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

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Abstract

We study Danish fixed-rate mortgage contracts, which are identical 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 buy-back 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 buy-back 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. Second, household mobility in Denmark is largely insensitive to increases in market interest 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 buy-back rights with refinancing frictions and tax incentives. Counterfactual experiments indicate that introducing a Danish-style buy-back 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, which relies on micro-data for all households in Denmark between 2010 and 2024, reveals three core facts. First, consistent with standard refinancing incentives and consistent with empirical evidence in the U.S. (Berger et al., 2021), refinancing hazards increase sharply when the coupon rate on an existing mortgage exceeds the prevailing market rate by 50-100 basis points ("bps"). Danish borrowers exercise their par prepayment option actively, refinancing into lower rates with minimal delay. Second, refinancing hazards also rise markedly when coupon gaps — defined as the difference between a mortgage's coupon and the current market interest rate — fall below -200 bps, reflecting widespread discounted buy-backs in which households repurchase mortgages below par to capture embedded capital gains. This behavior is largely absent in the U.S., where refinancing activity vanishes once market rates exceed existing coupons. It raises a key question: why do Danish households find it optimal to replace low-coupon, discounted debt with higher-coupon debt issued at par? Third, and most striking, Danish moving hazards are nearly flat across negative coupon gaps: households move at similar rates regardless of how far market rates exceed their mortgage coupon. In the U.S., Fonseca and Liu (2024) estimate that a 100 bps decrease in the coupon gap reduces annual moving rates by 57-120 bps; in Denmark, the corresponding estimate is economically negligible. The buy-back right allows Danish households to move without forfeiting embedded capital gains, effectively eliminating the lock-in channel. Our results are robust across nonparametric and parametric specifications, and to instrumenting household-specific coupon gaps with aggregate market conditions.

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 respond to coupon gaps in both directions 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 buy-backs 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 buy-backs 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 buy-back 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 across the rate cycle. Refinancing at negative coupon gaps remains muted, however, because U.S. tax law offers weaker mortgage interest deductibility and taxes capital gains from debt forgiveness; eliminating the latter would substantially strengthen both channels. Despite these differences, equilibrium mortgage rates under the two systems are remarkably similar — differing by only 1 bp on average in our calibration. The intuition is simple: under the current U.S. system, the only prepayments when coupon 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 negligible. The Danish system thus enhances borrower flexibility without materially increasing the cost of mortgage credit.

Introducing a repurchase-at-market option in the U.S. would require institutional adaptation. In the agency market, it would involve restructuring Fannie Mae and Freddie Mac's MBS issuance model toward a covered-bond-style system that allows direct borrower repurchases. 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. Buy-back 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). These studies document that U.S. FRM borrowers face constraints when market rates rise, with implications for geographic mobility and monetary transmission. 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 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 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 separte 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

As in the U.S., one of the dominant mortgage contracts in Denmark is the 30-year fixed-rate, fully amortizing loan with a par prepayment option.[1] 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.[2] As we will show

[1] Figure A-1 shows, year by year in our micro-data, the number of fixed-rate mortgages and adjustable rate mortgages in our data. In our sample period, over 48% of all mortgages are fixed rate.

[2] 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,

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).

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).[3] Finally, while capital gains realized by Danish households who repurchase their mortgages at a discount are not taxable, any form of debt forgiveness in the U.S. is generally treated as ordinary income and taxed accordingly.[4]

3 Empirical analysis

3.1 Data sources and sample selection

The micro data used for this article comes from various governmental institutions, but is made available to us by Statistics Denmark.[5] We observe the entire Danish population at

however, that assumptions occur at negligible frequency relative to discounted mortgage repurchases.

[3]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.

[4]Exceptions include debt discharged in bankruptcy, which is excluded from income, and mortgage debt cancelled in connection with foreclosure, which may generate either ordinary income or a capital gain depending on whether the debt is recourse or non-recourse.

[5]Mortgage data from 2012 and onward is collected from mortgage institutions by the Danish Central Bank. We are grateful to Finance Denmark for providing us with mortgage data from 2009 to 2011.

the beginning of each year, from 2010 until 2023.[6] Since we have data on the exact date of various events,[7] 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.[8]

In our data, we define 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.[9]

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.[10]

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

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.

[6]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.

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

[8]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.

[9]Our analysis focuses on the household's 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.

[10]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.

just under 3%.

In our data over our sample period, unweighted average refinancing rate for FRM (resp. ARM) borrowers is equal to 13% per year (resp. 6% per year), while these statistics are equal to 17% 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 3.1% per year (resp. 4.1% 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 Danish long-term mortgage market interest rates since 2010, proxied by the coupon on FRM bonds with the longest time to maturity (30-34 years) and with the highest market price below par. This measure closely tracks the market yield faced by new borrowers taking out standard 30-year callable FRMs, as Danish mortgage banks fund new lending by issuing covered bonds at market prices. The figure reveals a pronounced secular decline in mortgage market rates from 2010 through 2021, followed by a sharp and historically unprecedented increase 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 coupon on newly issued 30-year FRMs reached an all-time low of 0.50%. 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 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 rates surged from near 1% in early 2022 to a peak of roughly 5% by mid-2023. This sharp rise in mortgage rates, following a decade-long decline, generates a unique empirical environment. During the 2010–2021 period of falling rates, most outstanding mortgages exhibited a positive *coupon gap* — defined as the difference between the borrower's coupon rate and the contemporaneous market rate — placing the par prepayment option deeply in the money. Conversely, the recent period of rising rates features negative coupon gaps, with the prepayment option far out of the money. These contrasting episodes thus provide rich variation for evaluating households' refinancing, prepayment, and mobility behavior under both favorable and adverse refinancing conditions.

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 rates 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 2053 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 2053 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 regimes. During periods of declining rates, when the coupon gap is positive and the par prepayment option is in the money, households exercise their option to refinance at par, keeping outstanding bond prices near 100. In contrast, when rates rise sharply — as in 2022-2023 — the coupon gap turns negative, and borrowers can exploit the institutional feature unique to Denmark: the ability to repurchase their mortgage debt at a discount. This structural feature ensures that mortgage bond prices not only determine the funding cost for new loans but also directly shape household balance sheet dynamics and refinancing behavior across the interest rate cycle. Later on, we will exploit this variation in the coupon gap and mortgage bond discounts to identify how households adjust their prepayment, moving and refinancing decisions in response to changes in the coupon gap and thus the mark-to-market gains and losses on their outstanding debt.

3.2.3 Aggregate prepayment, refinancing, and moving rates

Using our microdata, we compute monthly 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.[11] 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 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.

Beginning in 2022, however, a qualitatively different refinancing regime emerges. As interest rates rise sharply and mortgage bond prices fall, FRM refinancing rates increase

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

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 emphasized in 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 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 Micro-data evidence

For this analysis, our unit of observation is a household-month, where i denotes the household identifier and t the month. We focus on households whose primary mortgage is an FRM; we denote c_{it} the fixed coupon of the primary mortgage of household i in month t, and m_t the 30 year mortgage market interest rate at such time.[12] Finally, the coupon gap is $z_{it} := c_{it} - m_t$. The top of Figure 4 shows the mean coupon gap in our

[12] To be precise, we measure m_t as the monthly coupon for those FRMs in the longest time-to-maturity category (30-34 years to maturity) that currently have the highest market price, below 100, in the dataset Værdipapircentralen.

microdata year by year. Throughout the 2010s, the mean coupon gap oscillates between 0 and +100 bps, as long-term mortgage rates decline and FRM borrowers frequently refinance at lower rates, so as to reset their coupon gap to zero. Instead, in 2022 and 2023, the mean coupon gap experiences a large downward jump, coinciding with the sudden increase in mortgage market interest rates. In the following sections, we focus on households' decisions to prepay, move or refinance, and how such decisions are related to the coupon gap z_{it}.

3.3.1 Who buys back his/her mortgage?

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

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

where $\mathbb{1}(\cdot)$ denotes the indicator function and coupon gaps z_{it} are discretized into 50 bps bins. The vector X_{it} contains controls. Specifically, we estimate the model (i) without controls, and (ii) with a control set closely mirroring Fonseca and Liu (2024).[13]

In addition to the nonparametric specification in equation (1), we estimate a piecewise-linear model that allows the sensitivity of prepayment hazards to differ across positive and negative coupon gaps:

$$\mathbb{1}\left(\text{prepay}_{it}\right) = \alpha_0 + \beta_0 z_{it} + \alpha_1 \mathbb{1}\left(z_{it} \geq 0\right) + \beta_1 \mathbb{1}\left(z_{it} \geq 0\right) z_{it} + \gamma X_{it} + \epsilon_{it}, \tag{2}$$

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

Figure 5 (resp. Figure 6) reports the estimated nonparametric relationships between coupon gaps and refinancing (resp. moving) probabilities implied by equation (1), while Table 2 presents the coefficient estimates from the piecewise-linear specification in equation (2).

Several findings emerge from this analysis. First, monthly refinancing hazards increase sharply once the coupon gap exceeds 50 bps. This upward slope reflects the financial incentive for borrowers to refinance into lower rates — a feature readily available

[13]When replicating the control vector of Fonseca and Liu (2024), X_{it} includes locality, year, and locality-by-year fixed effects, as well as log mortgage balance, log mortgage payment, remaining mortgage maturity, 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.

to Danish mortgage borrowers. A similar pattern is observed in U.S. mortgage data, although the increase in refinancing hazard in the U.S. is more modest, at approximately 200 bps/month (Berger et al., 2021), compared to nearly 300 bps/month in Denmark. This contrast highlights the faster refinancing speeds among Danish households, and suggests that Danish mortgage borrowers face fewer frictions — whether behavioral or financial — than U.S. borrowers (Andersen et al., 2020; Berger et al., 2024*a*).

Second, refinancing hazards rise sharply when the coupon gap falls below −200 basis points, 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 coupon 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 coupon 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 coupon gap, the moving hazard is modestly upward sloping across both specifications. The estimated slope of 0.036 in Column 2 in Table 2 implies that, when the par prepayment option is in the money, a 100 bps increase in the coupon gap raises monthly moving rates by 3.6 bps, or approximately 43 bps per year relative to an unconditional mean of 307 bps per year.[14] A qualitatively similar pattern is documented in Fonseca and Liu (2024), although the estimated gradient in that study is roughly twice as large as in Denmark. We interpret this relationship as reflecting the increasing value of mortgage prepayment as the coupon gap widens: when refinancing at par is attractive, moving — and thereby prepaying the outstanding FRM — becomes more valuable, generating a positive association between coupon gaps and mobility for positive gaps.

By contrast, conditional on a negative coupon 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 −0.016 when expressed using monthly hazard, or −0.198 using yearly hazard), implying that a 100 bps decrease in the coupon gap increases annual moving rates by about 20 bps; when using the control set of Fonseca and Liu (2024), the slope becomes mildly positive (slope of approximately 0.010 when expressed using

[14] 0.0362 is the sum of the baseline slope 0.0096 and the positive gap add-on 0.0266.

monthly hazard, or +0.12 using yearly hazard), implying that a 100 bps decrease in the coupon gap decreases annual moving rates by about 12 bps. 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 — an order of magnitude 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.

3.3.2 Dealing with possible biases

As in Fonseca and Liu (2024), a potential concern is that the estimation of equation (1) may be biased if prepayment behavior is correlated with unobserved determinants of the coupon gap. For example, more financially sophisticated households may both obtain lower mortgage rates and refinance or move more aggressively.

Several institutional features of the Danish mortgage market substantially mitigate this concern. At origination or refinancing, households have very limited discretion over the coupon they receive: in most cases, borrowers are assigned the highest-coupon mortgage trading below par,[15] and the associated market price (i.e., the discount to par) is publicly observable and not subject to bilateral negotiation, in contrast to the use of points in the U.S. system. This institutional design sharply constrains borrowers' ability to shop for rates or otherwise influence their coupon at origination.

The data strongly support this characterization. Regressions of the origination coupon on origination month fixed-effects yield an R^2 of 0.92, which remains unchanged when demographic controls are added. While some demographic coefficients are statistically significant, their economic magnitudes are negligible.[16] Consistent with this evidence, Figure A-3 shows that in most months the vast majority of newly issued mortgages cluster at a single coupon rate.

Taken together, these facts imply that nearly all cross-sectional variation in coupons is driven by timing rather than borrower characteristics. As a result, there is limited scope for prepayment behavior to be systematically correlated with unobserved determinants of the coupon gap, alleviating concerns about bias in equation (1).

That being said, mimicking what Fonseca and Liu (2024) do, we can still use our

[15] In Denmark, FRM coupons are set on a discrete grid rather than a continuous scale, taking values only in multiples of 0.50% (0%, 0.50%, 1.00%, 1.50%, etc.).

[16] See Table A-1. For example, in the saturated specification reported in column (6), the average coupon of the youngest and oldest households differs by only 2 bps. Similarly, income, wealth, and education gradients are economically small, each below 1 bp.

micro data and instrument the household-specific coupon gap z_{it} with a measure of the aggregate coupon gap z^*_{it}, computed as the difference between (a) the current mortgage market interest rate m_t and (b) the mortgage rate $m^*_{\tau(i)}$ prevalent at the time $\tau(i)$ at which the mortgage of household i was originated.[17] Specifically, the 2-stage least square design then consists in (a) projecting the piece-wise linear household-specific coupon gap variables $z_{it}, \mathbb{1}(z_{it} \geq 0)$ and their product $z_{it}\mathbb{1}(z_{it} \geq 0)$ onto a set of similarly constructed variables and indicators based off the aggregate coupon gap z^*_{it}, and (b) regressing our moving indicator onto the predicted variables.

Column 4 of Table 2 presents the IV results from this empirical specification. These results are overall entirely consistent with our OLS estimates: the point estimate for the coupon gap variable decreases slightly (from 0.00962 to 0.00897), while the point estimate for the interaction term increase slightly (from 0.0266 to 0.0362). Thus, our main conclusions remain unchanged when using this instrumental variable strategy.

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 coupon 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 coupon 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 [citation].

Moreover, the relative insensitivity of moving rates to the coupon gap (when such gap is negative) in Denmark indicates that household mobility is largely unaffected by the mortgage contract structure, specially 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

[17] Figure A-4 compares the instrument to the actual coupon gap and shows an almost 45 degrees relationship.

mobility when interest rates rise. Section 5 examines the institutional adjustments required to implement such a buy-back 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 coupon gap when the gap is negative. We then use the model to study a counterfactual policy experiment in which a buy-back 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 forcing 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 $\mathcal{L}$.[18] 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.[19] The remaining face value at time t is therefore $\phi_t = \phi_0 \exp(-\alpha t)$. 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:

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

[19] 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 mortgage at the prevailing market mortgage rate m_τ and with an unchanged face value relative to the outstanding balance. If the existing 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.

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

$$v(x,c) := \inf_{a \in \mathcal{A}} \mathbb{E}_{x,c} \left[\int_0^{+\infty} e^{-(\rho+\alpha)t} \left(\left((1-\theta) c_t^{(a)} + \alpha \right) dt + \right. \right.$$

$$a_t \sum_{\beta=\lambda,\psi} \left(\tilde{\kappa}_{\beta,t} - \max\left(0, 1 - p\left(x_{t-}, c_{t-}^{(a)}\right)\right) \right) dN_t^{(\beta)} \Bigg) \Bigg], \quad (3)$$

$$\text{s.t.} \qquad dc_t^{(a)} = \left(m(x_t) - c_{t-}^{(a)} \right) a_t \left(\sum_{\beta=\lambda,\psi} dN_t^{(\beta)} \right) \quad (4)$$

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 or refinancing opportunities) 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 mortgage at a time when the term structure state variable is equal to x.

Equation (3) 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 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 her 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 her existing mortgage at par and does not realize any market value gain. v satisfies the HJB equation

$$(\rho + \alpha)v(x, c) = \alpha + (1-\theta)c + \mathcal{L}v(x, c)$$
$$+ \sum_{\beta=\psi,\lambda} \beta \mathbb{E}\left[\min\left[0, v\left(x, m(x)\right) + \tilde{\kappa}_\beta - \max\left(0, 1 - p\left(x, c\right)\right) - v(x, c)\right]\right], \quad (5)$$

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 prepayment time. The martingale condition for mortgage prices is then

$$\begin{aligned}(r(x)+\alpha)p(x,c) = c + \alpha + \mathcal{L}p(x,c) \\ + \sum_{\beta=\lambda,\psi} \beta \left[1 - p(x,c)\right] \mathbb{P}\left(v(x,c) > v(x,m(x)) + \tilde{\kappa}_\beta\right), \end{aligned} \quad (6)$$

where $\mathbb{P}(\cdot)$ is the probability operator. This martingale condition captures borrowers' strategic prepayments (due to either a refinancing or a move) at par — these prepayments occur at rate $\beta \mathbb{P}\left(v(x,c) > v(x,m(x)) + \tilde{\kappa}_\beta\right)$. However, the martingale condition does not capture borrowers' prepayments at a discount, since in such case, investors simply get paid the market value of the mortgage, in other words they neither suffer a gain or a loss on their investment. The mortgage market interest rate $m(x)$ is defined implicitly, via the condition

$$p\left(x, m(x)\right) = 1. \quad (7)$$

We note that the game we have written is effectively a dynamic game with 3 players:

- the household, who makes after-tax payments $(1-\theta)c_t + \alpha$ in connection with her mortgage;
- mortgage lenders, who receives cash-flows $c_t + \alpha$;
- the Danish government, whose tax revenues are reduced via the mortgage interest deductions θc_t.

Absent refinancing and moving costs, this game would be a zero-sum game. Whenever a household buys back her mortgage and refinances (or moves) into a higher coupon mortgage, the present value of future fiscal revenues declines — a net loss for the government.

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 (5);
- given the refinancing and moving strategy a followed by households, mortgage prices satisfy the martingale condition (6);
- the mortgage market interest rate satisfies equation (7).

While the existence and uniqueness of an MPE are beyond the score of our paper, there are certain properties of an MPE that are straight-forward 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 (with $\beta = \lambda$ for refinancings and $\beta = \psi$ for moves). 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 (when $\beta = \lambda$) or moves (when $\beta = \psi$), prepays her mortgage and realizes a mark-to-market gain $1 - p\left(x, c\right)$;
- if $c \geq \bar{C}_\beta(x;\kappa_\beta)$, the household refinances (when $\beta = \lambda$) or moves (when $\beta = \psi$) and prepays her mortgage at a price of par.

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

$$v\left(x, \bar{C}_\beta(x;\kappa_\beta)\right) = v\left(x, m(x)\right) + \kappa_\beta \tag{8}$$

$$v\left(x, \underline{C}_\beta(x;\kappa_\beta)\right) = v\left(x, m(x)\right) + \kappa_\beta - 1 + p\left(x, \underline{C}_\beta(x;\kappa_\beta)\right) \tag{9}$$

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 (8) and (9) 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 coupon gap is $z_t = z\left(x_t, c_t\right) := c_t - m\left(x_t\right)$. 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:

$$f(x,c)dcdx := \lim_{t\to+\infty} \frac{1}{t}\int_0^t \mathbb{1}\left(x_t \in [x, x+dx]; c_t \in [c, c+dc]\right) dt. \tag{10}$$

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

$$0 = \mathcal{L}^* f(x,c) - \sum_{\beta=\lambda,\kappa} \beta F_\beta\left(v(x,c) - v\left(x, m(x)\right) + \max\left(0, 1 - p(x,c)\right)\right) f(x,c), \tag{11}$$

where $\mathcal{L}^*$ is the adjoint of the operator $\mathcal{L}$[20] and F_β is the cumulative distribution function for the random net cost $\tilde{\kappa}_\beta$. In equation (11), 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 coupon gap, that an econometrician would estimate, if she had an infinite time-series data available. One can characterize such hazard rates using the

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

ergodic density of our dynamic system:

$$h_\beta(z) = \beta \frac{\iint_{(x,c):c-m(x)=z} F_\beta\left(v(x,c) - v(x,m(x)) + \max\left(0, 1 - p(x,c)\right)\right) f(x,c)dcdx}{\iint_{(x,c):c-m(x)=z} f(x,c)dcdx}, \quad \beta = \lambda, \psi$$

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

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

$$dx_t = -\eta(x_t - \bar{x})dt + \sigma dZ_t, \tag{12}$$

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 flat marginal rate applicable to mortgage interest deductions in Denmark (Gruber, Jensen and Kleven, 2021). Following Agarwal, Driscoll and Laibson (2013) and Berger et al. (2024*a*), we assume a subjective discount rate of $\rho = 5\%$.

The term structure model is estimated by maximum likelihood using Danish 10-year government bond yields. 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.[21] 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%.[22] This estimate implies a refinancing opportunity arrival rate of $\lambda = -\ln(0.92)/0.25 \approx 33\%$ 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 coupon 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 coupon gap. Thus, consistent with our empirical results, for positive coupon gaps, the probability of exercising the moving option conditional on a moving opportunity is increasing in the coupon gap, implying that the moving hazard itself is increasing in the coupon 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 coupon gap for positive gaps (approximately equal to $0.0324 \times 12 \approx 0.39$, i.e. the moving rate increases by approximately 39 bps/year for each 100 bps increase in the coupon gap, see Table 2). This calibration yields $\psi = 5.5\%$ and $\sigma_\psi = 10\%$.

[21] 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.

[22] See Andersen et al. (2020), Model 3, which incorporates inattention through an "asleep" probability and abstracts from psychological costs, focusing exclusively on monetary refinancing costs, as in our calibration.

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 par 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 on average there are no net moving cost ($\bar{\kappa}_\psi = 0$), 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.

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 coupon 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 coupon gap. When a refinancing opportunity arrives and the coupon 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 coupon 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 coupon 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 coupon gap. Consequently, both the probability of moving conditional on receiving a moving opportunity and the moving hazard are mildly increasing in the coupon gap for positive values and mildly decreasing for negative values. Overall, the refinancing and moving hazards implied by the model as functions of the coupon gap align closely with the empirical patterns documented in Section 3.

The primary dimension along which the model fails to replicate the empirical refinancing and moving patterns concerns behavior at extreme coupon gaps. In the data, refinancing hazards plateau and then decline for very large positive coupon gaps (above 200 bps). This pattern is suggestive of heterogeneity in household attention (Berger et al., 2024*b*): at such high coupon gaps, the remaining observed borrowers are likely those with low attention rates, so that the average refinancing hazard declines as the coupon gap increases further. By contrast, the model assumes homogeneity in attention parameters across households. As a result, the refinancing hazard in the model plateaus mechanically at the constant attention rate λ, rather than declining at high coupon gaps. A symmetric pattern is evident in the data for very negative coupon gaps, where refinancing hazards again level off and then fall as the gap becomes more negative. This feature is likewise absent from the model.

A similar discrepancy arises for moving rates. In the data, moving hazards are initially increasing and then decreasing in the coupon gap for positive values, whereas in the model they increase monotonically and eventually plateau at the exogenous opportunity arrival rate, ψ. For sufficiently negative coupon gaps — below -200 bps — the model predicts that more negative gaps are associated with higher moving rates. Intuitively, larger negative gaps strengthen incentives to monetize embedded capital gains and to increase the value of the mortgage interest tax shield, generating a moving hazard that is decreasing in the coupon gap. In the data, however, this relationship — estimated after controlling for a set of covariates (see the estimation of equation (1) — is flat or even mildly upward sloping.

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 buy-back 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 coupon gaps are negative. This effect is intuitive: households that move while facing a negative coupon gap can do so without forfeiting the capital gains embedded in their FRM.

Second, mortgage interest deductibility plays a key role in motivating discounted buy-backs in Denmark. When coupon 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 buy-backs.

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 buy-backs 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.[23] 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 buy-backs, 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 buy-back 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 buy-backs may reflect households seeking to increase their tax shields, but also households who believe that elevated interest rates will be short-lived relative to market expectations.

4.9 U.S. prepayable mortgage debt

As discussed in Section 2, FRMs in the U.S. and Denmark share many contractual features, with one crucial exception: U.S. FRMs cannot be repurchased at prevailing market prices and may only be prepaid at par. In this section, we use the model to address the following counterfactual questions: how would U.S. household behavior change, and how would equilibrium U.S. mortgage interest rates respond, if FRM contracts were amended to include a repurchase-at-market option?

4.9.1 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

[23] 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).

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

$$
\begin{aligned}
(\rho+\alpha)v_{\text{us}}(x,c) &= \alpha + (1-\theta_i)c + \mathcal{L}v_{\text{us}}(x,c) \\
&\quad + \sum_{\beta=\psi,\lambda} \beta \mathbb{E}\left[\min\left[0, v_{\text{us}}\left(x, m_{\text{us}}(x)\right) + \tilde{\kappa}_\beta - v_{\text{us}}(x,c)\right]\right]
\end{aligned} \tag{13}
$$

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

The distinction between equation (13) — which applies to current U.S. FRMs — and the corresponding Danish equation (5) is straightforward. In Denmark, borrowers may repurchase their mortgage at the prevailing market price whenever they refinance or move, including at a discount when the mortgage trades below par. In contrast, U.S. borrowers must always repay at par. When we introduce the repurchase-at-market option in the U.S., as in (14), 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, regardless of whether contracts feature a repurchase-at-market option or whether capital gains are taxable, continue to satisfy a martingale condition analogous to (6), with appropriately indexed terms.

To bring the model to the data, we estimate the shadow-rate process (12) by maximum likelihood using U.S. 10-year government bond yields. 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. (2024*a*) for refinancing hazards. We set the marginal tax rate on mortgage interest deductions to 22% and the capital gains tax rate to 15%.[24] The resulting calibration is

[24] 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.

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 coupon gaps and increase monotonically for positive gaps, eventually converging to λ. Moving hazards also increase monotonically with the coupon 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 coupon gaps once borrowers can repurchase at market value.

The model also clarifies how the repurchase-at-market option affects the level of equilibrium mortgage rates. At first glance, one might expect the option to represent an additional borrower right that must be priced by lenders, thereby increasing mortgage rates. This intuition is misleading. In our calibration, equilibrium mortgage rates are on average only 1 bps higher with the option than without it. 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 under the two contract structures are nearly identical.

4.9.2 What if discount mortgage repurchases were not taxable?

Adopting a Danish-style buy-back 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 buy-backs 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 buy-back 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 (14) with $\theta_g = 0$.[25]

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

5 Implementing buy-back 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, just pricing additional prepayment risk into existing markets, while being less dependent on lender discretion and better suited to the realities of household mobility.

5.1 Buy-back option in the U.S. mortgage market

Agency market. One way to implement buyback rights in the U.S. is to restructure the agency market along the lines of the Danish covered bond system. Under the current framework, agency MBS are issued by bankruptcy-remote special purpose entities, insulating Fannie Mae and Freddie Mac from direct balance-sheet exposure. In a covered bond-style reform, agency mortgages would instead be issued as direct, secured obligations of Fannie and Freddie, with the agencies retaining explicit liability and providing overcollateralization and dual recourse, as in Denmark.

Implementing a Danish-style system in which mortgages are funded through the issuance of a single, large covered bond for each coupon-vintage pair would have significant implications for the secondary market, particularly the TBA and spec-pool segments. Because all mortgages originated within a given time window and carrying a given coupon would be delivered into a single covered bond, the resulting securities would be larger and more liquid than current passthrough pools. These issues could trade actively in both cash and forward markets, with the forward market serving a role closely analogous to today's TBA market. At the same time, such consolidation would

[25] 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 $\theta_g = 0$.

eliminate much of the heterogeneity that underpins the current spec-pool market: originators would no longer be able to extract value by segregating loans with superior prepayment profiles into specialized pools, and the economic rents associated with producing "better-than-TBA" collateral would likely dissipate. Such consolidation would also reshape origination incentives: the current originate-to-distribute model, in which non-bank lenders quickly sell loans into the TBA market, could give way to structures in which the agency retains direct balance-sheet exposure.

Jumbo market. In the jumbo segment, deposit-taking institutions often retain originations on their balance sheets as portfolio loans. When market rates rise above the mortgage coupon, borrowers could in principle approach the lender and offer to repurchase the mortgage at a discount — the loan is worth less than par, so lenders should be willing to accept. In practice, however, portfolio loans are typically held in available-for-sale or held-to-maturity accounts marked at par. Terminating a mortgage at a discount would immediately trigger an accounting loss for the lender, negatively affecting P&L and reported earnings. For non-GSIB banks, this is compounded by a regulatory capital impact, because accumulated other comprehensive income is not fully included in regulatory capital for these institutions. Consequently, banks are reluctant to entertain discounted buybacks even when economically justified. Reforming accounting and regulatory capital rules to better reflect mark-to-market values — so that unrealized losses flow through P&L and regulatory capital correspondingly — would reduce these barriers.

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. Common in Canada and the U.K., portability lets a household carry a below-market rate to a new home, subject to lender re-approval and underwriting of the new collateral. 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 household holding a \$400,000 mortgage at 3% that wishes to purchase a larger home requiring \$600,000 in financing after market rates have risen to 7%. With a buyback right, the household repurchases its existing loan at market value (approximately \$280,000) and originates a new mortgage for \$600,000 at 7% — operationally identical to a conventional refinance. Under portability, the household must transfer the existing mortgage to the new property and obtain an additional \$200,000 second lien, raising immediate coordination problems: which institution will underwrite the second lien, under what terms, and subject to what combined LTV restrictions? Under assumability, the household must find a buyer willing to assume the 3% loan — a bilateral bargaining problem — while simultaneously giving up the below-market contract when originating a new mortgage on the next property. Because house prices typically appreciate and loan balances amortize, the buyer assuming the existing mortgage would most likely need additional financing to complete the purchase, reintroducing the same coordination frictions. In equilibrium, the embedded subsidy capitalizes into the home's listing price, so the benefit attaches to the property rather than traveling with 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 or 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 4.9). Assumability and portability, by contrast, would require new tri-party workflows, collateral-swap tracking systems, and robust second-lien markets — infrastructure that does not currently exist at scale.

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 forfeit access to existing low-coupon mortgages, 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 buy-back rights and tax incentives jointly govern household decisions.

Our counterfactual analysis demonstrates that introducing a Danish-style buy-back 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		1,411	1,125	
Original Maturity (in years)	29.03	27.36		28.87	27.01		28.86	26.86	
Coupon (%)	2.73	5.00		0.39	1.95		0.82	2.96	
Coupon gap (%)	-2.27	0.00		-4.61	-3.05		-2.52	-0.43	
Simple averages									
Prepayment rate (in %)	9.33	24.47		10.26	17.49		11.80	19.65	
Refi rate (in %)	4.89	17.53		2.80	10.77		5.75	13.28	
Moving rate (in %)	3.64	2.88	3.60	4.14	3.32	4.64	4.13	3.07	3.84
Value weighted averages									
Prepayment rate (in %)	8.90	29.45		10.03	20.77		11.90	22.17	
Refi rate (in %)	4.64	23.28		3.18	14.34		6.03	16.59	
Moving rate (in %)	3.56	2.83		4.13	3.26		4.05	3.10	
Counts									
Count (in ,000)	528	581	342	523	606	350	8,660	8,074	5,083
Frequency (in %)	36.38	40.04	23.58	35.38	40.94	23.68	39.69	37.01	23.30

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 home owners 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) coupon gap

	OLS		IV
	(1)	(2)	(3)
	Moving (pct)	Moving (pct)	Moving (pct)
Coupon Gap (p.p.)	-0.0162***	0.00962***	0.00897**
	(0.00101)	(0.00148)	(0.00374)
Positive gap indicator	0.00893***	0.0151***	0.0525***
	(0.00333)	(0.00258)	(0.0135)
Coupongap X Positive gap	0.0589***	0.0266***	0.0362***
	(0.00163)	(0.00179)	(0.00509)
Controls		X	X
R-squared	0.0000440	0.000993	0.000470
Root MSE	5.435	5.374	5.394
F-stat			173.4
Observations	75176817	74030730	71988904

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; month fixed effects; year fixed effects; municipality fixed effects; and year-by-municipality fixed effects. Column (3) 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 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	0.33
α	amortization rate	1/30	1/30
Refinancing			
λ	refinancing opportunity hazard	0.33	0.30
κ_λ	refinancing costs (mean)	0.008	0.02
σ_λ	refinancing costs (s.d.)	0.005	0.02
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	0.15

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.

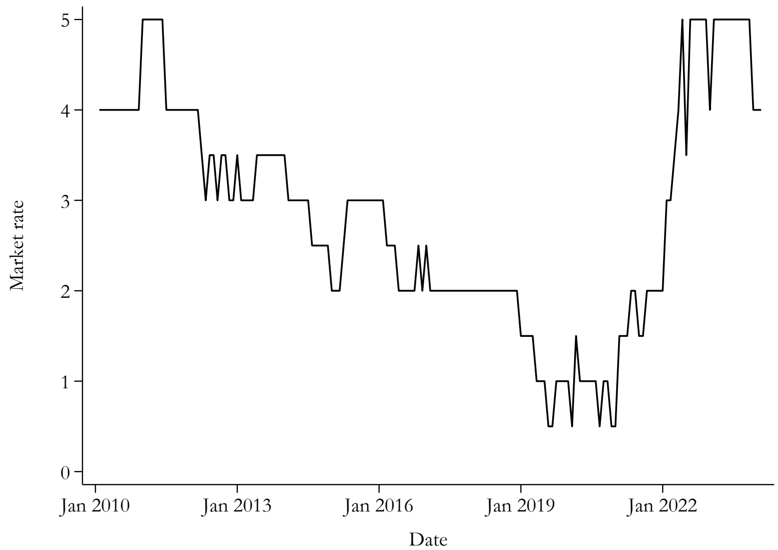
Table 4: Term structure model estimation

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%	$[1.39\%, 1.55\%]$

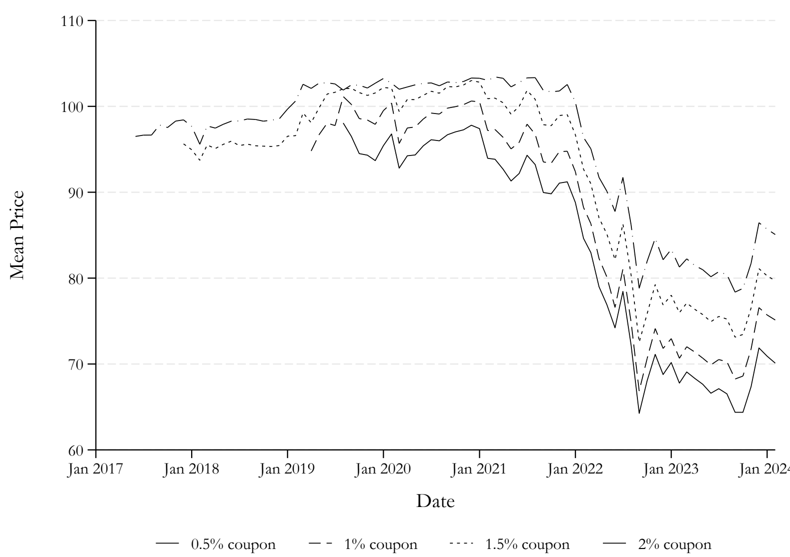
Note: This table reports parameter estimates from the shadow rate model described in Section 4.6. Estimates are obtained by maximum likelihood using monthly zero-coupon yield data from Danish and U.S. government bonds. For each parameter vector $(\bar{x}, \eta, \sigma)$, we numerically compute the model-implied 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



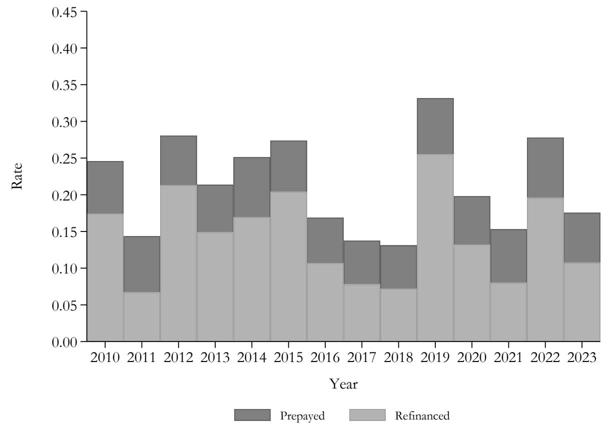
(b): Mortgage prices



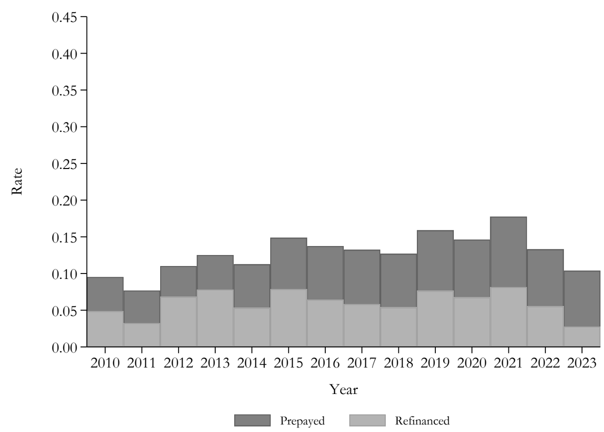
Note: Top figure shows the monthly coupon for those FRMs in the longest time-to-maturity category (30-34 years to maturity) that currently have the highest market price, below 100, in the dataset from Værdipapircentralen. Bottom figure shows the market price for 30-year fixed-rate mortgage bonds maturing 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



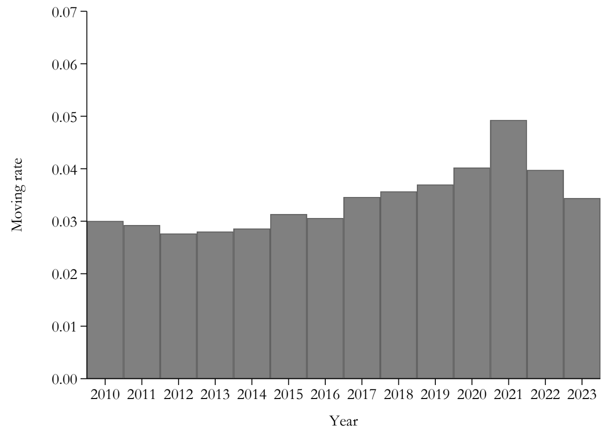
(b): ARMs



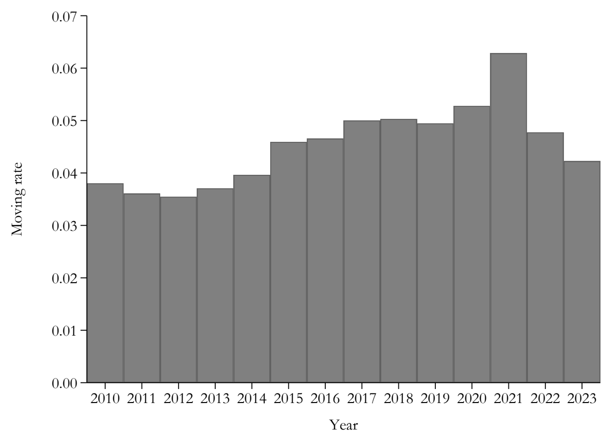
Note: Figure shows the primary mortgages of a given type prepaid or refinanced in a given year, as a fraction of the mortgage of that type outstanding at the beginning of the year. The top figure presents the data for fixed-rate mortgages (FRMs), while the bottom figure presents the data for adjustable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

Figure 3: Moving rates

(a): FRMs



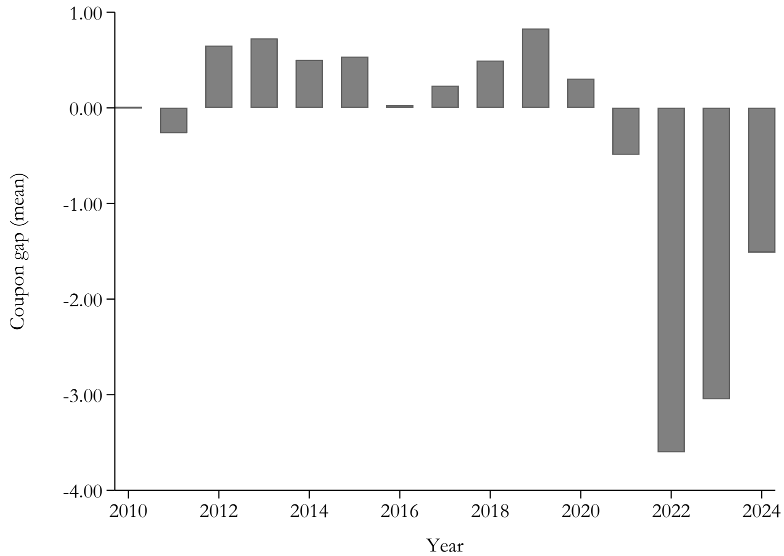
(b): ARMs



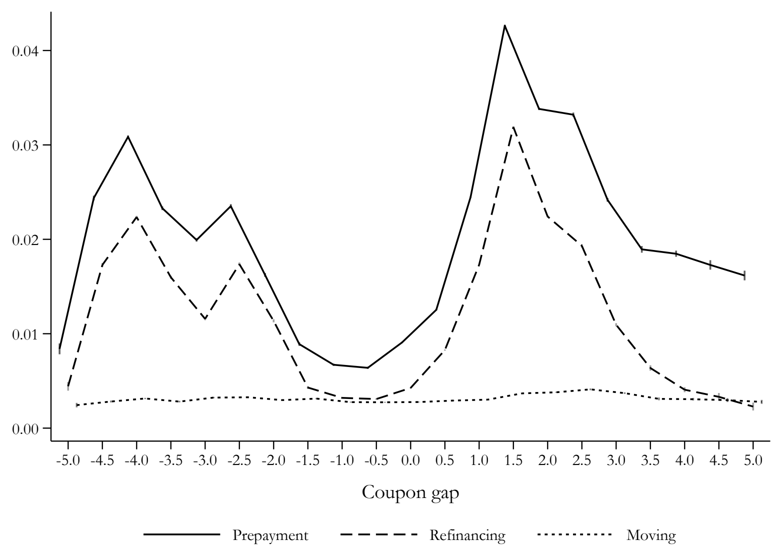
Note: The figure shows the aggregate moving rate among fixed rate mortgage (FRM) holders (Panel a) and among adjustable rate mortgage (ARM) holders (Panel b).

Figure 4: Prepayment rates and the coupon gap

(a): Average coupon gap over time



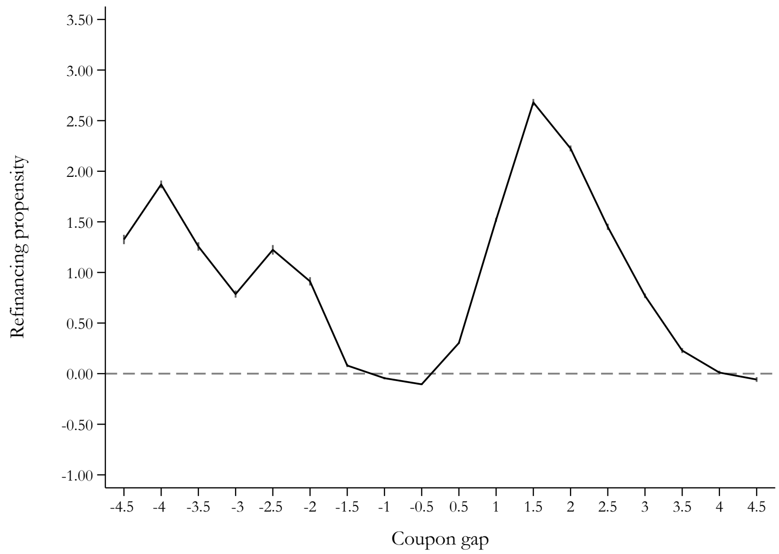
(b): Prepayment rate vs. coupon gaps



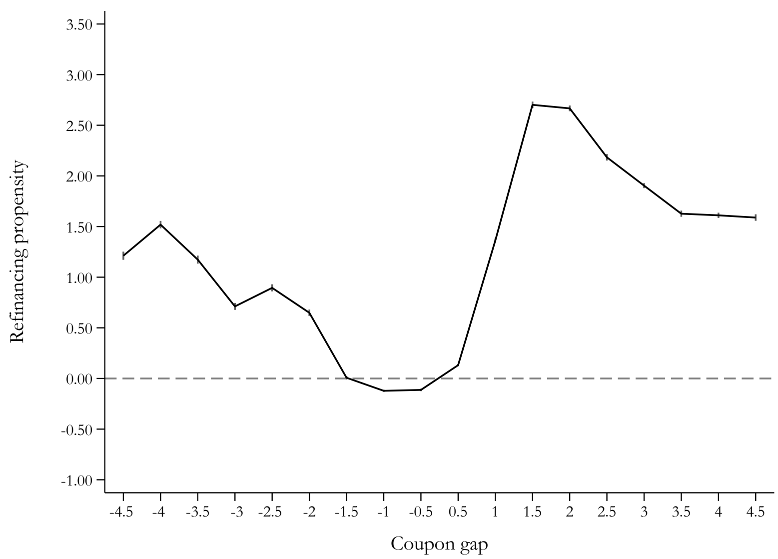
Note: Top figure shows the average coupon gap of all households with their largest mortgages being an FRM in a given year. Coupon gap is the difference between (a) the coupon of the household primary mortgage (if such mortgage is an FRM) and (b) the market coupon rate on a 30 year FRM, measured as the monthly coupon for those FRMs in the longest time-to-maturity category (30-34 years to maturity) that currently have the highest market price below 100 in the dataset Værdipapircentralen. Bottom figure shows the prepayment, refinancing and moving rates as a function of the coupon gap for FRM mortgage holders in the full sample. 95 percent confidence intervals are represented by (small) vertical lines.

Figure 5: Refinancing propensities

(a): No controls



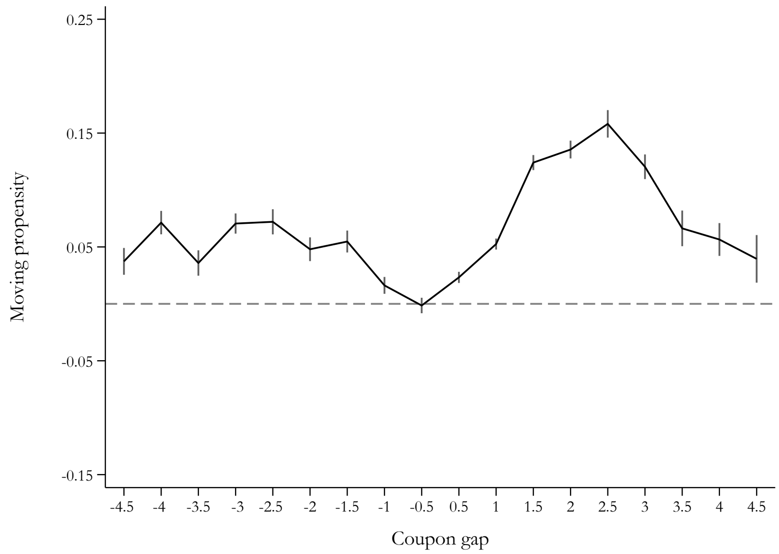
(b): Controls



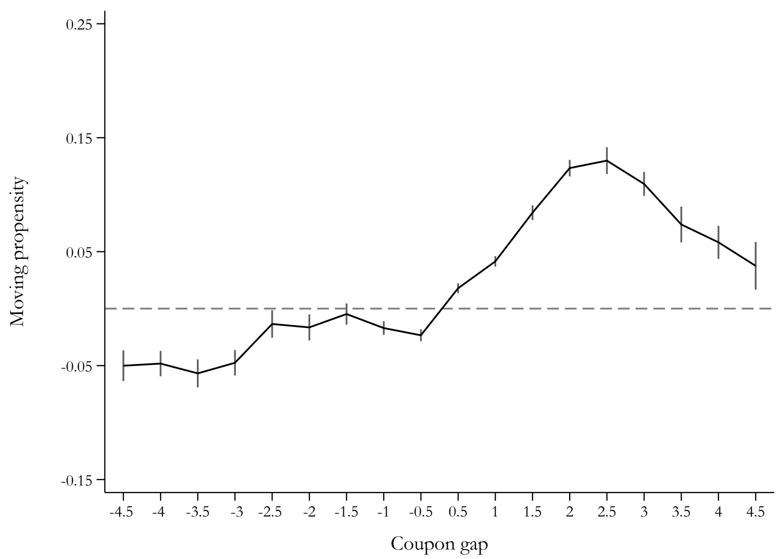
Note: **Panel A** shows the propensity to refinance as a function of coupongap dummies with 50 BPS intervals without controlling for further factors. **Panel B** shows refinancing propensities as a function of coupongap dummies at 50 bps intervals, while controlling for variables similar to Fonseca and Liu (2024) (household age, household age squarred, gender (couple, single female, single male), log face value, log of average monthly mortgage payment, month fixed effects, year fixed effects, municipality fixed effects, year-municipality fixed effects and remaining term of the mortgage. Across both panels the baseline coupon-gap is set at 0 for interpretational purposes. Standard errors are double clustered by issuance month-year and municipality).

Figure 6: Moving propensities

(a): No controls



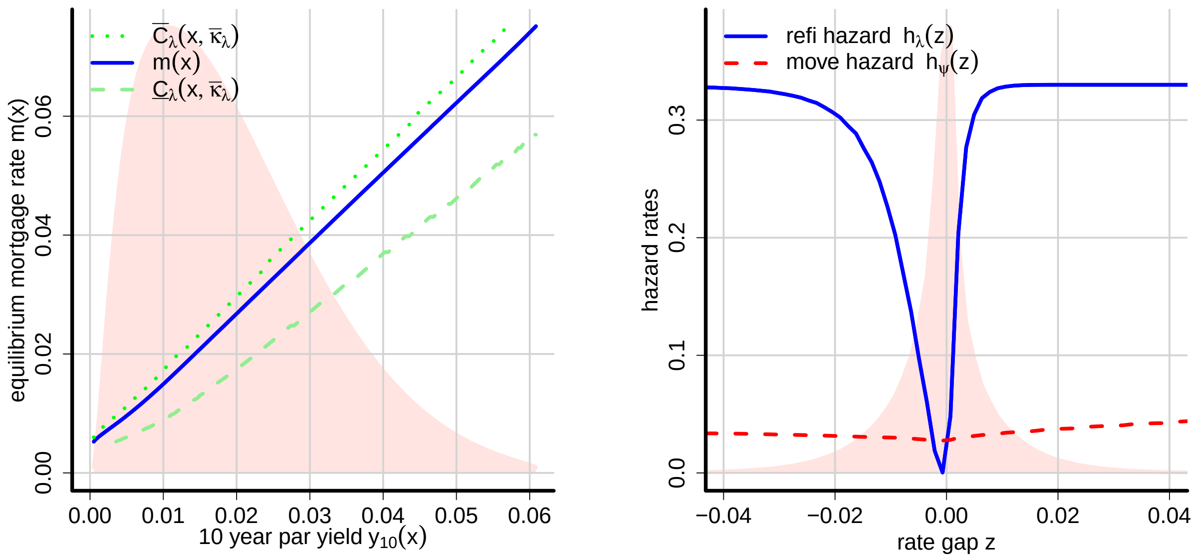
(b): Controls



Note: **Panel A** shows the propensity to move as a function of coupongap dummies with 50 BPS intervals without controlling for further factors. **Panel B** shows moving propensities as a function of coupongap dummies at 50 bps intervals, while controlling for variables similar to Fonseca and Liu (2024) (household age, household age squarred, gender (couple, single female, single male), log face value, log of average monthly mortgage payment, month fixed effects, year fixed effects, municipality fixed effects, year-municipality fixed effects and remaining term of the mortgage. Across both panels the baseline coupon-gap is set at 0 for interpretational purposes. Standard errors are double clustered by issuance month-year and municipality).

Figure 7: Equilibrium illustration

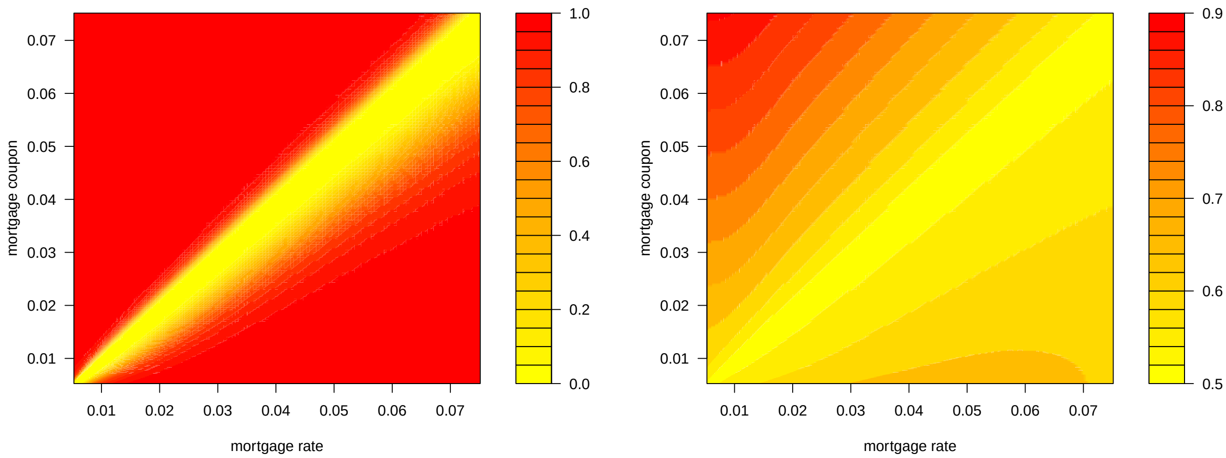
(a): Mortgage rate $m(x)$ **(b):** Hazard rates $h(z)$



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 par 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 coupon gap z. In both figures, the pink shaded area shows the ergodic density — on the left figure, the ergodic density of the 10-year par yield $y_{10}(x)$, and on the right figure, the ergodic density of the coupon gap z.

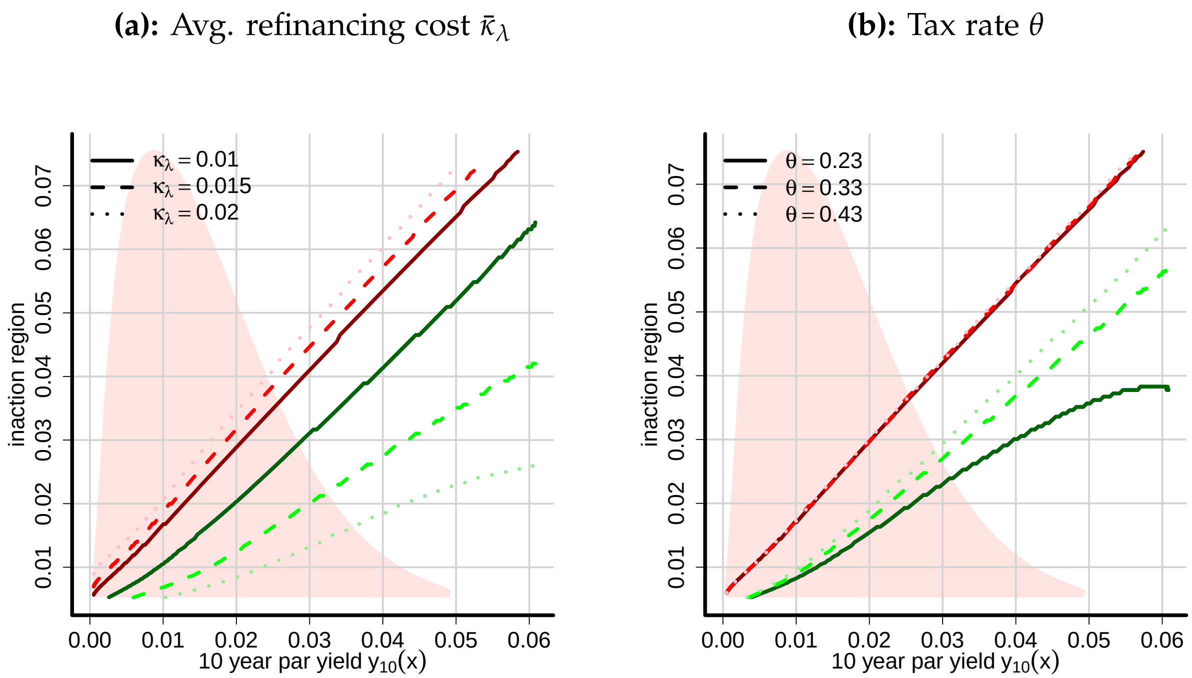
Figure 8: Exercise probabilities

(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.

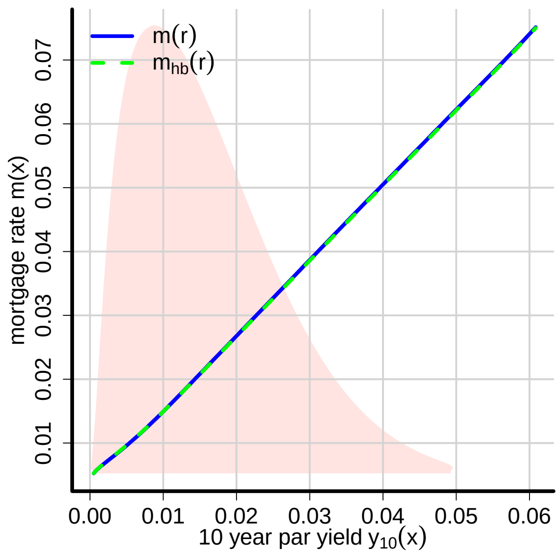
Figure 9: Comparative statics



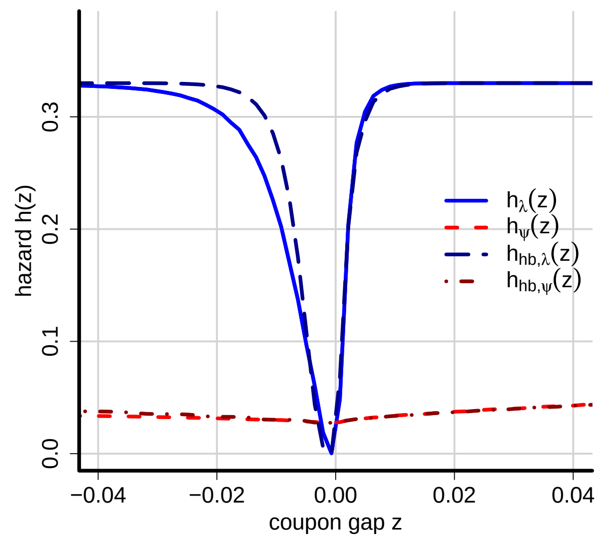
Note: Figures show the inaction region $\mathcal{I}_\lambda(x;\bar{\kappa}_\lambda)$ for varying values of the average refinancing cost $\bar{\kappa}_\lambda$ (left figure) and tax rate θ (right figure), plotted as a function of the 10-year par yield $y_{10}(x)$ (see Section A.3 for a reminder of its 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 $m(x)$



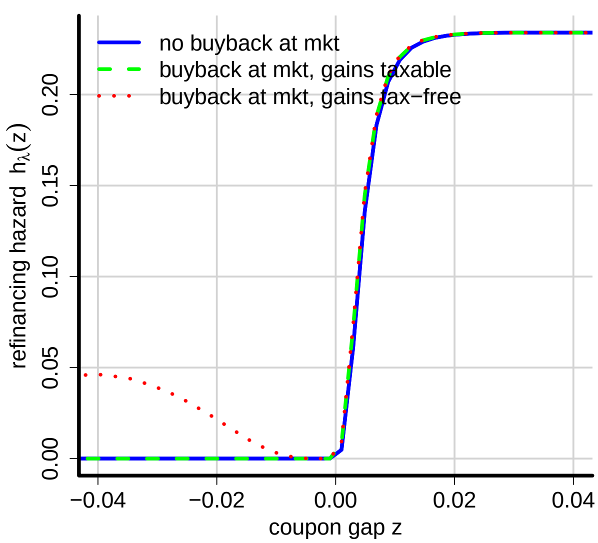
(b): Hazard rates $h(z)$

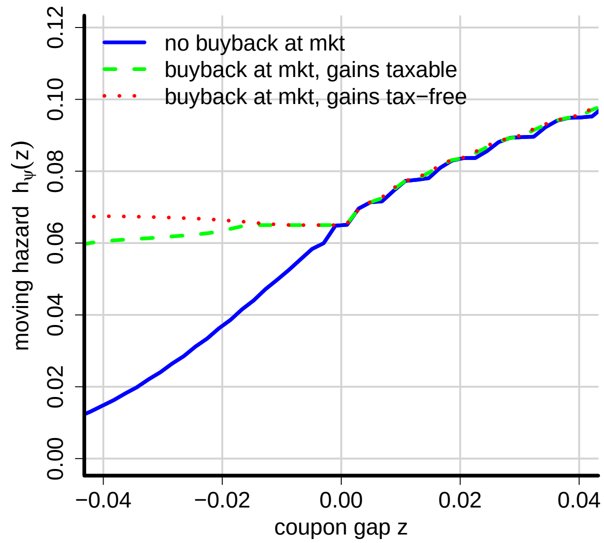


Note: Left figure shows the equilibrium mortgage rate $m(x)$ when households and the market have homogeneous beliefs (solid blue) and when households perceive the speed of mean reversion to be twice as fast as the market's belief (dash green). Right figure shows the implied refinancing, move and prepayment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

Figure 11: U.S. FRMs: with vs. without buy-back 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 coupon 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).

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

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

Mortgage prices follow the usual martingale condition (6). 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 $1\le i,j\le n$. 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:

$$\partial_x v^b_{i,j,k} := \frac{v_{i,j,k} - v_{i-1,j,k}}{\Delta_x} \qquad \partial_x v^f_{i,j,k} := \frac{v_{i+1,j,k} - v_{i,j,k}}{\Delta_x} \qquad \partial_x v^c_{i,j,k} := \frac{v_{i+1,j,k} - v_{i-1,j,k}}{2\Delta_x}.$$

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

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

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

$$\frac{v_{i,j,k} - v_{i,j,k-1}}{\Delta_t} + (\rho + \alpha)\, v_{i,j,k} = \alpha + (1-\theta)m_{j,k-1} + \sum_{\ell\in\{i-1,i,i+1\}} L_{i,\ell} v_{\ell,j,k}$$
$$+ \sum_{\beta=\lambda,\psi} \beta \min\left[0, v_{i,i,k-1} + \kappa_\beta - \max\left(0, 1 - p_{i,j,k-1}\right) - v_{i,j,k-1}\right] \quad \text{(B-2)}$$

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 $\sum_{\beta=\lambda,\psi} \beta \min\left[0, v_{i,i,k-1} + \kappa_\beta - \max\left(0, 1 - p_{i,j,k-1}\right) - v_{i,j,k-1}\right]$ 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:

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

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 exercises her par call option, via:

$$e^{\beta}_{i,j,k-1} := \mathbb{1}\left(v_{i,j,k-1} < v_{i,i,k-1} - \kappa_\beta\right),$$

where $e^{\beta}_{i,j,k-1}$ is an indicator for whether the borrower prepays (when $\beta = \lambda$) or moves (when $\beta = \psi$) while triggering a par prepayment. As a reminder, prepayments (whether refinancing or moves) at a discount do not affect mortgage prices directly, since upon such discounted buy-backs, investors receive exactly the market value of their mortgage. The discretization of equation (6) 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

$$\frac{p_{i,j,k} - p_{i,j,k-1}}{\Delta_t} + \left(r_i + \alpha + \sum_{\beta=\lambda,\psi} \beta e^{\beta}_{i,j,k-1}\right) p_{i,j,k} = \alpha + m_{j,k-1} + \sum_{\ell \in \{i-1,i,i+1\}} L_{i,\ell} p_{\ell,j,k} + \sum_{\beta=\lambda,\psi} \beta e^{\beta}_{i,j,k-1}, \quad \text{(B-3)}$$

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:

$$\left[\left(\frac{1}{\Delta_t} + \alpha\right) I + R + \sum_{\beta=\lambda,\psi} \beta E^{\beta} - L\right] \vec{p}_k = \frac{1}{\Delta_t}\vec{p}_{k-1} + \alpha\vec{1} + \vec{m}_{k-1} + \sum_{\beta=\lambda,\psi} \beta E^{\beta}\vec{1}, \quad \text{(B-4)}$$

where the $n^2 \times 1$ vector $\vec{p}_k$ has entry $p_{i,j,k}$ in row $i + (j-1)n$, where E^{β} is a square $n^2 \times n^2$ diagonal matrix with entry $e^{\beta}_{i,j,k-1}$ 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 (7).

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 (11) 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.:

$$\Lambda' \vec{f} = \vec{0} \qquad \vec{f} \cdot \vec{1} \Delta_r^2 = 1. \tag{B-5}$$

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 $R := \text{diag}(r(x_i))$, the price vector $\vec{P}(t; c)$ encodes the price of the coupon bond at each state x_i, and it solves

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

which admits the analytic solution

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

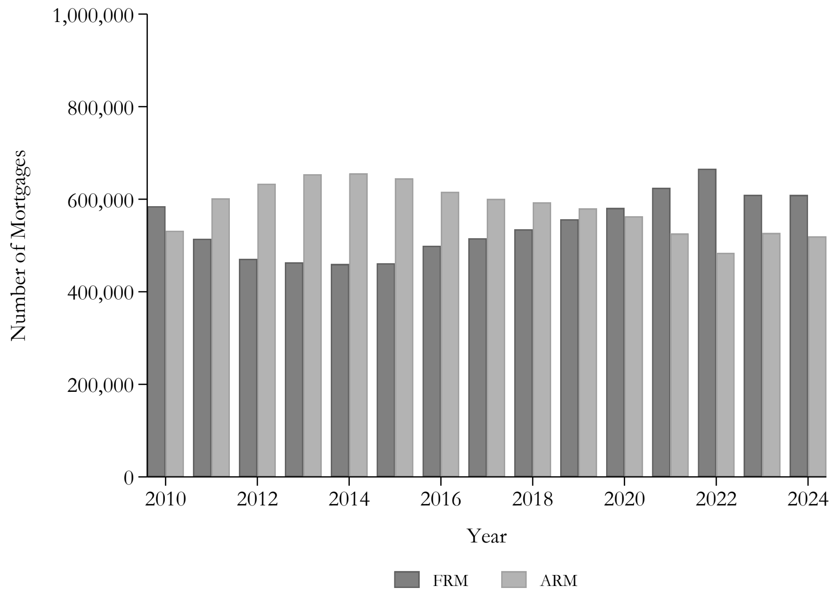
Given an empirical time series $\{y_{T,t}^*\}_{t=1,\ldots,n_t}$ of T-year spot rates, one can use our solution method to retrieve the shadow state x_t that solves $\ln P(x_t, T; 0) = -T y_{T,t}^*$. Once we have recovered the time-series of shadow short rates $\{x_t\}_{t=1,\ldots,n_t}$, it is straightforward 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 $P(x, T; y_T(x)) := 1$.

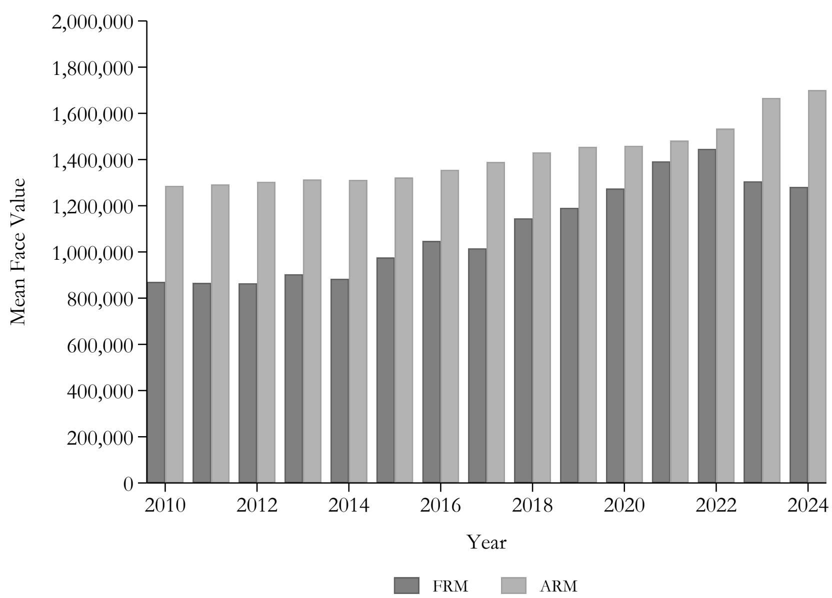
B Appendix: additional tables and figures

Figure A-1: FRMs vs. ARMs

(a): FRMs vs. ARMs outstanding

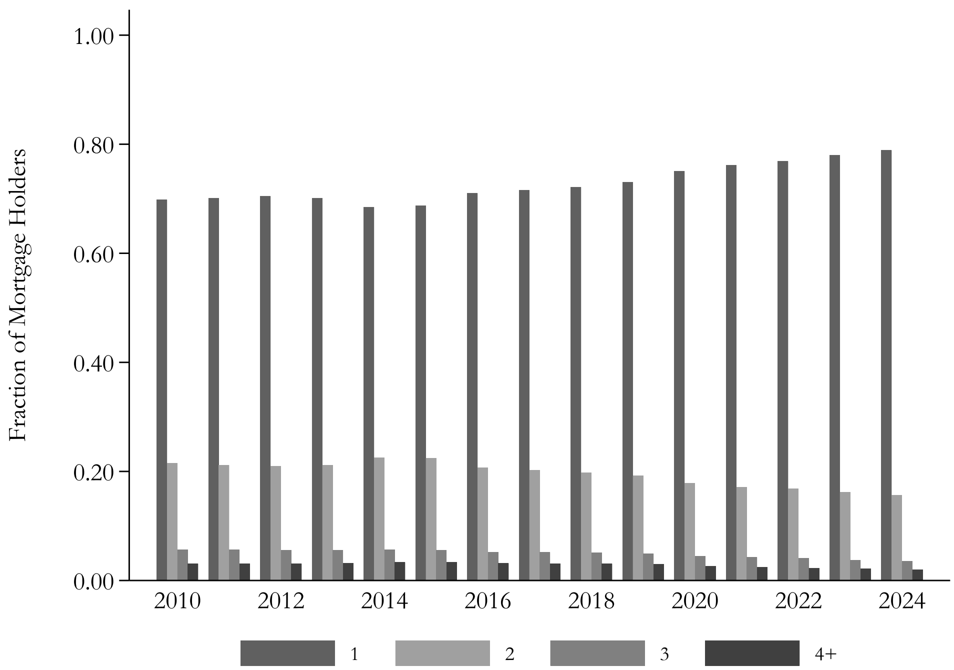


(b): FRMs vs. ARMs average face value



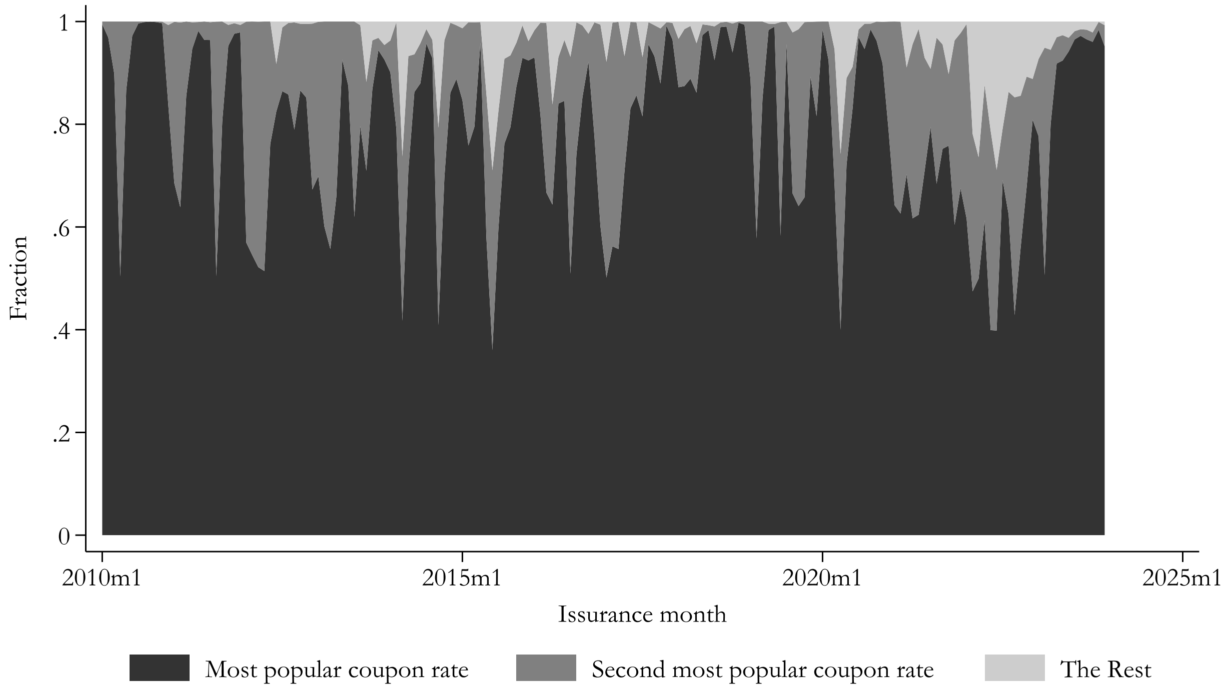
Note: Top figure shows the number of Danish households whose primary mortgage is either an ARM or an FRM at the beginning of each year. Bottom figure shows the average face value for households' primary mortgage, by type, in DKK.

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



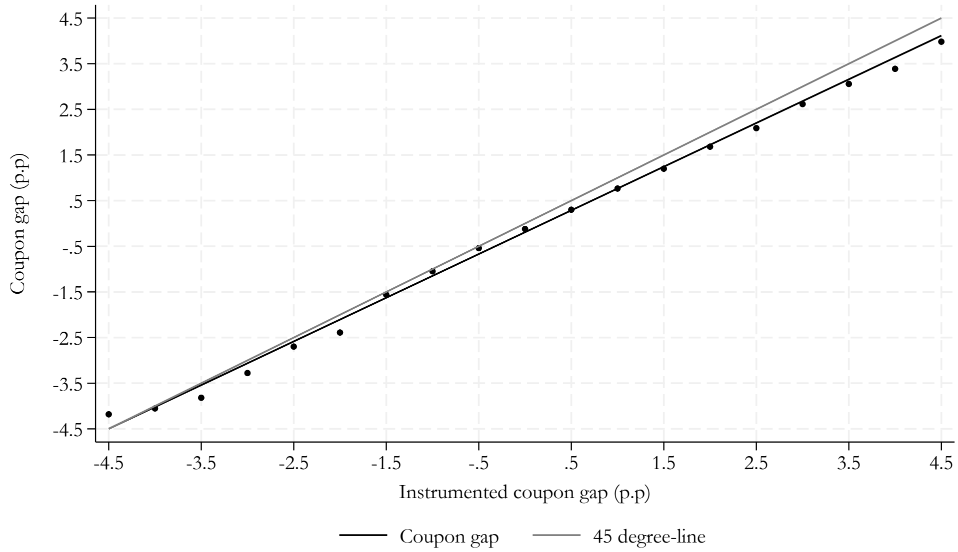
Note: Distribution of number of mortgages, showing the fraction of mortgage-indebted households with 1, 2, 3 or 4 + mortgages in the beginning of the year. The denominator consists of all households which have at least 1 mortgage in the beginning of the year.

Figure A-3: Coupon rates mass points at origination



Note: The graphs shows the monthly fraction of issued mortgages with the most popular coupon rate, the second most popular coupon rate, and a pool of all other rates.

Figure A-4: Instrument relevance



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

Table A-1: The cross-section of coupon rates at origination

	(1)	(2)	(3)	(4)	(5)	(6)
Age below 30		0.00423***				0.00657***
		(0.00119)				(0.00122)
Age 30-39		0.00539***				0.00572***
		(0.000847)				(0.000851)
Age 50-64		-0.0125***				-0.0127***
		(0.000792)				(0.000797)
Age 65+		-0.0159***				-0.0161***
		(0.00100)				(0.00107)
College education			0.00437***			0.00128**
			(0.000582)			(0.000629)
Income 1st quintile				-0.000526		0.00120
				(0.00194)		(0.00194)
Income 2st quintile				0.000952		0.00299**
				(0.00145)		(0.00146)
Income 4st quintile				0.00522***		0.00225**
				(0.000920)		(0.000934)
Income 5st quintile				0.00718***		0.00166*
				(0.000876)		(0.000949)
Net wealth 1st quintile					0.0158***	0.0186***
					(0.00124)	(0.00126)
Net wealth 2st quintile					0.0181***	0.0186***
					(0.00147)	(0.00147)
Net wealth 4st quintile					0.00646***	0.00728***
					(0.00125)	(0.00126)
Net wealth 5st quintile					0.0154***	0.0168***
					(0.00127)	(0.00129)
Constant	2.221***	2.226***	2.219***	2.216***	2.209***	2.209***
	(0.000289)	(0.000580)	(0.000418)	(0.000761)	(0.00112)	(0.00143)
Origination month-year FEs	X	X	X	X	X	X
Maturity Length FEs	X	X	X	X	X	X
LTV FEs	X	X	X	X	X	X
R-squared	0.923	0.923	0.923	0.923	0.923	0.923
Root MSE	0.362	0.362	0.362	0.362	0.362	0.362
Observations	1571563	1571563	1571563	1571563	1571563	1571563

Note: This table reports results from cross-sectional OLS regressions of FRM coupon rates on household characteristics, controlling for mortgage-specific fixed effects, using newly originated loans. All specifications include fixed effects for loan origination month–year, maturity length, and loan-to-value (LTV). Maturity length is grouped into five categories: less than 10 years, 10–19 years, 20–24 years, 25–29 years, and 30–34 years. LTV is categorized into four brackets: below 40 percent, 40–60 percent, 60–80 percent, and above 80 percent. Standard errors in parentheses: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$