for a refinancing cost equal to its average value $\bar{\kappa}_\lambda$. Since $\bar{\kappa}_\psi = 0$, the related inaction region is empty, $\mathcal{I}_\psi(x; \bar{\kappa}_\psi) = \emptyset$, and households optimally choose to move whenever a moving opportunity arises.[27]

and abstracts from psychological costs, focusing exclusively on monetary refinancing costs, as in our calibration.

[27]This is true in this particular case where we evaluate the inaction region *conditional* on the random moving cost being equal to $\bar{\kappa}_\psi = 0$. Of course, given the random nature of the moving costs, households do not always move whenever an opportunity arises — only when the net moving cost is sufficiently low.

Figure 8 provides an additional illustration of household behavior in the model by plotting the probability of refinancing (left panel) and moving (right panel), conditional on receiving a refinancing or moving opportunity. The left panel reveals a narrow region of relative inaction along the 45-degree line, corresponding to intermediate values of the yield gap. In this region, refinancing costs outweigh the potential benefits of refinancing — whether through a par prepayment that lowers future coupon payments or through a discount repurchase that realizes embedded capital gains and increases the present value of mortgage interest deductions. The right panel displays an analogous mechanism for moving decisions. However, both the inaction region and the transition to active adjustment are more diffuse, reflecting the substantially higher dispersion of net moving costs relative to refinancing costs.

Finally, the right panel of Figure 7 reports the refinancing and moving hazard rates implied by the model as functions of the yield gap. When a refinancing opportunity arrives and the yield gap z exceeds $\bar{C}_\lambda(x;\tilde{\kappa}_\lambda) - m(x)$, the borrower optimally prepays at par, implying a refinancing hazard equal to the arrival rate of refinancing opportunities, λ. Conversely, when a refinancing opportunity arrives and z falls below $\underline{C}_\lambda(x;\tilde{\kappa}_\lambda) - m(x)$, the borrower repurchases the mortgage at a discount, again generating a refinancing hazard of λ. For intermediate values of the yield gap, $\underline{C}_\lambda(x;\tilde{\kappa}_\lambda) - m(x) < z < \bar{C}_\lambda(x;\tilde{\kappa}_\lambda) - m(x)$, the borrower optimally remains inactive. Randomness in refinancing costs smooths these sharp thresholds, yielding the refinancing hazard $h_\lambda(z)$ shown in Figure 7.

As discussed above, when the net moving cost $\tilde{\kappa}_\psi$ is less than or equal to its mean value of zero — that is, when moving yields a net benefit rather than a cost — the model features no moving inaction region, and the moving hazard equals the exogenously specified arrival rate of moving opportunities, ψ. When net moving costs are positive, however, an inaction region emerges, analogous to that for refinancing decisions, and this region expands as net moving costs increase. Abstracting from net moving costs, sufficiently large positive or negative yield gaps allow moving households to reduce the present value of future mortgage costs — either by refinancing into a lower coupon when the gap is large and positive, or by monetizing embedded capital gains and increasing the mortgage interest tax shield when the gap is large and negative. Moreover, the incentive to move strengthens with the absolute magnitude of the yield gap. Consequently, both the probability of moving conditional on receiving a moving opportunity and the moving hazard are mildly increasing in the yield gap for positive values and mildly decreasing for negative values. Overall, the refinancing and moving hazards implied by the model as functions of the yield gap align closely with the empirical patterns documented in Section 3.

4.7.2 Key economic mechanisms: fixed costs and tax incentives

We next discuss the key economic mechanisms embedded in the model that generate refinancing and moving hazards consistent with those observed in the data. To clarify these mechanisms, we rely on comparative statics. Figure 9 presents comparative statics with respect to the average refinancing cost, $\bar{\kappa}_\lambda$, and the mortgage interest tax rate, θ.

The left panel illustrates a simple intuition: higher refinancing costs widen the region of inaction. This expansion is asymmetric. The lower threshold, $\underline{C}_\lambda(x;\bar{\kappa}_\lambda)$ — below which borrowers optimally repurchase their mortgages at a discount — shifts more in response to increases in refinancing costs than does the upper threshold, $\bar{C}_\lambda(x;\bar{\kappa}_\lambda)$, above which borrowers prepay and refinance at par.

The right panel highlights the role of mortgage interest deductibility in shaping the lower boundary of the inaction region. A reduction in the tax rate θ lowers the present value of future interest deductions, thereby delaying the exercise of the buyback option and shifting $\underline{C}_\lambda(x;\bar{\kappa}_\lambda)$ downward. By contrast, the upper threshold, $\bar{C}_\lambda(x;\bar{\kappa}_\lambda)$, is largely insensitive to changes in the tax rate, reflecting the fact that par refinancing decisions are driven primarily by interest rate considerations rather than tax incentives.

Taken together, these comparative statics highlight two central mechanisms. First, the repurchase-at-market option mitigates mortgage lock-in by strengthening moving incentives when yield gaps are negative. This effect is intuitive: households that move while facing a negative yield gap can do so without forfeiting the capital gains embedded in their FRM.

Second, mortgage interest deductibility plays a key role in motivating discounted buybacks in Denmark. When yield gaps are negative, refinancing into a higher-coupon mortgage raises future interest deductions and thereby lowers the present value of lifetime tax liabilities. This mechanism closely parallels the trade-off theory of corporate leverage (Leland, 1994), in which firms balance the tax benefits of debt against expected distress costs. Analogously, households in our model trade off the tax advantages of higher mortgage interest payments against the fixed costs associated with mortgage buybacks.

4.8 Different beliefs over rate persistence

Our theory highlights the role of tax deductibility of mortgage interest in generating an incentive for borrowers to repurchase their mortgages at a discount. An alternative interpretation, however, is that some of the observed discounted buybacks in Denmark reflect differences in beliefs about the persistence of interest rates. Specifically, some households may view the current high-rate environment as transitory, in contrast to market expectations. Incorporating this mechanism requires relaxing the assumption of rational expectations. Consider, for instance, a setting in which households believe that the short-term interest rate exhibits a faster speed of mean reversion than lenders or the market anticipate.[28] Let η_b and η_ℓ denote the perceived mean-reversion parameters of borrowers and lenders, respectively, with $\eta_b > \eta_\ell$. Under this specification, borrowers' expectations of more rapid future rate declines can rationalize earlier buybacks, over and above the incentives created by tax deductibility.

Figure 10 illustrates this mechanism by comparing the implied mortgage rate, refinancing hazard, and moving hazard under homogeneous versus heterogeneous beliefs. In this example, $\eta_b = 2\eta_\ell$, i.e. households perceive the half-life of the rate process to be half as long as what the market expects. The figure shows that the discounted buyback hazard is substantially higher when borrowers perceive interest rates to be less persistent than the market, relative to the benchmark with homogeneous beliefs. This effects has however negligible effects onto equilibrium mortgage rates.

Empirically, both mechanisms are likely to operate: discounted buybacks may reflect households seeking to increase their tax shields, but also households who believe that elevated interest rates will be temporary relative to market expectations. Our interpretation is also informed by discussions with a senior practitioner at a large Danish mortgage lender. These conversations indicate that refinancing decisions are guided by structured advisory practices that emphasize both after-tax cash-flow comparisons and expectations about future interest rates. Advisors proactively contact borrowers when internal screening tools identify loans with substantial refinancing potential, and recommendations are typically based on break-even analyses comparing projected after-tax payments under the existing and prospective loans. In the context of upward conversion — replacing a low-coupon, discount-priced mortgage with a higher-coupon loan issued near par — advisors focus on the horizon over which the refinancing is expected to break even and on the borrower's expectations about future rate movements and the likelihood of subsequently refinancing again into a lower-coupon loan. These institutional features suggest that two economic forces are central to understanding discounted mortgage buybacks during recent rate increases: tax incentives, which make the relevant comparison one of

[28] Our framework would then be a special case of the more general case with heterogeneous beliefs, where agents are fully aware of each others' beliefs and they simply "agree to disagree" (Harrison and Kreps, 1978; Scheinkman and Xiong, 2003).

after-tax payments, and beliefs about interest rate mean reversion, which shape whether borrowers view the higher-coupon refinancing as a temporary bridge. Together, these considerations rationalize why borrowers may optimally replace low-coupon, discount-priced debt with higher-coupon, par-priced debt even when current market rates exceed the original contract rate.

4.9 Alternative channels

In addition to the tax and belief-based mechanisms discussed above, other economic forces — abstracted from in our framework — may also shape discount mortgage repurchases in Denmark.

For instance, another mechanism that may encourage discounted buybacks arises from the structure of the contribution fee charged by Danish mortgage institutions. This fee, which compensates lenders for the credit risk associated with the loan, depends on the LTV ratio at loan origination. When refinancing of a discounted mortgage reduces the outstanding principal relative to the property value, such transactions are accompanied by a decline in LTV and therefore a lower contribution fee. For example, in a cash-neutral conversion, a borrower who repurchases a DKK 1,000,000 mortgage trading at 75 and replaces it with a new DKK 750,000 loan issued at par substantially lowers the LTV of the mortgage, reducing the contribution fee going forward. While this mechanism may contribute to the attractiveness of discounted buybacks, we do not model it explicitly for three reasons. First, the empirical gradient of the contribution fee with respect to LTV appears relatively small: our estimates suggest that the fee increases by roughly 5 bps for each 10 p.p. increase in LTV. Second, incorporating this channel would require introducing LTV as an additional state variable in the model, increasing its dimensionality and complexity. Third, in our baseline model, upon the repurchase of a discount mortgage, the borrower extracts cash and keeps its mortgage face value constant, i.e. the mortgage LTV — and thus the contribution fee — would not change. For these reasons, we view the contribution-fee channel as a secondary force relative to the tax and belief-based mechanisms emphasized in our analysis.

Similarly, another potential motive for discounted buybacks is the opportunity to extract home equity and relax short-term liquidity constraints. In particular, borrowers facing lumpy expenditures or limited access to unsecured credit may use refinancing as a vehicle to convert housing wealth into liquid funds. Discounted buybacks are especially well suited for this purpose, as they allow households to retire existing debt at a discount and simultaneously issue new debt at par, generating cash proceeds whenever the new mortgage market value is strictly greater than the old mortgage market value. Capturing this mechanism in a fully satisfactory way would require a framework with risk-averse households, incomplete markets, idiosyncratic income risk, and endogenous liquid savings, in which refinancing decisions interact with consumption-smoothing motives. In contrast, our baseline model features risk-neutral borrowers without binding liquidity constraints, abstracting from these considerations. As a result, while home equity extraction may be a driver of refinancing behavior in practice, particularly for constrained households, it lies outside the scope of the present analysis.

4.10 U.S. prepayable mortgage debt

As discussed in Section 2, FRMs in the United States and Denmark share many contractual features, with one crucial exception: U.S. FRMs may only be prepaid at par, whereas Danish FRMs can also be repurchased at prevailing market prices. This distinction fundamentally alters borrowers' refinancing and moving incentives.[29] In this section, we use the model to study a counterfactual: how would U.S. household behavior and equilibrium mortgage interest rates change if U.S. FRMs were amended to include a repurchase-at-market option analogous to that in Denmark?

4.10.1 Introducing repurchase-at-market option in the U.S.

To fix ideas, it is useful to characterize FRM borrower behavior under two institutional regimes. First, we consider the current U.S. environment, in which borrowers cannot repurchase their mortgage debt at market prices; we denote all equilibrium objects in this case with the subscript "us". Second, we consider a counterfactual regime in which borrowers are allowed to repurchase their mortgage at market value, but in which realized capital gains from discount repurchases are taxable; equilibrium objects in this case are denoted with the subscript "us∗". Let θ_i denote the marginal tax rate on mortgage interest deductions and θ_g the marginal tax rate on capital gains.[30] The borrower value

[29] The Danish and U.S. mortgage systems differ along several additional dimensions, but these differences are unlikely to materially affect the quantitative conclusions of this section. For instance in Denmark, mortgage institutions retain borrower credit risk and charge a separate credit contribution fee (bidrag) to compensate for this risk. In the U.S. agency FRM market, credit risk is borne by the housing agencies, which charge a guarantee fee (G-fee) embedded in the mortgage coupon. Importantly, in both systems the interest cash flows received by mortgage investors exclude compensation for borrower credit risk, which instead accrues to the mortgage institution or agency. In both countries, credit compensation varies with borrower characteristics and the loan's initial LTV ratio.

[30] Following our discussion of Section 2.4, we assume for the purpose of this counterfactual analysis that gains related to discount mortgage repurchases would be treated as capital gains by the U.S. tax authorities.

functions v_{us} and $v_{\text{us}*}$ satisfy the following HJB equations:

$$\begin{aligned}(\rho+\alpha)v_{\text{us}}(x,c) &= \alpha+(1-\theta_i)c+\mathcal{L}v_{\text{us}}(x,c)\\ &\quad+\sum_{\beta=\psi,\lambda}\beta\mathbb{E}\left[\min\left[0,v_{\text{us}}\left(x,m_{\text{us}}(x)\right)+\tilde{\kappa}_\beta-v_{\text{us}}(x,c)\right]\right]\end{aligned} \tag{14}$$

$$\begin{aligned}(\rho+\alpha)v_{\text{us}*}(x,c) &= \alpha+(1-\theta_i)c+\mathcal{L}v_{\text{us}*}(x,c)\\ &\quad+\sum_{\beta=\psi,\lambda}\beta\mathbb{E}\left[\min\left[0,v_{\text{us}*}\left(x,m_{\text{us}*}(x)\right)+\tilde{\kappa}_\beta-v_{\text{us}*}(x,c)\right.\right.\\ &\qquad\qquad\left.\left.-(1-\theta_g)\max\left(0,1-p_{\text{us}*}\left(x,c\right)\right)\right]\right]\end{aligned} \tag{15}$$

The distinction between equation (14) — which applies to current U.S. FRMs — and the corresponding Danish equation (6) is straightforward. In Denmark, borrowers may repurchase their mortgage at market price or par, whichever is lower. In contrast, U.S. borrowers must always repay at par. When we introduce the repurchase-at-market option in the U.S., as in (15), we must additionally account for the fact that capital gains — whether arising from assets or liabilities — are taxable at rate θ_g. This contrasts with Denmark, where capital gains from discount mortgage repurchases are tax-exempt. Mortgage prices satisfy the martingale condition:

$$\begin{aligned}(r(x)+\alpha)p_{us}(x,c) &= c+\alpha+\mathcal{L}p_{us}(x,c)\\ &\quad+\sum_{\beta=\lambda,\psi}\beta\left[1-p_{us}(x,c)\right]\mathbb{P}\left(v_{us}(x,c)>v_{us}(x,m_{us}(x))+\tilde{\kappa}_\beta\right)\end{aligned} \tag{16}$$

$$\begin{aligned}(r(x)+\alpha)p_{\text{us}*}(x,c) &= c+\alpha+\mathcal{L}p_{\text{us}*}(x,c)\\ &\quad+\sum_{\beta=\lambda,\psi}\beta\min\left[0,1-p_{\text{us}*}(x,c)\right]\mathbb{P}\left(v_{\text{us}*}(x,c)>v_{\text{us}*}(x,m_{\text{us}*}(x))+\tilde{\kappa}_\beta\right.\\ &\qquad\qquad\left.-(1-\theta_g)\max\left[0,1-p_{\text{us}*}(x,c)\right]\right)\end{aligned} \tag{17}$$

As in our baseline model of Section 4.1, we abstract from default risk, since the credit risk of U.S. agency mortgages (the market most relevant for our counterfactual calculation) is borne by the GSEs in exchange for a guarantee fee embedded in the mortgage note rate, and agency MBS investors receive a coupon net of credit compensation; from their perspective, default is treated identically to prepayment.

To bring the model to the data, we estimate the shadow-rate process (13) by maximum likelihood using U.S. 10-year government bond yields for the time period 1987-2019. The resulting parameter estimates are reported in Table 4. Relative to Denmark, U.S. shadow rates are higher on average, slightly more volatile, and somewhat less persistent. We calibrate the remaining parameters using the same procedure described in Section 4.6, relying on U.S. data and the empirical evidence in Fonseca and Liu (2024) for moving hazards and Berger et al. (2025) for refinancing hazards. We set the marginal tax rate on mortgage interest deductions to 22% and the capital gains tax rate to 15%.[31] The resulting calibration is summarized in Table 3.

Figure 11 plots the model-implied refinancing and moving hazards with and without the repurchase-at-market option. Absent the option, refinancing hazards are zero for negative yield gaps and increase monotonically for positive gaps, eventually converging to λ. Moving hazards also increase monotonically with the yield gap, with a slope closely aligned with the empirical estimates in Fonseca and Liu (2024). Introducing the repurchase-at-market option has little effect on refinancing behavior. Although borrowers can realize capital gains and increase the value of the mortgage interest tax shield, this channel is substantially attenuated relative to Denmark by (i) lower marginal tax rates on mortgage interest deductions and (ii) taxation of realized capital gains. In contrast, moving behavior is significantly affected: moving hazards become much less sensitive to negative yield gaps once borrowers can repurchase at market value.

4.10.2 How much would mortgage rates increase by?

The model also clarifies how the repurchase-at-market option affects the level of equilibrium mortgage rates. In our calibration, equilibrium mortgage rates are on average only 18 bps higher with the option than without it. This cost, while non-trivial, remains modest. The reason is that the repurchase-at-market feature is not a true option from the lender's perspective: repurchases occur at fair market value, so their exercise does not directly affect lender payoffs. With the standard U.S. FRM, when mortgages trade below par, refinancing-related prepayments are non-existent and only a small number of move-related prepayments occur. These move-related prepayments benefit mortgage investors, who receive par for an asset trading at a discount, making U.S. FRMs slightly more valuable ex ante and thereby exerting downward pressure on mortgage rates. Because such events are infrequent, equilibrium mortgage rates for the contract with the repurchase-at-market option are only 18bps higher (on average) than those without the option.

Figure 12 provides a more detailed analysis of the difference in equilibrium mortgage rates between contracts with and without the repurchase-at-market option as a function

[31] A 22% marginal income tax rate applies to households with taxable income between $100,800 and $211,400 in FY 2025, while 15% is the federal long-term capital gains tax rate for households with income below $553,850. In practice, the U.S. tax code is more complex: mortgage interest deductions are available only to itemizing households and are capped at $750,000 of mortgage principal.

of the level of interest rates. When rates are low, the option increases mortgage rates by roughly 40 bps per year. By contrast, when rates are high, the difference in equilibrium rates between the two contracts is negligible. The intuition is straightforward. When rates are low, the term structure is typically upward sloping, so that even mortgages initially issued at par are likely to trade at a discount at some point in the future. It is precisely in these states — when mortgages trade below par — that contractual differences matter: move-related prepayments at par generate capital gains for investors holding discounted mortgages, lowering equilibrium mortgage rates under the current U.S. system. Allowing borrowers to repurchase at market value eliminates these gains, raising equilibrium rates. When rates are high, however, the term structure tends to be downward sloping, making it unlikely that newly issued high-coupon mortgages will trade at a discount. In that environment, the repurchase-at-market option has little value and therefore little effect on equilibrium mortgage rates.

4.10.3 What if discount mortgage repurchases were not taxable?

Adopting a Danish-style buyback system would substantially reduce the lock-in effects that characterize the U.S. mortgage market and could stimulate refinancing even in rising-rate environments. A key institutional difference, however, weakens this mechanism in the U.S.: unlike Denmark, where capital gains from mortgage buybacks are tax-exempt, U.S. tax law generally taxes capital gains on both assets and liabilities. This raises a natural counterfactual question: if the U.S. were to implement a Danish-style buyback system without taxing capital gains from discount mortgage repurchases, how much additional refinancing and mobility would result relative to a regime in which such gains are taxable? Our framework is well suited to address this question. The counterfactual simply requires solving (15) with $\theta_g = 0$.[32]

The results are shown in Figure 11. Relative to the taxable-gains case, refinancing hazards become strictly positive at negative yield gaps and increase in magnitude as the gap widens until the gap reaches -300 bps. Moving hazards are similarly amplified, rising by approximately 1 p.p. per year when the yield gap falls below -300 bps. Once again, equilibrium mortgage rates remain only marginally higher (18 bps on average) than in the absence of the repurchase-at-market option.

[32]To be precise, we need to solve for the entire MPE in the case where $\theta_g = 0$; in other words, not only do we need to find the value function $v_{\text{us}*}$, but we also need to solve for mortgage prices $p_{\text{us}*}$ and equilibrium mortgage rates $m_{\text{us}*}$ in the case where $\theta_g = 0$.

4.10.4 Neutralizing the pricing impact of the repurchase-at-market option

We then consider a simple modification of the prepayment rule that neutralizes the average effect of the repurchase-at-market option on equilibrium mortgage rates. Specifically, we allow borrowers to prepay at the minimum of (i) the market value of the mortgage and (ii) par plus a prepayment premium, where the premium is set so that the ergodic average mortgage rate coincides with that under the current U.S. contract (which is prepayable at par only). Intuitively, while the repurchase-at-market option removes the windfall to lenders associated with par prepayments when mortgages trade at a discount, the prepayment premium restores this value in expectation. Calibrating this premium within our model yields a value of 1.7% of outstanding principal. Under this contract, the average level of mortgage rates is unchanged, yet the state-contingent benefits of the repurchase-at-market option — most notably the mitigation of rate-induced lock-in — are preserved. This exercise highlights that the aggregate pricing impact of the option can be offset through modest adjustments to prepayment terms, without undoing its effects on household mobility.

4.10.5 Robustness

We assess the robustness of our estimate of the value of the repurchase-at-market option — 18 bps per annum on average in our baseline calibration — through a series of sensitivity analyses.

Figure 13 reports comparative statics for the ergodic average difference in equilibrium mortgage rates between contracts with and without the repurchase-at-market feature across alternative parameter values. The value of the option is primarily governed by two factors: the arrival intensity of moving opportunities and the dispersion of moving costs (and to a lesser extent the rate volatility). A higher arrival intensity increases moving rates uniformly, thereby raising the likelihood that move-related par prepayments occur when mortgages without the repurchase-at-market option trade at a discount. Similarly, greater dispersion in moving costs flattens the sensitivity of the moving hazard to the yield gap, increasing the probability that such prepayments occur in discount states. In both cases, the value of the repurchase-at-market option rises. Quantitatively, however, these effects remain moderate: even when the arrival intensity of moving opportunities increases by 25%, the ergodic average mortgage rate under the repurchase-at-market contract exceeds that under the current system by only 22 basis points.

A related question is whether the cost of the option depends on the treatment of home equity extraction at refinancing. In our baseline model, which features risk-neutral households and abstracts from liquidity motives, borrowers who refinance discounted mortgages keep the face value of their debt constant and extract the implied gains as cash. To assess the importance of this assumption, we solve an alternative specification in which refinancing is cash-neutral: households replace the existing mortgage with a new loan whose face value equals the market value of the old mortgage. Section A.1 provides details of this alternative model. Recomputing equilibrium mortgage rates with and without the repurchase-at-market option yields an option value that remains essentially unchanged at 18 bps per annum.

As a last robustness exercise, Section A.4 replaces our baseline one-factor shadow-rate term structure model with a two-factor specification in which the second factor captures stochastic interest-rate volatility.[33] The model is estimated using Treasury yields jointly with the Treasury Volatility Index (TYVIX), following the procedure described in the appendix. Re-estimating the counterfactual using this richer term structure model leaves our conclusions essentially unchanged: introducing a Danish-style buyback option into U.S. mortgages increases equilibrium mortgage rates by approximately 15 bps, compared with 18 bps under our baseline specification. This modest difference reflects the shorter estimation sample required by the availability of TYVIX data, which begins only in 2003, rather than the introduction of stochastic volatility itself.

Taken together, these results indicate that our conclusions are robust across a wide range of parameter values and modeling assumptions, and that introducing repurchase-at-market rights would increase equilibrium mortgage rates by a modest amount only.

5 Implementing buyback rights in the U.S.

This section outlines how a Danish-style buyback right could be implemented in the U.S. We compare this approach to the main alternatives — assumability and portability — and argue that buyback rights require no new infrastructure, only marginally alter the duration properties of prepayable fixed-rate mortgage debt, while being less dependent on lender discretion and better suited to the realities of household mobility.

5.1 Buyback option in the U.S. mortgage market

Agency market. There are at least two possible ways to introduce repurchase-at-market rights within the existing U.S. agency mortgage framework.

[33] We thank Dan Greenwald for making this suggestion.

A first approach would modify the prepayment provisions embedded in agency MBS contracts. Under this implementation, a borrower exercising the repurchase option would retire the mortgage by paying the lower of par and the prevailing market value of the loan. The corresponding amount of principal would then be written off from the associated MBS pool, with investors effectively realizing the resulting mark-to-market loss through reduced principal repayments. Because no secondary-market securities transaction would occur under this approach, the precise definition of "market value" would be of first-order importance for investors and would therefore need to be transparent, objective, and standardized. For example, market value could be determined using observable prices of agency MBS with similar characteristics, according to a methodology specified ex ante by the GSEs or regulators. This approach would be relatively simple to administer because it would require only modifications to prepayment and guarantee rules, while leaving the existing pooling, servicing, and trading infrastructure largely unchanged.[34] However, unlike the Danish system, it would force all investors in the affected securities to realize losses whenever borrowers exercise the option.

A second approach would more closely mirror the Danish covered-bond system. Under this implementation, a centralized registry would record a unique identifier for each mortgage and link it to the agency MBS pool in which it resides. A borrower wishing to repurchase a mortgage would transact through a broker or dealer acting on the borrower's behalf. Using the registry, the intermediary would identify the relevant MBS pool and acquire, in the secondary market, a quantity of securities corresponding to the outstanding principal balance of the loan. Once the required securities had been assembled and delivered, the mortgage would be extinguished and the corresponding amount of principal retired from the pool. The repurchase price would therefore be determined directly by observed market transactions in the relevant agency MBS. An important advantage of this approach is that it preserves the voluntary nature of mark-to-market realization. Investors wishing to retain discounted agency MBS could continue to hold them, while only investors choosing to sell would realize any associated capital losses. In this respect, the mechanism closely resembles the Danish system, where mortgage repurchases are funded through purchases of outstanding mortgage bonds in the sec-

[34] Implementing this approach would require revising the GSE guarantee from "timely payment of principal and interest" to a structure that preserves timely interest while allowing principal payments at market value. We thank Ed Golding for highlighting the analogy to REMIC structures: GSEs already guarantee securities whose principal repayment rules differ from simple par pass-through. Similar to the introduction of UMBS, credit risk transfer ("CRT") securities, or adjustments in guarantee fees, implementing repurchase-at-market rights for new agency mortgages would likely require regulatory action by FHFA to modify guarantee language and MBS contracts, but would not necessarily require congressional legislation.

ondary market rather than through mandatory principal write-downs imposed on all bondholders. The primary additional operational requirement would be the creation of a standardized registry linking individual mortgages to their corresponding MBS pools.

Both approaches could, in principle, coexist with the existing agency mortgage infrastructure. Mortgages would continue to be originated, pooled, guaranteed, serviced, and traded through the current agency MBS and TBA framework. The first implementation emphasizes administrative simplicity, whereas the second more faithfully reproduces the economic structure of the Danish system by relying on voluntary secondary-market transactions.[35]

Jumbo market. In the jumbo segment, deposit-taking institutions frequently retain newly originated mortgages on their balance sheets as portfolio loans. When market interest rates rise above the mortgage coupon, borrowers could in principle approach the lender and offer to repurchase the mortgage at a discount: economically, the market value of the loan has fallen below par, implying that a discounted payoff may still exceed the loan's market value to the lender. In practice, however, portfolio mortgages are generally classified as held-for-investment ("HFI") and carried at amortized cost rather than marked to market. As a result, increases in interest rates typically do not generate corresponding mark-to-market losses in reported earnings or regulatory capital. A discounted repurchase, by contrast, would crystallize part of the loan's unrealized economic loss into a realized accounting loss, to the extent that the repurchase price falls below the loan's carrying value net of loan-loss allowances. Such losses would immediately reduce reported earnings and, potentially, regulatory capital ratios. Consequently, banks may be reluctant to entertain discounted buybacks even when they are economically efficient ex ante. More generally, the accounting and regulatory treatment of HFI loans creates an asymmetry between the economic and accounting valuation of fixed-rate mortgages when interest rates rise, thereby discouraging discounted repurchases relative to the Danish mortgage system. Reforming accounting and regulatory capital rules to better reflect mark-to-market values — so that unrealized losses are recognized more transparently in earnings and regulatory capital — would reduce these barriers and facilitate the adoption of repurchase-at-market provisions in the jumbo mortgage market.

[35]Our quantitative analysis abstracts from these implementation details and instead focuses on the economic consequences of granting borrowers the right to retire mortgage debt at market value. Because both approaches ultimately allow borrowers to capture the market value of their mortgage liabilities when rates rise, we expect the implications for household mobility, refinancing behavior, and equilibrium mortgage rates to be broadly similar across implementations.

5.2 Comparison with alternative mechanisms

Assumability and portability represent the main alternatives for addressing lock-in while preserving fixed-rate contracts. Assumable mortgages allow a home buyer to take over the seller's existing mortgage, preserving the original contract rate even when market rates have risen. This feature exists in U.S. government-backed programs: FHA, VA, and USDA loans contain qualifying-assumption clauses that permit a creditworthy buyer to assume the seller's loan, subject to lender approval and underwriting. Portable mortgages, by contrast, allow the borrower to transfer an existing mortgage from one property to another when moving. Portability is institutionalized in Canada and the U.K., with regulatory recognition (OSFI/Bank of Canada classify straight ports as collateral substitution; the FCA records ported mortgages in regulatory sales data) and standard product offerings at major lenders. Canadian lenders offer port-and-increase, port-and-decrease, and delayed-port variants. In both systems, however, porting requires re-underwriting of the household and the new collateral, and incremental borrowing is priced at current market rates. Both mechanisms aim to preserve the below-market contract rate across moves, but they do so by changing either the obligor (assumability) or the collateral (portability), and both require lender consent at each transaction.

At first glance, assumability and portability appear to offer benefits similar to buyback rights. In practice, buyback rights dominate: they convert discretionary lender approval into contractual obligations at market prices, they function regardless of whether households upsize or downsize, and they operate through existing refinancing infrastructure rather than requiring new systems that favor sophisticated borrowers.

Discretion and price mismatch. The fundamental difference between buyback rights and alternatives lies in institutional architecture. Buyback rights convert discretionary approval processes into contractual obligations relying on market-based pricing, while portability and assumability multiply decision points where lenders or counterparties can deny access. Assumability changes the obligor and therefore always requires lender consent and full re-underwriting of the buyer. Portability changes the collateral and therefore requires re-underwriting of the property, updated loan-to-value checks, product-eligibility screens, and new title and lien work. Each step adds veto points where institutional discretion can block the transaction. These frictions become acute when we recognize that most household moves involve changing home values — households upsize as income grows, downsize in retirement, or relocate across markets with different price levels. Consider a homeowner with a $400,000 mortgage carrying a 3% coupon who wishes to move and purchase a larger home requiring $600,000 in financing after market mortgage rates have risen to 7%. Under a buyback regime, the homeowner first sells the existing property and uses part of the sale proceeds to repurchase the outstanding mortgage at its market value (approximately \$280,000), thereby realizing a \$120,000 gain on the discount mortgage repurchase. The homeowner then purchases the new property and originates a new first-lien mortgage for \$600,000 at the prevailing 7% market rate. Operationally, the transaction resembles a conventional sale-and-purchase financed with a new mortgage, except that the original mortgage is retired at market value rather than at par.

Under assumability, the household must find a buyer willing to assume the existing \$400,000 loan at 3% — a bilateral bargaining problem — while the seller simultaneously gives up the below-market contract when originating a new mortgage on the next property. Even if a buyer is found, the embedded subsidy on the assumed loan capitalizes into the home's listing price: a rational buyer values the 3% loan at its \$120,000 market premium over a new 7% loan and bids the listing price up accordingly. The benefit attaches to the property rather than traveling with the household. Moreover, because the buyer typically needs additional financing beyond the \$400,000 assumed balance — since house prices appreciate and loan balances amortize — the buyer faces the same coordination problem of layering new debt at current rates on top of the assumed loan.

Under portability, the household retains the contract but cannot retain its rate on the full new balance. The \$400,000 old balance ports at 3%, but the additional \$200,000 must be financed at the prevailing 7% market rate, typically through a blended-rate "port-and-increase" structure as in Canada. The blended rate on the new \$600,000 mortgage is approximately $\$400{,}000/\$600{,}000 \times 3\% + \$200{,}000/\$600{,}000 \times 7\% \approx 4.33\%$ — better than refinancing entirely at 7%, but well above the 3% rate the household retained by staying. The borrower still bears the full market rate on the incremental \$200,000 of borrowing. Buyback rights eliminate this wedge: the gain on the old balance is monetized rather than tied to the unchanged portion of the loan.

This asymmetry concentrates on the moves that matter most. Households upsize in response to income growth, family formation, and job-driven relocation — precisely the lifecycle transitions where mobility frictions generate the largest welfare and allocative costs. Portability provides the least relief on these moves; assumability transfers the subsidy to sellers rather than to the moving household; buyback rights deliver full mobility regardless of move direction or size, with the gain accruing to the household.

Revealed preference. A natural benchmark is the existing assumability feature in FHA and VA loans, which is contractually permitted yet almost never used. Between 2001 and 2019, only about 104,000 FHA loans were assumed, with annual assumption rates falling from 0.27% of active loans in 2001 to roughly 0.05% by 2006 (Park, 2022, exhibits 5–6). More recent data are equally stark: FHA assumptions totaled just 2,221 in 2022 and 3,825 in 2023, while VA assumptions were 308 and 2,244, respectively (Lerner, 2024; U.S. House of Representatives, Committee on Financial Services, 2024). With 7-8 million active FHA-insured loans outstanding, these volumes represent well under 0.05% of eligible mortgages annually.

The Danish mortgage system provides a second benchmark. To quantify the prevalence of mortgage assumption, we examine Danish registry data (see data description in Section 3.1) and identify assumed mortgages using two complementary approaches. First, we track mortgages that persist from one year to the next but become associated with a new borrower identification number. Second, to ensure that observed changes are not driven by administrative reassignment of loan identifiers, we identify cases in which property ownership changes while the mortgage retains the same coupon rate and maturity year. Both methods yield nearly identical counts: fewer than 2,500 assumed mortgages from 2020 to 2023, against approximately 100,000 discount FRM repurchases in 2022 and again in 2023. Even in a market explicitly designed to facilitate transferability, assumptions remain exceedingly rare.

These experiences demonstrate that contractual assumability alone is insufficient to generate meaningful take-up. Discretionary underwriting, coordination frictions at closing, and lender gatekeeping keep utilization negligible and access highly unequal. A common critique of buyback rights is that they disproportionately benefit sophisticated borrowers. If anything, the opposite is true: assumability and portability require navigating discretionary approvals, bilateral bargaining, and complex multi-lien structures, while buyback rights are contractually self-executing at observable market prices. They operate through existing payoff-and-origination infrastructure, require no new servicing systems or investor disclosures, and are universally accessible by design. The mortgage market already prices and hedges prepayment risk extensively; introducing a buyback right at market value simply removes move-related par-prepayments of discount mortgages, slightly increasing equilibrium mortgage rates and durations (see discussion in Section 4.10). Assumability and portability, by contrast, would require building tri-party workflows, collateral-swap tracking systems, and robust second-lien markets in the U.S. — infrastructure that exists in Canada and the U.K. but does not currently exist in the U.S. mortgage system.

5.3 ARMs vs. FRMs

Finally, one alternative for eliminating lock-in is adjustable-rate mortgages, which index payments to market rates and thus carry no embedded capital gains to forfeit. Whatever the merits of ARMs — whether for reducing lock-in, lowering borrowing costs, or improving monetary policy transmission — we do not view them as a realistic solution for the U.S. at this time. Over 85 percent of U.S. mortgage borrowers hold fixed-rate products, and the 30-year FRM is deeply embedded in American housing finance. Rather than prescribe a different mortgage type, we take households' preferences over interest rate exposure as given (Auclert, 2019) and ask how to reduce the frictions embedded in their chosen contracts. In the U.S., these frictions are substantial: households face high fixed refinancing costs, and when they move, they give up their mortgage coupon, effectively surrendering embedded capital gains. Based on 2024 Q2 data, Batzer et al. (2024) estimate these foregone gains at approximately USD 2.4 trillion.

6 Conclusion

Our paper shows that mortgage contract design plays a central role in shaping how households respond to interest rate shocks. In the Danish fixed-rate mortgage system, the ability to repurchase debt at market value fundamentally alters refinancing and moving behavior, weakening the rate-induced lock-in that characterizes the U.S. mortgage market. We document these patterns empirically and develop an equilibrium model that highlights how buyback rights and tax incentives jointly govern household decisions.

Our counterfactual analysis demonstrates that introducing a Danish-style buyback option into U.S. fixed-rate mortgages would substantially reduce lock-in and preserve household mobility, with only modest effects on equilibrium mortgage pricing. The strength of these effects depends on institutional details, particularly the tax treatment of mortgage interest and capital gains from debt forgiveness. More broadly, our findings emphasize that liability-side contract features are an important margin through which interest rate risk is distributed between households and lenders. Designing mortgage contracts that allow households to actively manage the market value of their liabilities with limited frictions can meaningfully alter the transmission of interest rate shocks, improve the functioning of housing and mortgage markets, and enhance household mobility.

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Table 1: Summary statistics for homeowners

	2010			2023			Pooled		
	ARM	FRM	NM	ARM	FRM	NM	ARM	FRM	NM
Mortgage characteristics									
Face value (in ,000)	1,286	874		1,667	1,315		1,393	1,113	
Original Maturity (in years)	29.03	27.36		28.87	27.01		28.85	26.85	
Coupon (%)	2.73	5.00		0.39	1.95		0.74	3.00	
Coupon gap (%)	-2.27	0.00		-3.61	-2.05		-2.11	0.23	
Issuance yield (%)		5.29			2.18			3.31	
Yield gap (%)		0.10			-2.73			0.38	
Simple averages									
Prepayment rate (in %)	9.37	24.48		10.26	17.48		12.60	21.22	
Refi rate (in %)	4.89	17.53		2.80	10.77		6.09	14.31	
Moving rate (in %)	3.64	2.88	3.60	4.14	3.32	4.64	4.39	3.31	4.16
Value weighted averages									
Prepayment rate (in %)	8.94	29.45		10.02	20.77		12.86	24.19	
Refi rate (in %)	4.64	23.28		3.17	14.34		6.48	18.08	
Moving rate (in %)	3.56	2.83		4.13	3.26		4.36	3.38	
Counts									
Count (in ,000)	528	581	342	523	606	350	8,151	7,489	4,703
Frequency (in %)	36.38	40.04	23.58	35.38	40.94	23.68	40.07	36.81	23.12

Note: The sample/data consists of the primary mortgages of all Danish households who own property. The statistics are computed for the years 2010, 2023 and for the full pooled sample. The frequency shows the percentage of each homeowner type among all homeowners. Prepayment, refinancing and moving rates are calculated for each individual homeowner type. Weighted averages are weighted by face value, while all homeowners are equally weighted for the simple averages. We use the abbreviation "NM" for homeowners with no mortgage.

Table 2: Moving and the (piece-wise linear) yield gap

	OLS		
	(1)	(2)	(3)
	Moving (pct)	Moving (pct)	Moving (pct)
Yield gap (p.p.)	-0.0115***	0.0158***	0.00851
	(0.00394)	(0.00488)	(0.00742)
Positive yield gap indicator	0.0140	0.0312***	0.0145
	(0.0142)	(0.00827)	(0.00972)
Yield gap X positive gap	0.0273**	0.0303***	0.0825***
	(0.0105)	(0.00529)	(0.00882)
Controls		X	X
Household FE			X
R-squared	0.00000894	0.000981	0.0410
Root MSE	5.659	5.508	5.427
F-stat			
Observations	64655942	61776297	61773308

Note: The table reports marginal effects on moving propensity of the yield gap, an indicator for a positive yield gap, and the interaction. For scaling purposes, the dependent variable is a binary indicator that takes the value 100 if the household moves. Column (1) reports estimates without additional controls. Column (2) adds a set of baseline controls following Fonseca and Liu (2024), including household age and age squared; household type (couple, single female, single male); log face value of the mortgage; log average monthly mortgage payment; remaining mortgage term fixed effects; month fixed effects; and year-by-municipality fixed effects. Column (3) adds household fixed effects to the regression of Column (2). Standard errors are double clustered at the issuance month–year and municipality levels and reported in parentheses, $^{*}\ p < 0.10$, $^{**}\ p < 0.05$, $^{***}\ p < 0.01$.

Table 3: Model parameters

Parameter	Description	Value Denmark	Value U.S.
Borrowers and mortgage contract			
ρ	discount rate	0.05	0.05
θ	marginal tax rate	0.33	0.22
θ_g	capital gains' tax rate	0	0.15
α	amortization rate	1/30	1/30
Refinancing			
λ	refinancing opportunity hazard	0.33	0.23
κ_λ	refinancing costs (mean)	0.008	0.015
σ_λ	refinancing costs (s.d.)	0.005	0.005
Moving			
ψ	moving opportunity hazard	0.055	0.13
κ_ψ	net moving costs (mean)	0	0
σ_ψ	net moving costs (s.d.)	0.10	0.20

Note: This table reports parameters for our baseline model. Refinancing costs are assumed to be lognormally distributed, while net moving costs are assumed to be normally distributed.

Table 4: Term structure model estimation

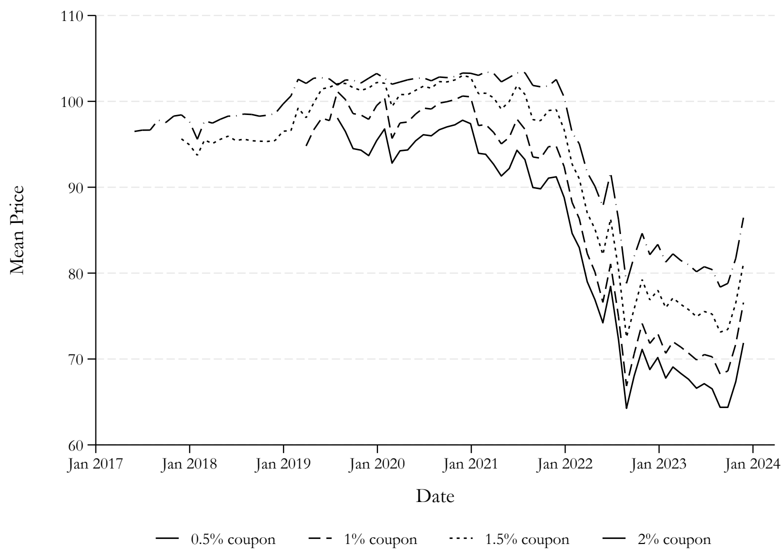
Parameter	Estimate	Std. Error	C.I.
Denmark			
$\bar{x}$	0.51%	0.04%	$[0.43\%, 0.58\%]$
η	0.0917	0.0103	$[0.0715, 0.1118]$
σ	1.31%	0.01%	$[1.29\%, 1.34\%]$
United States			
$\bar{x}$	3.97%	0.06%	$[3.85\%, 4.10\%]$
η	0.1195	0.0021	$[0.1153, 0.1236]$
σ	1.47%	0.04%	$[1.39\%, 1.55\%]$

Note: This table reports parameter estimates from the shadow rate model described in Section 4.6. Estimates are obtained by maximum likelihood using monthly zero-coupon yield data from Danish and U.S. government bonds. For each parameter vector $(\bar{x}, \eta, \sigma)$, we numerically compute the model-implied term structure of interest rates $\{y_T(x)\}_{T\geq 0}$, and for each monthly zero coupon yield observation in our sample we retrieve the shadow rate x_t. Once we have retrieved the time-series of shadow rates $\{x_t\}_{t\geq 0}$, the likelihood of the data is straightforward to compute given that the increments of x_t are Gaussian. Confidence intervals are computed using the observed information matrix.

Figure 1: 30-year FRMs

(a): Mortgage rates

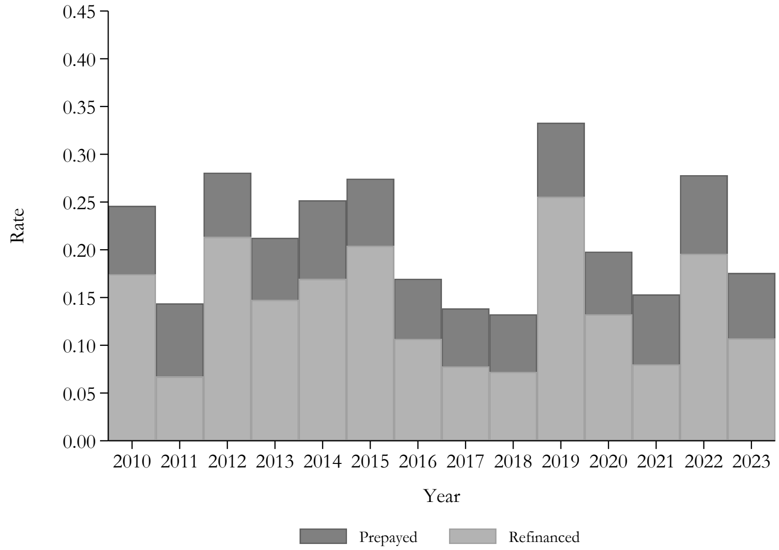
(b): Mortgage prices



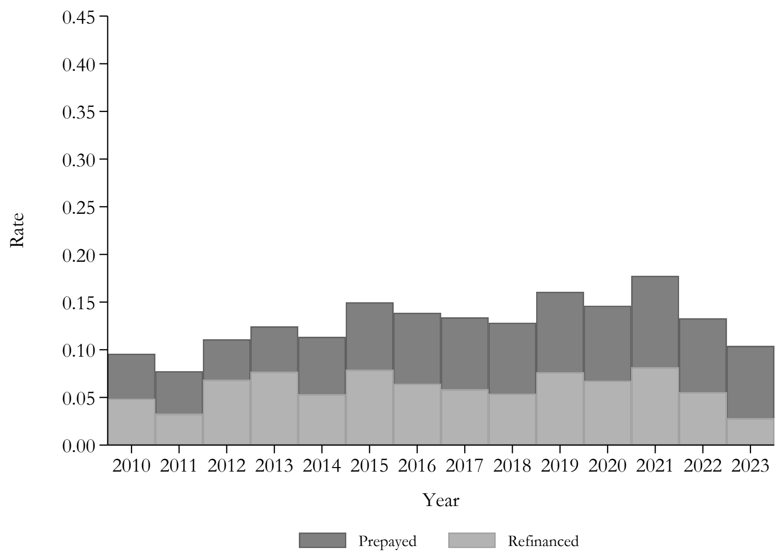
Note: Top figure shows the yields on newly-issued long-term FRMs, as provided by FinansDanmark. Bottom figure shows the market price for 30-year fixed-rate mortgage bonds maturing in 2050, carrying various fixed coupons, averaged across 7 of the largest mortgage institutions in Denmark: Nykredit, Totalkredit, LR, Jyske, Nordea, Realkredit Danmark, and BRF (source: Værdipapirs Centralen).

Figure 2: Prepayment and refinancing rates

(a): FRMs



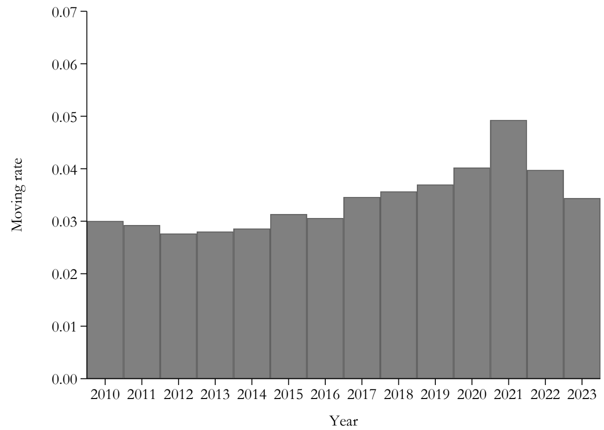
(b): ARMs



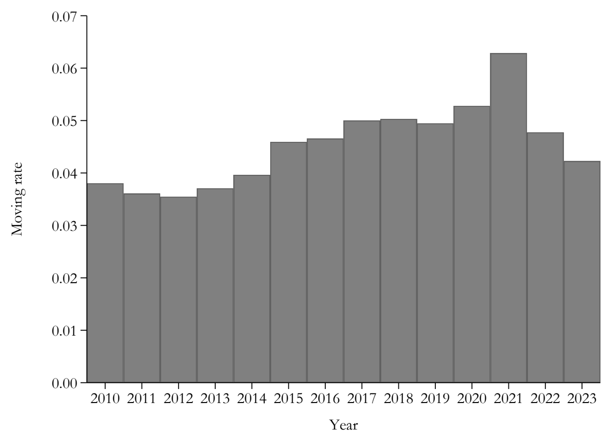
Note: Figure shows the primary mortgages of a given type prepaid or refinanced in a given year, as a fraction of the mortgage of that type outstanding at the beginning of the year. The top figure presents the data for fixed-rate mortgages (FRMs), while the bottom figure presents the data for adjustable rate mortgages (ARMs).

Figure 3: Moving rates

(a): FRMs

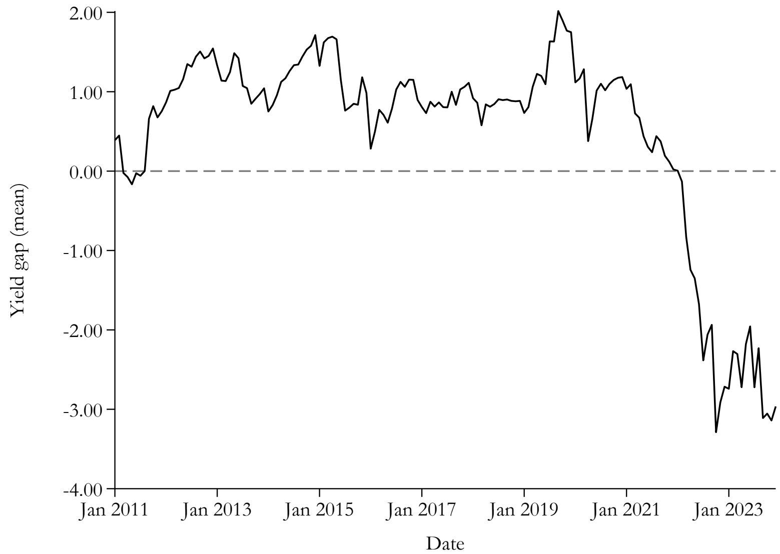


(b): ARMs



Note: The figure shows the aggregate moving rate among fixed-rate mortgage (FRM) holders (Panel a) and among adjustable-rate mortgage (ARM) holders (Panel b).

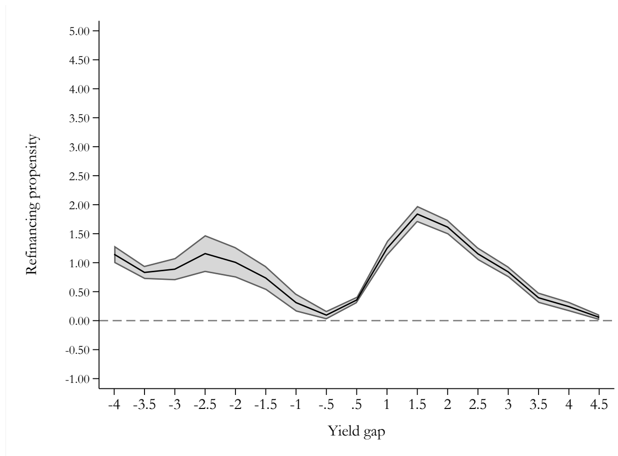
Figure 4: Average yield gap over time



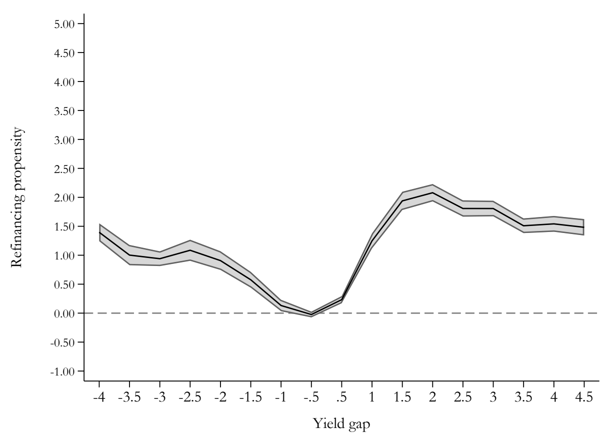
Note: Figure shows the average yield gap of all households with their largest mortgages being an FRM in a given year. Yield gap is the difference between (a) the (long-term) mortgage market yield prevailing when the household originated its mortgage and (b) the contemporaneous (long-term) mortgage market yield.

Figure 5: Refinancing propensities

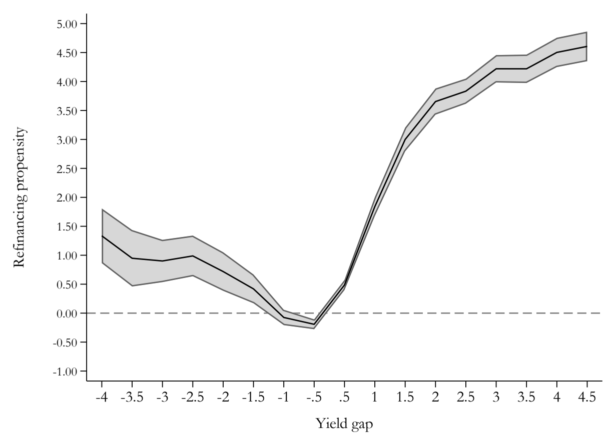
(a): No controls



(b): Controls



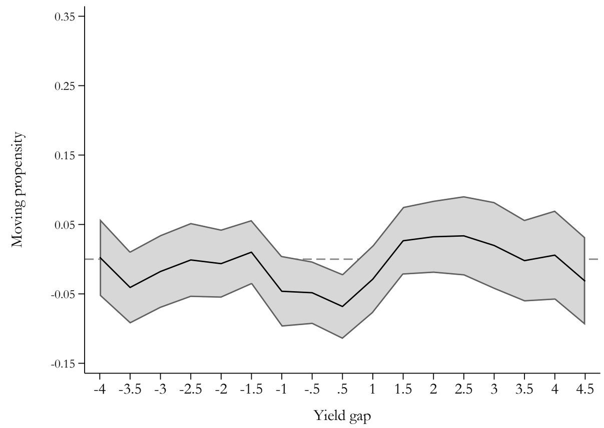
(c): Household Fixed Effects



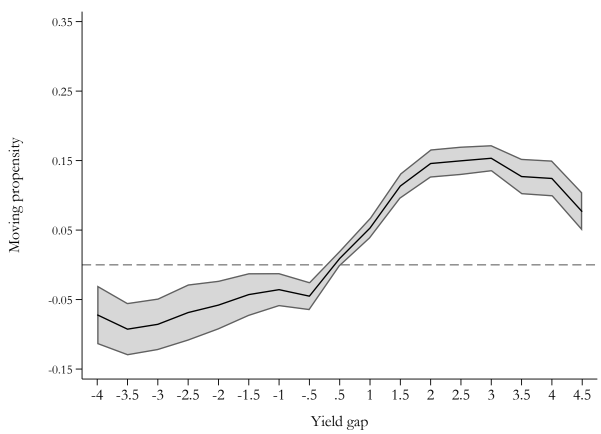
Note: **Panel A** shows the propensity to refinance as a function of yield gap dummies with 50 bps intervals without controlling for further factors. **Panel B** shows refinancing propensities as a function of yield gap dummies at 50 bps intervals, while controlling for variables similar to Fonseca and Liu (2024) (household age, household age squared, gender (couple, single female, single male), log face value, log of average monthly mortgage payment, month fixed effects, year-municipality fixed effects and remaining mortgage term fixed effects). **Panel C** shows the coefficient estimates controlling for household fixed effects. For interpretational purposes, the plots display the interval spanning the 0.5th to the 99.5th percentile of yield gap values grouped into 50 bps bins, with the baseline yield gap category set to zero across all panels. Standard errors are double clustered by issuance month-year and municipality.

Figure 6: Moving propensities

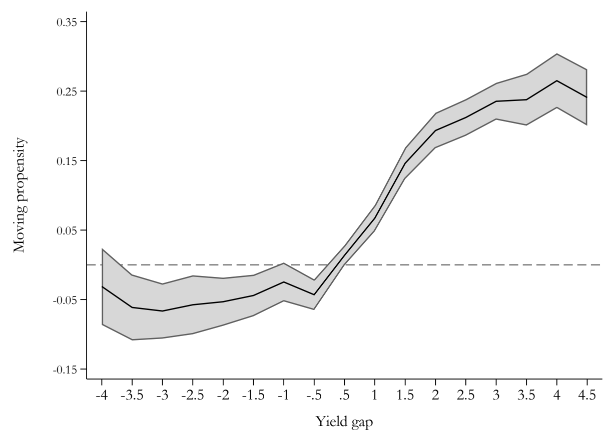
(a): No controls



(b): Controls



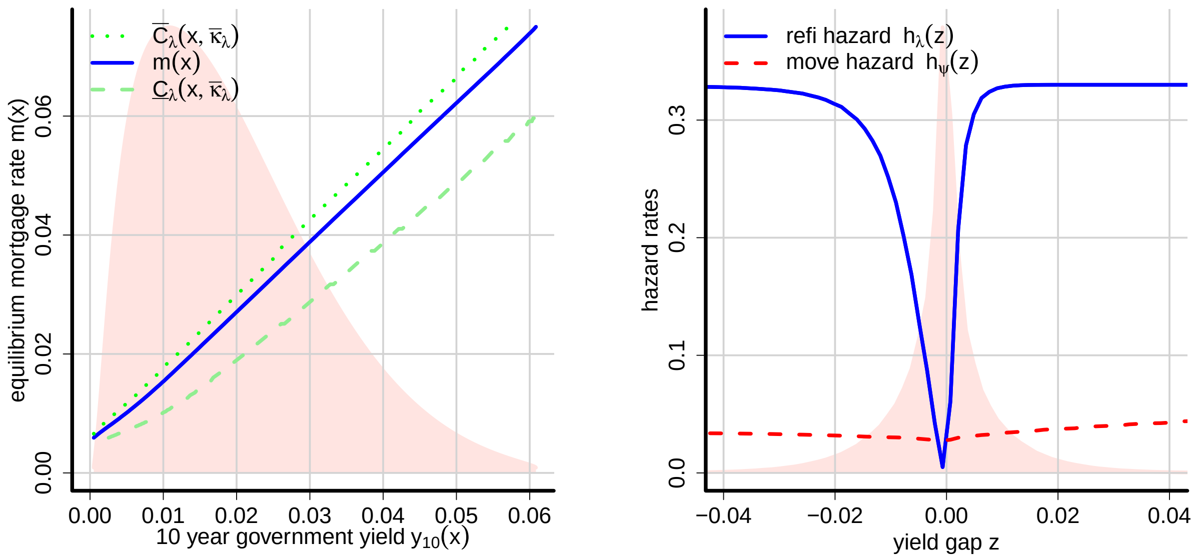
(c): Household Fixed Effects



Note: **Panel A** shows the propensity to move as a function of yield gap dummies with 50 bps intervals without controlling for further factors. **Panel B** shows moving propensities as a function of yield gap dummies at 50 bps intervals, while controlling for variables similar to Fonseca and Liu (2024) (household age, household age squared, gender (couple, single female, single male), log face value, log of average monthly mortgage payment, month fixed effects, year-municipality fixed effects and remaining mortgage term fixed effects). **Panel C** shows the coefficient estimates controlling for household fixed effects. For interpretational purposes, the plots display the interval spanning the 0.5th to the 99.5th percentile of yield gap values grouped into 50 bps bins, with the baseline yield gap category set to zero across all panels. Standard errors are double clustered by issuance month-year and municipality.

Figure 7: Equilibrium illustration

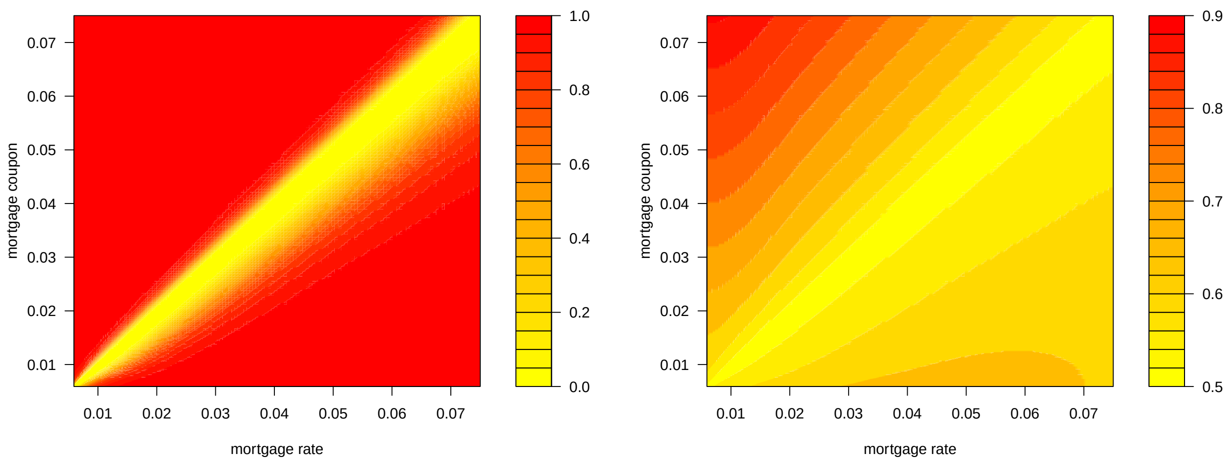
(a): Mortgage rate $m(x)$ **(b):** Hazard rates $h(z)$



Note: Left figure shows the equilibrium mortgage rate $m(x)$ (solid blue), the lower boundary of the inaction region $\underline{C}_\lambda(x;\bar{\kappa}_\lambda)$ (dashed green, below which the borrower optimally buys back her mortgage at a discount, when the refinancing cost is equal to its mean $\bar{\kappa}_\lambda$) and the upper boundary of the inaction region $\bar{C}_\lambda(x;\bar{\kappa}_\lambda)$ (dotted green, above which the borrower optimally prepays her mortgage at par, when the refinancing cost is equal to its mean $\bar{\kappa}_\lambda$), plotted as a function of the 10-year government yield $y_{10}(x)$ (see Section A.3 for a reminder of its definition). Right figure shows the implied refinancing, move and prepayment hazard rates, as a function of the yield gap z. In both figures, the pink shaded area shows the ergodic density — on the left figure, the ergodic density of the 10-year government yield $y_{10}(x)$, and on the right figure, the ergodic density of the yield gap z.

Figure 8: Exercise probabilities

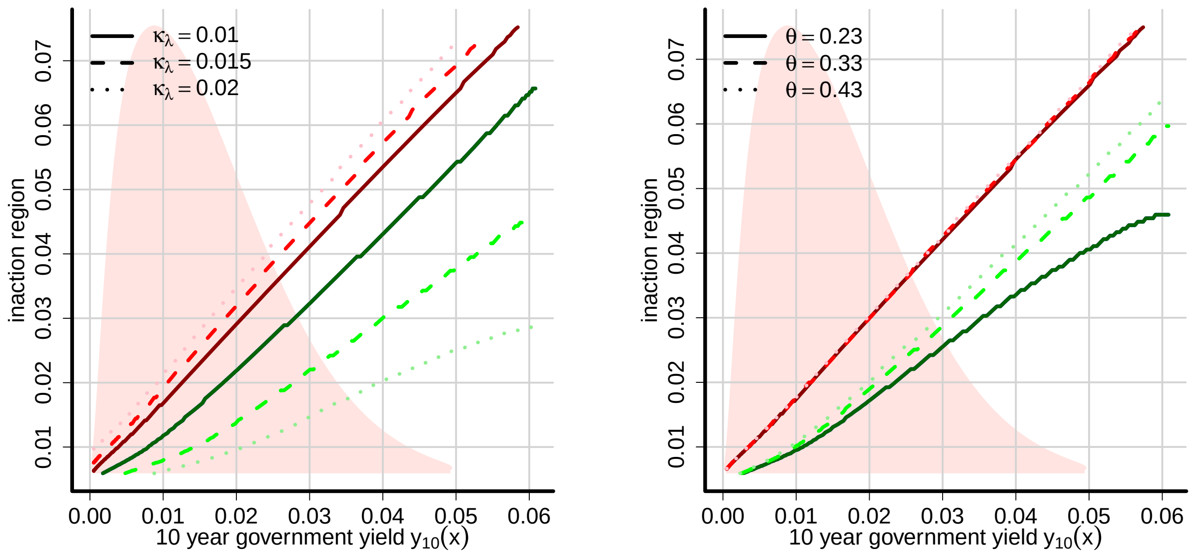
(a): Refinancing probability **(b):** Moving probability



Note: Figures show the refinancing (left-hand side) and moving (right-hand side) probabilities for the baseline calibration of our model, conditional on getting an opportunity to refinance or move. These probabilities are illustrated as functions of the current coupon c on the mortgage, and current mortgage market interest rate $m(x)$ when the borrower receives an opportunity to refinance or move.

Figure 9: Comparative statics

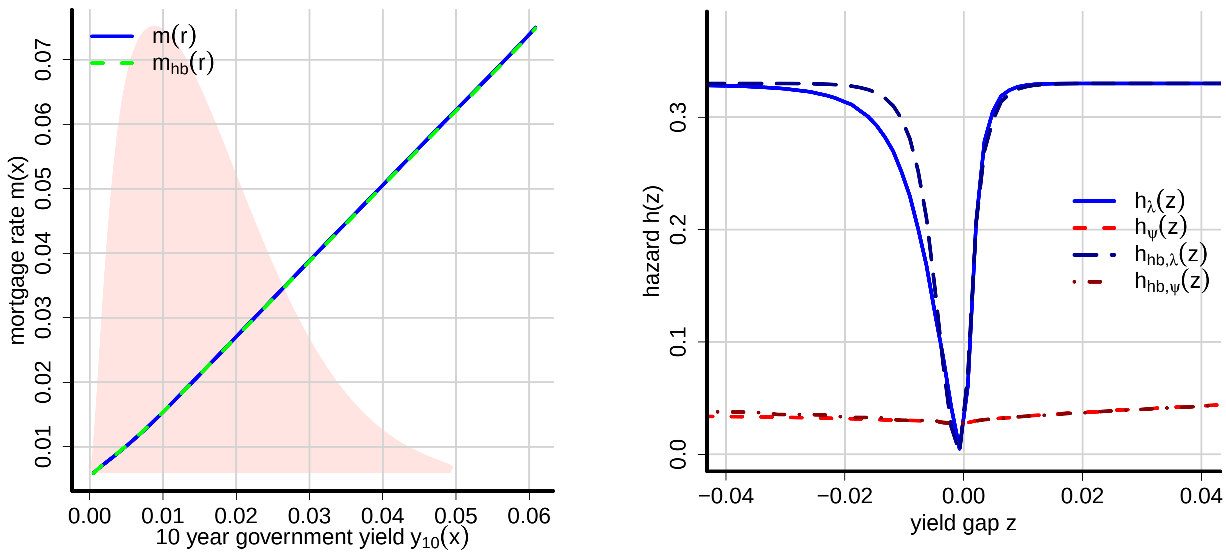
(a): Avg. refinancing cost $\bar{\kappa}_\lambda$ **(b):** Tax rate θ



Note: Figures show the refinancing inaction region $\mathcal{I}_\lambda(x; \bar{\kappa}_\lambda)$ for varying values of the average refinancing cost $\bar{\kappa}_\lambda$ (left figure) and tax rate θ (right figure), plotted as a function of the 10-year government yield $y_{10}(x)$ (see Section A.3 for a reminder of its definition). In each figure, the upper boundary $\bar{C}_\lambda(x; \bar{\kappa}_\lambda)$ of the inaction region is represented in red, while the lower boundary $\underline{C}_\lambda(x; \bar{\kappa}_\lambda)$ of the inaction region is represented in green, and both these inaction regions are evaluated when the random refinancing cost is equal to $\bar{\kappa}_\lambda$.

Figure 10: Different beliefs over rate persistence

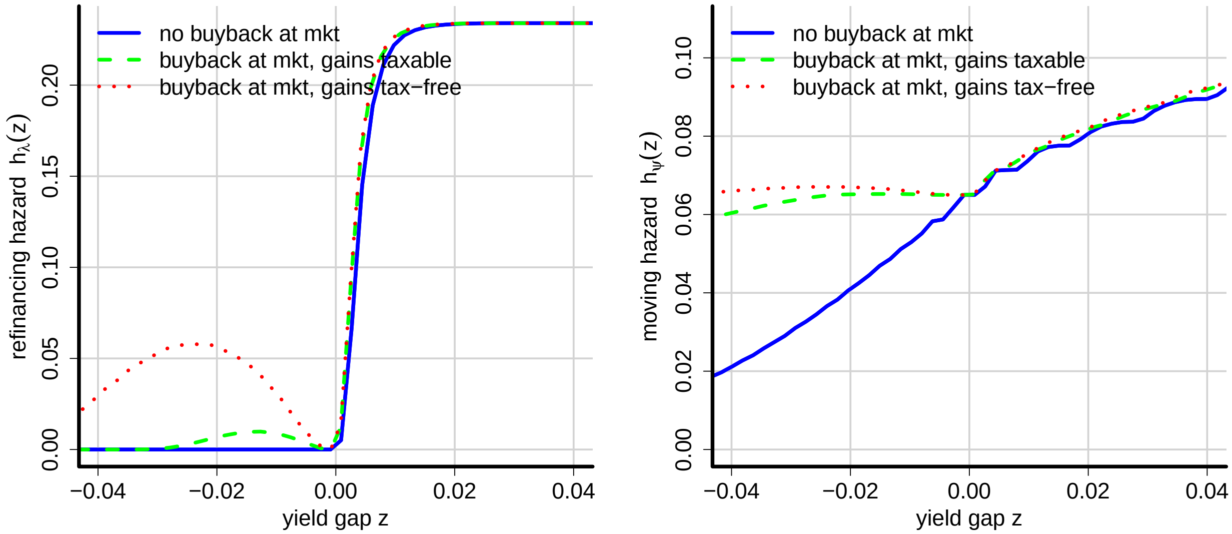
(a): Mortgage rate $m(x)$ **(b):** Hazard rates $h(z)$



Note: Left figure shows the equilibrium mortgage rate $m(x)$ when households and the market have homogeneous beliefs (solid blue) and when households perceive the speed of mean reversion to be twice as fast as the market's belief (dash green). Right figure shows the implied refinancing, move and prepayment hazard rates, as a function of the yield gap z.

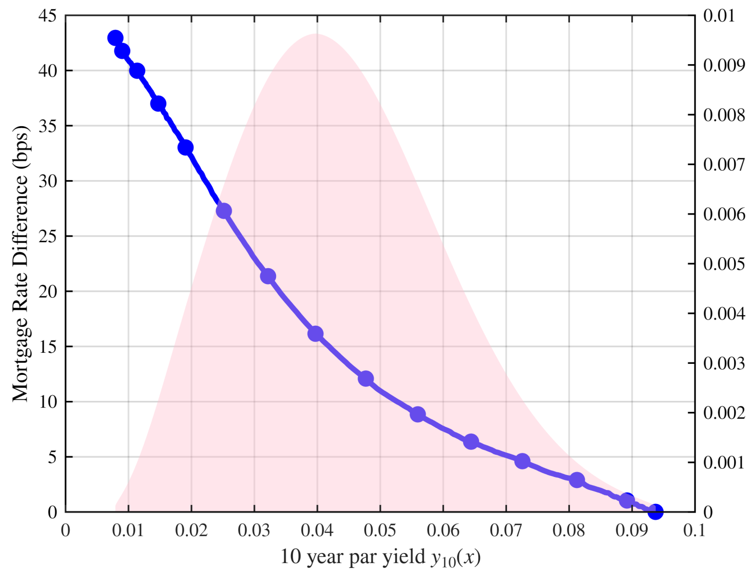
Figure 11: U.S. FRMs: with vs. without buyback option

(a): Refinancing hazard $h_\lambda(z)$ **(b):** Moving hazard $h_\psi(z)$



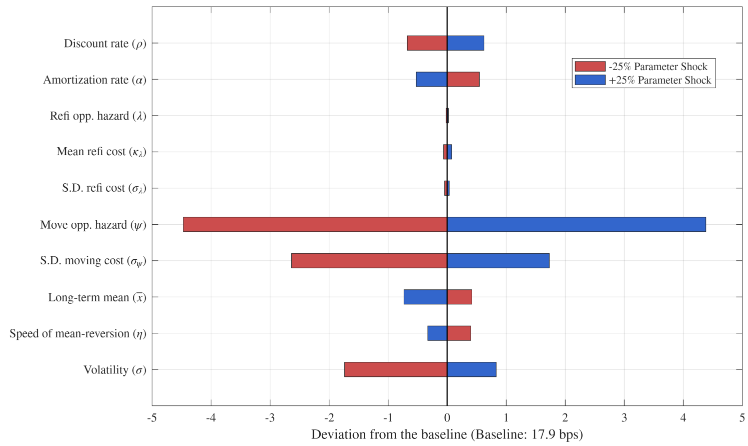
Note: Left (resp. right) figure shows the implied refinancing (resp. moving) hazard rates, as a function of the yield gap z, for FRMs without a repurchase-at-market option (solid blue line), with a repurchase-at-market option with capital gains taxes on discount repurchases (dash green line), and with a repurchase-at-market option with capital gains on discount repurchases non-taxable (dotted red line).

Figure 12: Effect of repurchase-at-market option on U.S. mortgage rates



Note: The blue dotted line shows the difference in U.S. equilibrium mortgage rates (in bps) between (a) the contract with the buyback option and (b) the contract without it. The pink shaded area shows the ergodic density of the 10-year government yield $y_{10}(x)$.

Figure 13: Sensitivity analysis on the effect of repurchase-at-market option on U.S. mortgage rates



Note: This figure illustrates the sensitivity of the effect of the repurchase-at-market option on equilibrium mortgage rates to parameter variations. The bars plot the deviation in the average mortgage rate difference between the two contracts relative to the benchmark calibration. Blue (red) bars represent the results with a 25% increase (decrease) in the specified parameter, holding all other parameters constant.

A Appendix: theory and numerical analysis

A.1 Extension: no cash-out upon discounted buybacks

We revisit an assumption in our baseline model of Section 4.1: when refinancing or moving, the household is assumed to maintain the original mortgage balance and extracts home equity whenever the mortgage trades at a discount. We now consider an alternative behavior. Suppose that, upon refinancing or moving, the household instead chooses to conduct a cash-neutral transaction. That is, if the mortgage is trading at a discount when the opportunity to refinance or move arrives, the household reduces the face value of the new mortgage so that the transaction requires no net cash outlay. Under this alternative assumption, the household's problem becomes:

$$v(x,c) = \inf_{a\in\mathcal{A}} \mathbb{E}_{x,c}\left[\int_0^{+\infty} e^{-\int_0^t (\rho+\alpha)ds + a_s \sum_{\beta=\lambda,\psi} \ln\min(1,p(x_{s-},c_{s-}))dN_s^\beta} \left(\left((1-\theta)c_t^{(a)}+\alpha\right)dt + a_s \sum_{\beta=\lambda,\psi} \kappa_\beta dN_s^\beta\right)\right],$$

$$\text{s.t.} \qquad dc_t^{(a)} = \left(m(x_t) - c_{t-}^{(a)}\right) a_t \left(\sum_{\beta=\lambda,\psi} dN_t^{(\beta)}\right)$$

This formulation makes it clear that the mortgage debt face value jumps discretely whenever buy-backs are done at a discount to par. The corresponding HJB equation for households' value function is

$$(\rho+\alpha)v(x,c) = \alpha + (1-\theta)c + \mathcal{L}v(x,c) + \sum_{\beta=\lambda,\psi} \beta \min\left[0, \min\left(1,p(x,c)\right)\cdot v(x,m(x)) + \kappa_\beta - v(x,c)\right] \quad \text{(B-1)}$$

Consequently, the lower bound of the inaction region $\underline{C}_\beta(x;\kappa_\beta)$, which was (10) in the baseline, is now modified to:

$$v(x,\underline{C}_\beta) = p(x,\underline{C}_\beta)\cdot v(x,m(x)) + \kappa_\beta \quad \text{(B-2)}$$

The ergodic density $f(x,c)$ is governed by the modified KF equation as below:

$$0 = \mathcal{L}^* f(x,c) - \sum_{\beta=\lambda,\psi} \beta F_\beta\Big(v(x,c) - \min(1,p(x,c))\cdot v(x,m(x))\Big) f(x,c) \quad \text{(B-3)}$$

The aggregate hazard rates are now calculated as:

$$h_\beta(z) = \beta \frac{\int F_\beta\Big(v(x,z+m(x)) - \min(1,p(x,z+m(x)))\cdot v(x,m(x))\Big) f(x,z+m(x))dx}{\int f\left(x,z+m(x)\right)dx}, \quad \beta=\lambda,\psi$$

$$h(z) = h_\lambda(z) + h_\psi(z).$$

Mortgage prices follow the usual martingale condition (7). In figure (xxx), we compare the inaction regions in the model with cash-outs upon discount repurchases to the model with discrete face value reductions upon discount repurchases.

A.2 Equilibrium computation

A.2.1 Notation

Since we assume a univariate process for the term structure state variable x_t, and since we assume that $r(\cdot)$ is monotone, one can introduce the variable x^*, defined as the value of the state x that was prevalent the last time a household took on a new mortgage: $m(x^*) := c$. For numerical calculations, we find it convenient to transform our state vector from (x, c), to (x, x^*). We implement a finite difference scheme to compute the functions (v, p) at $n \times n$ discrete points $\left(x_i, x_j^*\right)$ of the state space, for $1 \leq i, j \leq n$. Our discrete points are equally spaced by Δ_x. In order to calculate $v(x, x^*)$ and $p(x, x^*)$, we will look for a stationary solution to time-dependent functions $v^{(k)}(x, x^*)$, $p^{(k)}(x, x^*)$ (where k represents the iteration step) obtained iteratively via a false transient algorithm. We note $v_{i,j,k} = v^{(k)}(x_i, x_j^*)$ the borrower value function at iteration k, and use similar notation for mortgage prices. We note $m_{i,k} = m^{(k)}(x_i)$ the mortgage rate at iteration k, when the term structure state variable is x_i. We start with arbitrary chosen values $\left(v_{i,j,0}\right)_{i,j \leq n}$ and $\left(p_{i,j,0}\right)_{i,j \leq n}$, as well as a mortgage rate function $(m_{i,0})_{i \leq n}$. We define the forward, backward and centered difference approximations of $\partial_x v$ at iteration k as follows:

$$\partial_x v_{i,j,k}^b := \frac{v_{i,j,k} - v_{i-1,j,k}}{\Delta_x} \qquad \partial_x v_{i,j,k}^f := \frac{v_{i+1,j,k} - v_{i,j,k}}{\Delta_x} \qquad \partial_x v_{i,j,k}^c := \frac{v_{i+1,j,k} - v_{i-1,j,k}}{2\Delta_x}.$$

The finite difference approximation of $\partial_x v$ at step k will then be implemented using an upwinding scheme as follows:

$$\partial_x v_{i,j,k} := \mathbf{1}_{\{\mu_{x,i} < 0\}} \partial_x v_{i,j,k}^b + \mathbf{1}_{\{\mu_{x,i} \geq 0\}} \partial_x v_{i,j,k}^f,$$

where we have used the notation $\mu_{x,i} := \mu(x_i)$. We use a similar finite difference approximation of $\partial_x p$ at step k. Lastly, for both v and p, the finite difference approximation of $\partial_{xx}\phi$ (for $\phi = v$ or $\phi = p$) at iteration k will then be:

$$\partial_{xx}\phi_{i,j,k} := \frac{\phi_{i+1,j,k} + \phi_{i-1,j,k} - 2\phi_{i,j,k}}{\Delta_x^2}.$$

A.2.2 Borrower value function

The discretization of equation (6) leads to a system of equations in the $n \times n$ unknown $\left(v_{i,j,k}\right)_{i,j \leq n}$:

$$\frac{v_{i,j,k} - v_{i,j,k-1}}{\Delta_t} + (\rho + \alpha)\, v_{i,j,k} = \alpha + (1-\theta) m_{j,k-1} + \sum_{\ell \in \{i-1,i,i+1\}} L_{i,\ell} v_{\ell,j,k}$$
$$+ \sum_{\beta=\lambda,\psi} \beta \int \min\left[0, v_{i,i,k-1} + \kappa_\beta - \max\left(0, 1 - p_{i,j,k-1}\right) - v_{i,j,k-1}\right] dF_\beta(\kappa_\beta) \quad \text{(B-4)}$$

This system of $n \times n$ equations, with unknown elements $v_{i,j,k}$ for $1 \leq i, j \leq n$, can be encoded in matrix form:

$$\left[\left(\frac{1}{\Delta_t} + \rho + \alpha\right) I - L\right] \vec{v}_k = \frac{1}{\Delta_t} \vec{v}_{k-1} + \alpha \vec{1} + (1-\theta) \vec{m}_{k-1} + \vec{o}_{k-1},$$

where the $n^2 \times 1$ vector $\vec{v}_k$ has entry $v_{i,j,k}$ in row $i + (j-1)n$, where I is a square $n^2 \times n^2$ identity matrix, where the $n^2 \times 1$ vector $\vec{1}$ has entries 1 at each row, where the $n^2 \times 1$ vector $\vec{m}_{k-1}$ has entry $m_{j,k-1}$ in all rows $i + (j-1)n, i \in \{1, ..., n\}$, where the $n^2 \times 1$ vector $\vec{o}_{k-1}$ has entry $\sum_{\beta=\lambda,\psi} \beta \int \min\left[0, v_{i,i,k-1} + \kappa_\beta - \max\left(0, 1 - p_{i,j,k-1}\right) - v_{i,j,k-1}\right] dF_\beta(\kappa_\beta)$ in row $i + (j-1)n$, and where the $n^2 \times n^2$ matrix L is block-diagonal, where each of the n sub-blocks have dimension $n \times n$ and are identical and equal to L_x. The $n \times n$ matrix L_x is the discrete state counterpart to the Feynman-Kac operator $\mathcal{L}$. It is a tri-diagonal matrix encoding the dynamic evolution of x_t. Its diagonal elements ($L_{x,i,i}$) and off-diagonal terms ($L_{x,i,i-1}$ and $L_{x,i,i+1}$) are the following:

$$L_{x,i,i} = -\left(\frac{|\mu_{x,i}|}{\Delta_x} + \frac{\sigma_{x,i}^2}{\Delta_x^2}\right) \qquad L_{x,i,i-1} = -\frac{\min\left(0, \mu_{x,i}\right)}{\Delta_x} + \frac{\sigma_{x,i}^2}{2\Delta_x^2} \qquad L_{x,i,i+1} = \frac{\max\left(0, \mu_{x,i}\right)}{\Delta_x} + \frac{\sigma_{x,i}^2}{2\Delta_x^2}$$

A.2.3 Mortgage prices

For given value function $\left(v_{i,j,k-1}\right)_{i,j \leq n}$ at step $k-1$, we can compute the optimal moving and refinancing strategies of the borrower. In particular, one can determine when the borrower prepays (either at par, or at a discount), via:

$$\pi_{i,j,k-1}^{\beta} := \Pr\left(v_{i,j,k-1} > v_{i,i,k-1} + \tilde{\kappa}_\beta - \max\left(0, 1 - p_{i,j,k-1}\right)\right),$$

where $\pi_{i,j,k-1}^{\beta}$ is the probability that the borrower prepays (when $\beta = \lambda$) or moves (when $\beta = \psi$). The discretization of equation (7) leads to a system of equations in the n^2 unknown $\left(p_{i,j,k}\right)_{i,j \leq n}$, which can be written

$$\frac{p_{i,j,k} - p_{i,j,k-1}}{\Delta_t} + \left(r_i + \alpha + \sum_{\beta=\lambda,\psi} \beta \pi_{i,j,k-1}^{\beta}\right) p_{i,j,k} = \alpha + m_{j,k-1} + \sum_{\ell \in \{i-1,i,i+1\}} L_{i,\ell} p_{\ell,j,k}$$
$$+ \sum_{\beta=\lambda,\psi} \beta \pi_{i,j,k-1}^{\beta} \min\left(1, p_{i,j,k-1}\right), \quad \text{(B-5)}$$

where $r_i := r(x_i)$. This system of n^2 equations, with unknown elements $p_{i,j,k}$ for $1 \leq i, j \leq n$, can be encoded in matrix form:

$$\left[\left(\frac{1}{\Delta_t} + \alpha\right) I + R + \sum_{\beta=\lambda,\psi} \beta\Pi^\beta - L\right] \vec{p}_k = \frac{1}{\Delta_t}\vec{p}_{k-1} + \alpha\vec{1} + \vec{m}_{k-1} + \sum_{\beta=\lambda,\psi} \beta\Pi^\beta \min\left(\vec{p}_{k-1}, \vec{1}\right), \tag{B-6}$$

where the $n^2 \times 1$ vector $\vec{p}_k$ has entry $p_{i,j,k}$ in row $i + (j-1)n$, where Π^β is a square $n^2 \times n^2$ diagonal matrix with entry $\pi^\beta_{i,j,k-1}$ in row (and column) $i + (j-1)n$, and where R is a square $n^2 \times n^2$ diagonal matrix with entry $r(x_i)$ in row (and column) $i + (j-1)n$, for all $1 \leq j \leq n$. Once we have computed mortgage prices at iteration k, we can update equilibrium mortgage rates, via identity (8).

A.2.4 Ergodic density

The discretization of the dynamic system (x_t, x^*_t) can then be encoded via an $n^2 \times n^2$ matrix Λ, which encodes both (i) state transitions driven by the exogenous process x_t, and (ii) (endogenous) prepayments leading to changes in the state variable x^*_t. The ergodic density of the dynamic system follows equation (12) is then a vector $\vec{f}$ that is an eigen-vector of the matrix Λ', associated with the eigen-value zero, and which integrates to 1, i.e.:

$$\Lambda'\vec{f} = \vec{0} \qquad \vec{f} \cdot \vec{1}\Delta^2_x = 1. \tag{B-7}$$

A.3 Interest rate process estimation

In this section, we provide details of the estimation of the interest rate process for the Danish and U.S. term structure of interest rates. Imagine that the short term rate is $r(x_t) = \max(0, x_t)$, where x_t follows a Vasicek process:

$$dx_t = -\eta_x (x_t - \bar{x})\, dt + \sigma_x dZ_t.$$

The price of a T-maturity bullet bond with coupon c is by definition equal to

$$P(x, T; c) := \mathbb{E}_x \left[\int_0^T e^{-\int_0^t r(x_s)ds} c\,dt + e^{-\int_0^T r(x_s)ds}\right].$$

The T-maturity spot yield is then equal to $y^*_T(x) := -(1/T) \ln P(x, T; 0)$. The function $P(x, t; c)$ satisfies the standard PDE

$$\begin{aligned} r(x)P(x,t;c) &= c - \eta_x (x - \bar{x})\, \partial_x P(x,t;c) + \frac{\sigma_x^2}{2} \partial_{xx} P(x,t;c) - \partial_t P(x,t;c) \\ P(x,0;c) &= 1 \end{aligned}$$

Assume now that we have discretized the state variable x on a grid spaced by Δ_x, and that the infinitessimal operator has also been discretized, with associated intensity matrix L_x. Denote $R := \mathrm{diag}(r(x_i))$, the price vector $\vec{P}(t;c)$ encodes the price of the coupon bond at each state x_i, and it solves

$$(R - L_x)\vec{P}(t;c) = c\vec{1} - \partial_t \vec{P}(t;c)$$
$$\vec{P}(0;c) = \vec{1},$$

which admits the analytic solution

$$\vec{P}(t;c) = \exp\left((L_x - R)t\right)\vec{1} + c(R - L_x)^{-1}\left[I - \exp\left((L_x - R)t\right)\right]\vec{1}$$

Given an empirical time series $\{y^*_{T,t}\}_{t=1,\dots,n_t}$ of T-year spot rates, one can use our solution method to retrieve the shadow state x_t that solves $\ln P(x_t, T; 0) = -Ty^*_{T,t}$. Once we have recovered the time-series of shadow short rates $\{x_t\}_{t=1,\dots,n_t}$, it is straightforward to compute the likelihood of this sequence of shadow rates, since the increments of x_t are normally distributed.

To end this section, we remind the reader of the definition of the T-maturity par yield $y_T(x)$: it is defined as the coupon of a T-maturity fixed rate bond that is trading at par at time of issuance, when the term-structure state variable is equal to x. In other words, the T-maturity par yield must satisfy $P(x, T; y_T(x)) := 1$.

A.4 Regime-switching volatility in the shadow-rate model

The counterfactual analysis of Section 4.10 prices the repurchase-at-market option in a single-factor shadow-rate model, estimated by maximum likelihood as described in Section A.3. This appendix assesses the robustness of that exercise to a richer description of interest-rate dynamics. We augment the single latent factor with a two-state, regime-switching stochastic volatility, and discipline the volatility process with the CBOE Treasury-note volatility index (TYVIX), estimating the system jointly on the 10-year U.S. Treasury yield and TYVIX using a simulation-based Bayesian procedure.

A.4.1 Model and bond pricing

As in the main text, the instantaneous short rate is a shadow rate,

$$r_t = \max(0,\, x_t), \tag{B-8}$$

where the latent shadow rate x_t follows the Ornstein–Uhlenbeck process of (13), with a volatility that now depends on a latent regime s_t:

$$dx_t = -\eta\,(x_t - \bar{x})\,dt + \sigma_{s_t}\,dZ_t, \qquad s_t \in \{\ell, h\}. \tag{B-9}$$

Here $\eta > 0$ is the speed of mean reversion, $\bar{x}$ the long-run mean, and $\sigma_{s_t} \in \{\sigma_\ell, \sigma_h\}$ the regime-dependent volatility with $\sigma_h > \sigma_\ell$; setting $\sigma_\ell = \sigma_h$ recovers the single-factor process (13) of Section 4.6. The regime s_t is a continuous-time Markov chain with generator

$$\Lambda = \begin{pmatrix} -\lambda_{\ell h} & \lambda_{\ell h} \\ \lambda_{h\ell} & -\lambda_{h\ell} \end{pmatrix}, \qquad \Pi(\tau) = e^{\Lambda\tau}, \tag{B-10}$$

where $\lambda_{\ell h}, \lambda_{h\ell} > 0$ are transition *intensities* (rates per year) and $\Pi(\tau)$ is the matrix of transition probabilities over horizon τ. The parameter vector is $\Theta = (\eta, \bar{x}, \sigma_\ell, \sigma_h, \lambda_{\ell h}, \lambda_{h\ell})$, augmented by two measurement-error scales introduced below at the estimation stage. As in Section A.3, the estimated dynamics serve as the pricing dynamics, so that the volatility regimes are pinned down jointly by the yield and by TYVIX.

Bond pricing is unchanged from Section A.3 except that the diffusion now carries a regime label. We discretize the state space in the direction x as before, numerically solve for bond prices $P(x, s, t; c)$ as a function of the arbitrary coupon c, and define the 10-year (zero-coupon) yield via:

$$y^*_{10}(x, s) := -\frac{1}{10} \log P(x, s, 10; 0), \tag{B-11}$$

That is, $y^*_{10}(x, s)$ is the regime-conditional counterpart of the spot yield $y^*_{10}(x)$ of Section A.3, computed conditional on the prevailing regime.

A.4.2 From the model to TYVIX: the measurement equations

The two observables are the 10-year Treasury spot yield y_t and TYVIX v_t. The yield maps directly into the model through the pricing function, so its measurement equation is

$$y_t = y^*_{10}(x_t, s_t; \Theta) + \varepsilon^y_t, \qquad \varepsilon^y_t \sim \mathcal{N}(0, \sigma^2_y). \tag{B-12}$$

Mapping TYVIX requires more care, because TYVIX is a price volatility rather than a state variable. By construction, TYVIX is the (annualized) market-implied expected volatility of the 10-year Treasury futures price over the next 30 days,

$$\mathrm{TYVIX}^2_t \;\approx\; \tfrac{1}{\Delta}\,\mathbb{E}_t \int_t^{t+\Delta} \sigma^2_F(u)\, du, \qquad \Delta := \tfrac{30}{365}, \tag{B-13}$$

where $\sigma_F(u)$ is the instantaneous volatility of the futures price. To connect σ_F to the model, apply Itô's lemma to the (log) bond price as a function of the shadow rate: locally $d \log P \approx (\partial_x \log P)\, dx_t$, so the price inherits a volatility $|\partial_x \log P|\, \sigma_{s_t}$. Defining the duration-like loading

$$D^{10}(x, s) := \partial_x \log P(x, s, 10; 0) = -10 \partial_x y^*_{10}(x, s), \tag{B-14}$$

one finds that $\sigma_F(u) \approx D^{10}(x_u, s_u)\, \sigma_{s_u}$ is a good approximation to the futures-price volatility—the product of the bond's sensitivity to the state and the state's own volatility. Substituting and conditioning on the current regime gives the regime-switching expression

$$V^{10}(x_t, s_t) \approx \frac{1}{\Delta}\int_0^{\Delta} \sum_{j\in\{\ell,h\}} \Pi_{s_t j}(u)\big(D^{10}(x_t, j)\sigma_j\big)^2 du, \qquad \text{TYVIX}_t = 100\sqrt{V^{10}(x_t, s_t)}. \quad \text{(B-15)}$$

Because both x_t and s_t are highly persistent relative to the 30-day horizon Δ, the integral is well approximated by freezing the state at its current value,

$$V^{10}(x_t, s_t) \approx \big(D^{10}(x_t, s_t)\sigma_{s_t}\big)^2. \quad \text{(B-16)}$$

This persistence approximation removes the need to integrate the transition density over the option horizon at every likelihood evaluation and substantially accelerates the estimation, at negligible cost in accuracy. The TYVIX measurement equation is then taken in *levels* (percentage volatility), matching the model-implied price volatility directly to the observed index:

$$v_t = 100D^{10}(x_t, s_t)\sigma_{s_t} + \varepsilon_t^v, \qquad \varepsilon_t^v \sim \mathcal{N}(0, \sigma_v^2). \quad \text{(B-17)}$$

Equations (B-12) and (B-17) make the latent state (x_t, s_t) a nonlinear, non-Gaussian, regime-switching state-space system, with the yield identifying the level factor and the volatility index speaking to the volatility regime.

A.4.3 Estimation and data

Because the regime-switching shadow-rate process makes the state-space system nonlinear and non-Gaussian, the exact-inversion maximum-likelihood approach of Section A.3 is unavailable here. The process can no longer be inverted in closed form and its filtering distribution is non-Gaussian. The same obstacle rules out the Kalman filter, the standard tool in the shadow-rate literature (e.g., Wu and Xia, 2016). We therefore evaluate the likelihood with a *bootstrap particle filter*. The filter carries a swarm of $N = 2{,}000$ "particles", each a candidate value of the hidden state (x_t, s_t). Each month the particles are propagated through the model dynamics (a regime draw from $\Pi(\Delta)$ and an Ornstein–Uhlenbeck step with the regime's volatility) and re-weighted by how well they explain the observed yield and TYVIX through equations (B-12) and (B-17). The mean particle weight each month estimates that month's likelihood contribution, and the product across the T months gives an estimate of the joint likelihood $\widehat{p}(y_{1:T}, v_{1:T} \mid \Theta)$ that is *noisy but unbiased*.

The posterior is then obtained by *particle marginal Metropolis–Hastings* (PMMH; Andrieu, Doucet and Holenstein, 2010), a Bayesian MCMC algorithm in which the intractable likelihood in the Metropolis–Hastings acceptance ratio is replaced by the particle-filter estimate $\widehat{p}$. The pseudo-marginal property guarantees that, because $\widehat{p}$ is unbiased, the chain retains the *exact* posterior as its stationary distribution for any number of particles; more particles improve mixing rather than removing bias. We use a random-walk, one-at-a-time proposal, Gaussian priors with hard support bounds, and Robbins–Monro adaptation of the proposal scales during burn-in. A fresh filter is run at each proposal and the current likelihood is carried between accepted draws, as required for validity. The measurement-error scales σ_y, σ_v are estimated jointly with Θ.

TYVIX is available only from 2003, so, unlike the 1987–2019 single-factor estimation, the regime-switching model is estimated on monthly data from January 2003 to December 2019 ($T = 204$) using the 10-year constant-maturity Treasury yield and TYVIX (FRED series VXTYN).

A.4.4 Estimation results

Table A-3 reports the baseline posterior. The chain is run for 5,000 iterations (1,000 burn-in); the reported posterior standard deviations and 95% intervals are the standard deviation and the 2.5–97.5 percentile (equal-tailed credible) interval of the post-burn-in draws.

The level factor is estimated with a mean-reversion speed $\eta \approx 0.17$ (a half-life of about four years) toward a long-run shadow rate $\bar{x} \approx 1.8\%$. The lower long-run mean relative to the single-factor U.S. estimate in Table 4 ($\bar{x} = 3.97\%$) reflects the shorter, lower-rate 2003–2019 window; the two regime volatilities, $\sigma_\ell \approx 1.1\%$ and $\sigma_h \approx 2.1\%$, straddle the single-factor estimate of 1.47%. The two volatility states are well separated, with $\sigma_h/\sigma_\ell \approx 1.8$. The transition intensities imply a mean duration of roughly $1/\lambda_{\ell h} \approx 3.1$ years in the low-volatility state and $1/\lambda_{h\ell} \approx 1.2$ years in the high-volatility state, and an ergodic probability of the high-volatility state of $\lambda_{\ell h}/(\lambda_{\ell h} + \lambda_{h\ell}) \approx 0.29$. The high-volatility regime probability is elevated over 2008–2013, consistent with the financial-crisis and post-crisis period.

The estimates are stable across a range of checks. Doubling the iterations (to 10,000) and raising the particle count (to 4,000) leaves the posterior essentially unchanged, confirming particle-independence and that the particle-filter noise is not biasing the posterior. The estimates are likewise insensitive to the random seed and to $\pm 10\%$ changes in the starting values. Fixing the transition intensities at the estimates of Kalimipalli and Susmel (2004), $\lambda_{\ell h} \approx 0.32$ and $\lambda_{h\ell} \approx 1.80$, leaves the remaining parameters close to the baseline, with only a small fall in the log-likelihood.

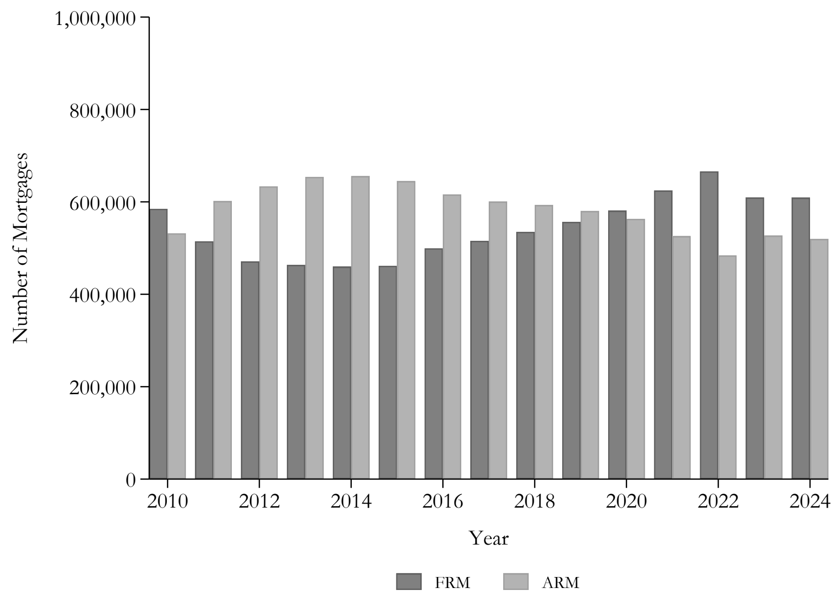
A.4.5 Value of the repurchase-at-market option

Using the baseline regime-switching estimates, the ergodic-average difference in equilibrium U.S. mortgage rates between the contract with and without the repurchase-at-market option is approximately 15 bps, close to the single-factor baseline of 18 bps. The difference between these two numbers arises from the different sample periods used for estimation of one-factor and two-factor models, since data on the TYVIX is not available before 2003.

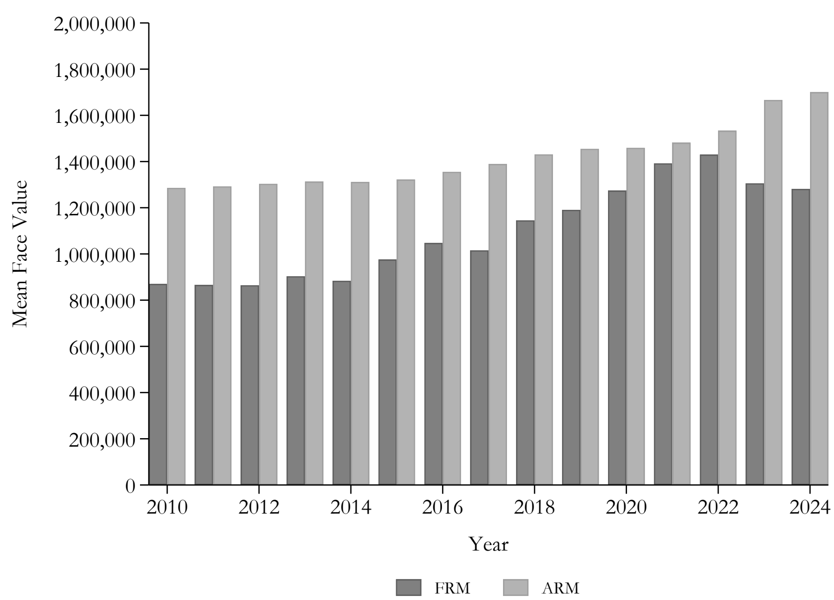
B Appendix: additional tables and figures

Figure A-1: FRMs vs. ARMs

(a): FRMs vs. ARMs outstanding

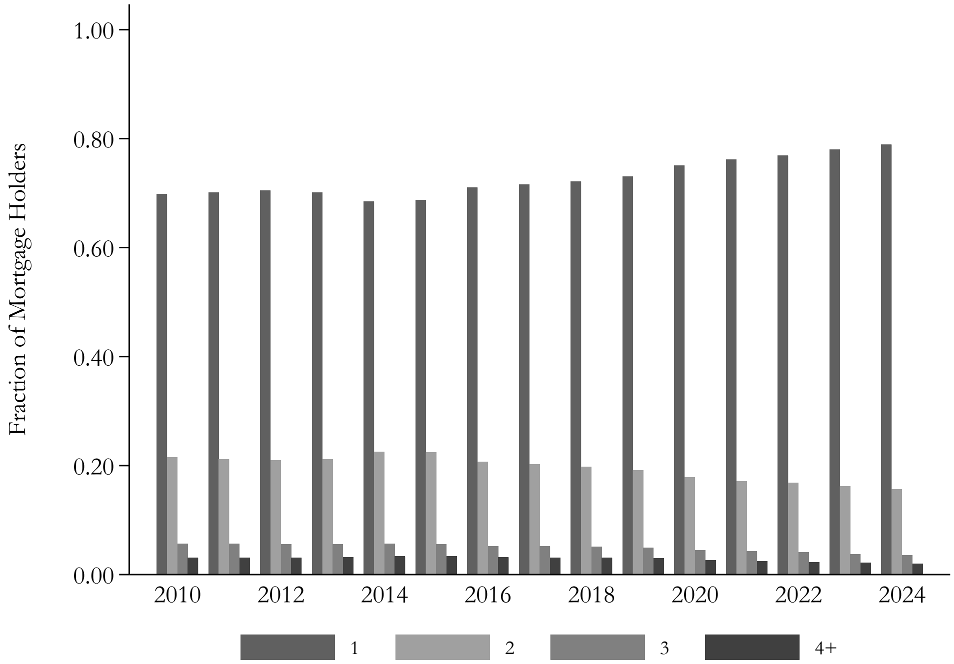


(b): FRMs vs. ARMs average face value



Note: Top figure shows the number of Danish households whose primary mortgage is either an ARM or an FRM at the beginning of each year. Bottom figure shows the average face value for households' primary mortgage, by type, in DKK.

Figure A-2: Number of mortgages, for households with at least one mortgage

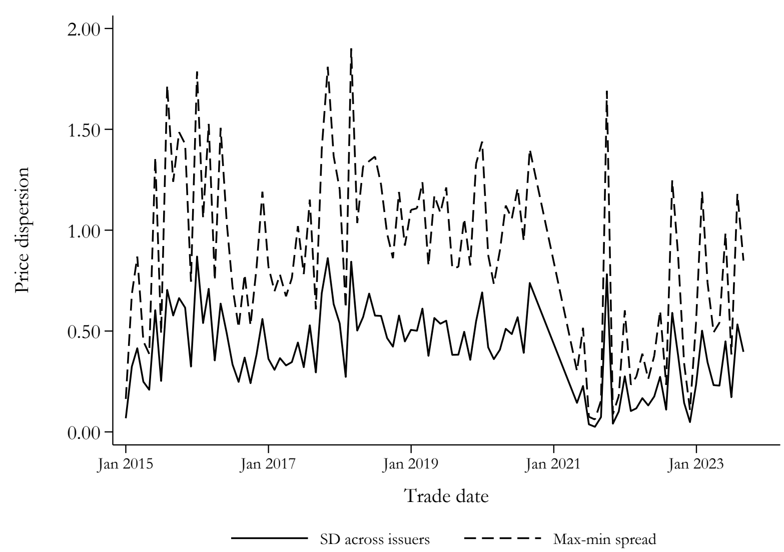


Note: Distribution of number of mortgages, showing the fraction of mortgage-indebted households with 1, 2, 3 or 4 + mortgages in the beginning of the year. The denominator consists of all households which have at least 1 mortgage in the beginning of the year.

Figure A-3: Mortgage bond prices across issuers

(a): Prices for 2% coupon bond

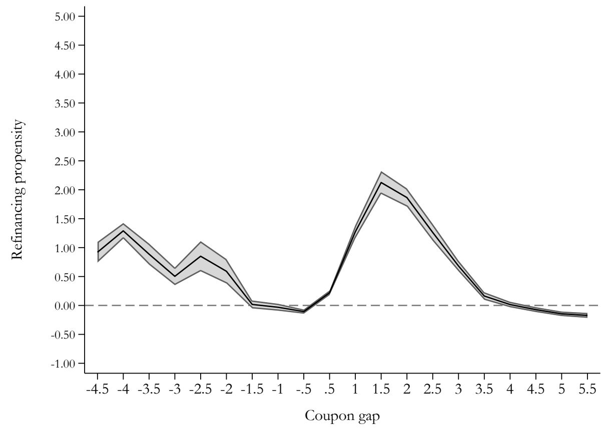
(b): Cross-sectional standard deviation over time



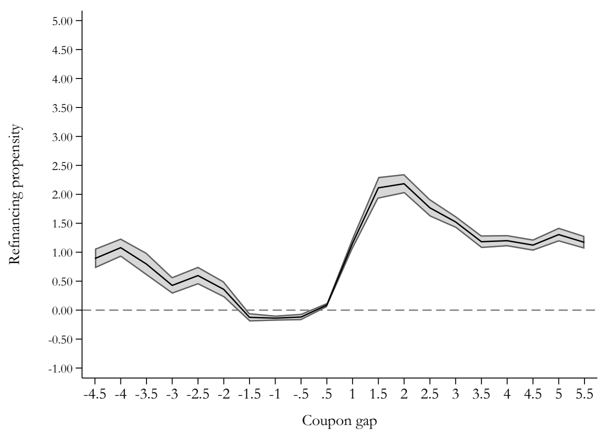
Note: Top figure shows the monthly average prices for long-term FRM mortgage bonds with a coupon of 2% across the four largest Danish mortgage issuers: Nykredit, Nordea, Realkredit Danmark and Jyske Realkredit. Bottom figure shows the dispersion in mortgage bond monthly average prices for long-term mortgages with a 2% coupon, based on non-winsorized prices. For each month, for 2% coupon bonds with a maturity above 30 years, we first compute the average bond price within each issuer. We then calculate the standard deviation of these issuer-level prices as well as the difference between the highest and lowest issuer price between issuers (source: Værdipapirs Centralen).

Figure A-4: Refinancing propensities vs. coupon gaps

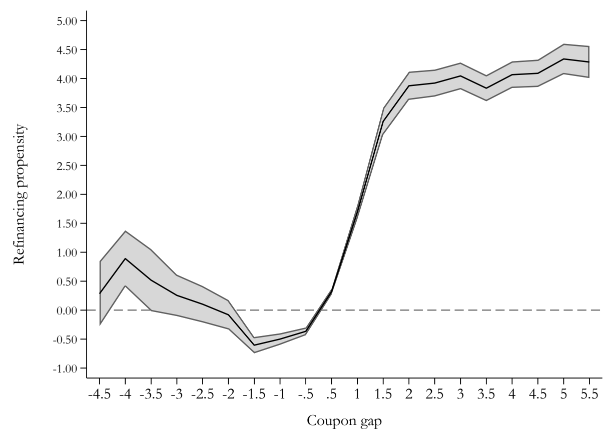
(a): No controls



(b): Controls



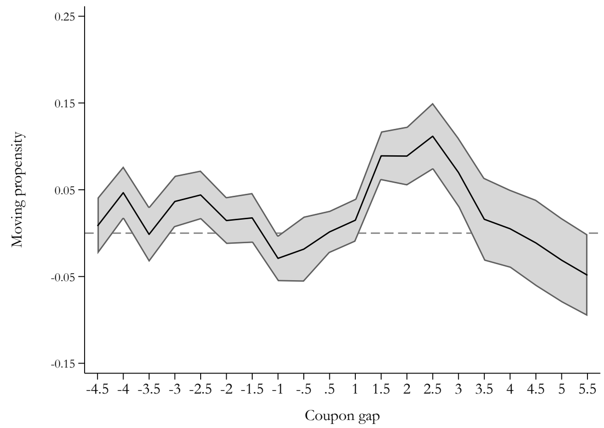
(c): Household Fixed Effects



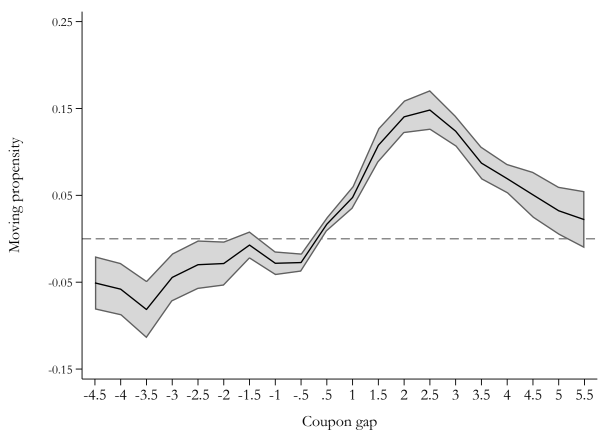
Note: **Panel A** shows the propensity to refinance as a function of coupon gap dummies with 50 bps intervals without controlling for further factors. **Panel B** shows refinancing propensities as a function of coupon gap dummies at 50 bps intervals, while controlling for variables similar to Fonseca and Liu (2024) (household age, household age squared, gender (couple, single female, single male), log face value, log of average monthly mortgage payment, month fixed effects, year-municipality fixed effects and remaining mortgage term fixed effects). **Panel C** shows the coefficient estimates controlling for household fixed effects. For interpretational purposes, the plots display the interval spanning the 0.5th to the 99.5th percentile of coupon gap values grouped into 50 bps bins, with the baseline coupon gap category set to zero across all panels. Standard errors are double clustered by issuance month-year and municipality.

Figure A-5: Moving propensities vs. coupon gaps

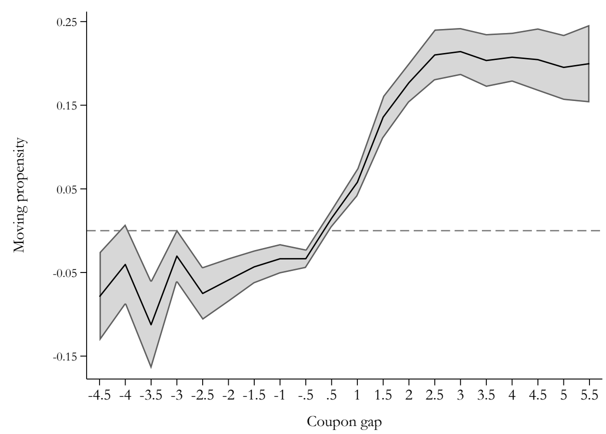
(a): No controls



(b): Controls

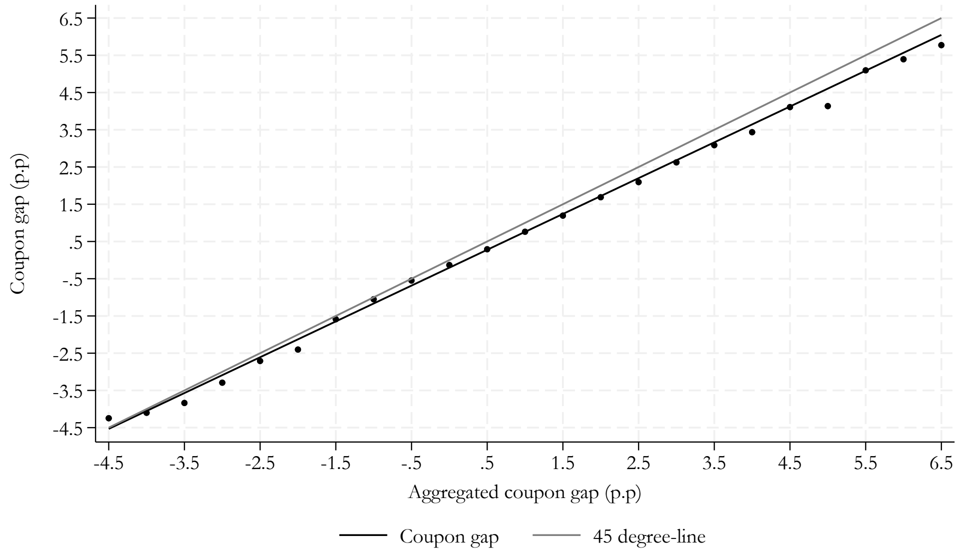


(c): Household Fixed Effects



Note: **Panel A** shows the propensity to move as a function of coupon gap dummies with 50 bps intervals without controlling for further factors. **Panel B** shows moving propensities as a function of coupon gap dummies at 50 bps intervals, while controlling for variables similar to Fonseca and Liu (2024) (household age, household age squared, gender (couple, single female, single male), log face value, log of average monthly mortgage payment, month fixed effects, year-municipality fixed effects and remaining mortgage term fixed effects). **Panel C** shows the coefficient estimates controlling for household fixed effects. For interpretational purposes, the plots display the interval spanning the 0.5th to the 99.5th percentile of coupon-gap values grouped into 50 bps bins, with the baseline coupon gap category set to zero across all panels. Standard errors are double clustered by issuance month-year and municipality.

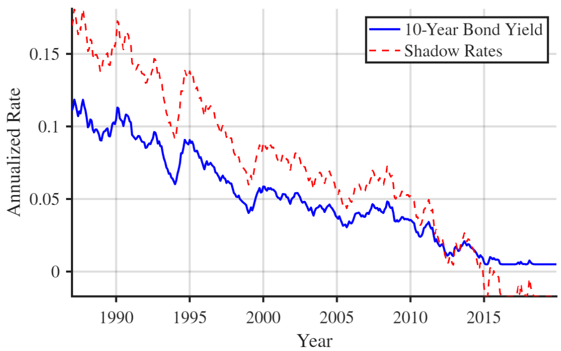
Figure A-6: Instrument relevance



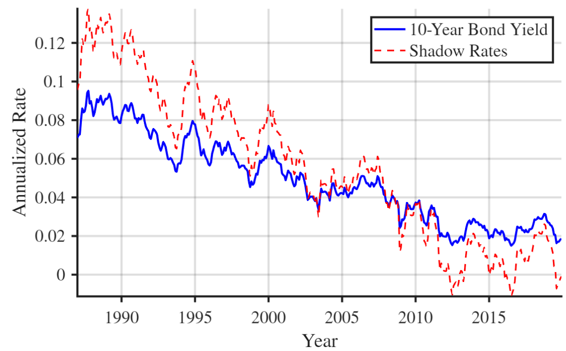
Note: The binscatter plots realized coupon gaps against the aggregate coupon-gap instrument, together with a fitted linear relationship and a 45-degree line.

Figure A-7: 10-Year bond yield and estimated shadow rates

(a): Denmark



(b): U.S.



Note: The blue solid line plots the observed 10-year bond yield and the red dashed line shows the shadow rates over the period from January 1987 to December 2019. The shadow rates are estimated following the methodology described in Section A.3.

Table A-1: Summary statistics for price dispersion

	Mean		Median		
Coupon (%)	SD	Spread	SD	Spread	N
0.5	0.26	0.57	0.23	0.51	50
1	0.35	0.74	0.32	0.72	58
1.5	0.29	0.62	0.26	0.54	98
2	0.41	0.89	0.39	0.87	98
2.5	0.44	0.92	0.37	0.79	103
3	0.49	1.06	0.41	0.87	83
3.5	0.38	0.82	0.36	0.77	78
4	0.35	0.70	0.28	0.60	147
5	0.46	0.98	0.28	0.62	199
5.5	5.07	7.17	5.30	7.50	3
6	0.32	0.69	0.24	0.50	134
6.5	1.92	2.72	1.77	2.50	4
7	0.35	0.77	0.28	0.61	74
All	0.40	0.84	0.31	0.65	1,129

Note: This table reports the monthly cross-sectional dispersion in issuer prices for fixed-rate mortgage bonds with 30–35 years to maturity. For each month, issuer prices are first averaged within each issuer and coupon bucket. The table reports the mean and median of the standard deviation of issuer prices ("SD") and the spread between the highest and lowest issuer prices across issuers ("Spread"). The "All" row pools all coupon buckets. N denotes the number of monthly observations.

Table A-2: Moving and the (piece-wise linear) coupon gap

	OLS			IV
	(1)	(2)	(3)	(4)
	Moving (pct)	Moving (pct)	Moving (pct)	Moving (pct)
Coupon gap (p.p.)	-0.0143***	0.0106**	0.00999	0.00400
	(0.00463)	(0.00453)	(0.00639)	(0.00445)
Positive coupon gap indicator	0.0398**	0.0330***	0.0258***	0.0780***
	(0.0152)	(0.00640)	(0.00821)	(0.0141)
Coupon gap X positive gap	0.0257***	0.0156***	0.0572***	0.0399***
	(0.00812)	(0.00460)	(0.00714)	(0.00573)
Controls		X	X	X
Household FE			X	
R-squared	0.0000113	0.000958	0.0411	0.000472
Root MSE	5.637	5.489	5.408	5.522
F-stat				217.8
Observations	66232863	63296890	63293856	60704869

Note: The table reports marginal effects on moving propensity of the coupon gap, an indicator for a positive coupon gap, and the interaction. For scaling purposes, the dependent variable is a binary indicator that takes the value 100 if the household moves. Column (1) reports estimates without additional controls. Column (2) adds a set of baseline controls following Fonseca and Liu (2024), including household age and age squared; household type (couple, single female, single male); log face value of the mortgage; log average monthly mortgage payment; remaining mortgage term fixed effects; month fixed effects; and year-by-municipality fixed effects. Column (3) adds household fixed effects to the regression of Column (2). Column (4) instruments the realized coupon gap using the difference between the market rate at the time of mortgage issuance and the market rate in the current month and year. Standard errors are double clustered at the issuance month–year and municipality levels and reported in parentheses, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. The reported F-statistic is the Kleibergen–Paap rk Wald F-statistic, which tests instrument relevance in the presence of multiple endogenous regressors and cluster-robust standard errors.

Table A-3: Regime-switching shadow-rate model estimation

	Prior		Posterior		
Parameter	Mean	SD	Mean	SD	95% C.I.
η	0.170	0.050	0.1738	0.0116	[0.1554, 0.2003]
$\bar{x}$	0.030	0.020	0.0182	0.0043	[0.0083, 0.0261]
σ_{L}	0.008	0.008	0.0114	0.0006	[0.0105, 0.0128]
σ_{H}	0.025	0.020	0.0209	0.0009	[0.0201, 0.0233]
λ_{LH}	0.350	0.200	0.3260	0.1067	[0.0947, 0.4899]
λ_{HL}	1.000	0.500	0.8112	0.2123	[0.5146, 1.3635]
σ_y	0.0010	0.0015	0.00098	0.00003	[0.00095, 0.00108]
σ_v	0.800	0.100	1.0936	0.0438	[1.0035, 1.1743]

Note: This table reports posterior estimates from the regime-switching shadow-rate model of Section A.4, estimated by particle marginal Metropolis–Hastings on monthly 10-year U.S. Treasury yields and TYVIX over 2003–2019. The volatility and rate parameters $(\bar{x}, \sigma_{\mathrm{L}}, \sigma_{\mathrm{H}}, \sigma_y)$ are reported in annualized decimal units and σ_v is in TYVIX (percentage-volatility) points. "95% C.I." is the 2.5–97.5 percentile credible interval of the post-burn-in draws.