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journal homepage: [www.elsevier.com/locate/jfec](http://www.elsevier.com/locate/jfec)Systemic risk and the refinancing ratchet effect<sup>☆</sup>Amir E. Khandani<sup>a,c</sup>, Andrew W. Lo<sup>b,c,d,\*</sup>, Robert C. Merton<sup>b</sup><sup>a</sup> Morgan Stanley, New York, United States<sup>b</sup> MIT Sloan School of Management, 100 Main Street, E62-618, Cambridge, MA 02142, United States<sup>c</sup> Laboratory for Financial Engineering, MIT Sloan School of Management, United States<sup>d</sup> AlphaSimplex Group, LLC, United States

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## ABSTRACT

The combination of rising home prices, declining interest rates, and near-frictionless refinancing opportunities can create unintentional synchronization of homeowner leverage, leading to a “ratchet” effect on leverage because homes are indivisible and owner-occupants cannot raise equity to reduce leverage when home prices fall. Our simulation of the U.S. housing market yields potential losses of \$1.7 trillion from June 2006 to December 2008 with cash-out refinancing vs. only \$330 billion in the absence of cash-out refinancing. The refinancing ratchet effect is a new type of systemic risk in the financial system and does not rely on any dysfunctional behaviors.

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## 1. Introduction

Home mortgage loans—one of the most widely used financial products by U.S. consumers—are collateralized

mainly by the value of the underlying real estate. This feature makes the market value of the collateral very important in measuring the risk of a mortgage.<sup>1</sup> To reduce the risk of default, mortgage lenders usually ask for a down payment of 10–20% of the value of the home from the borrower, creating an “equity buffer” that absorbs the first losses from home price declines. Any event or action that reduces the value of this buffer, e.g., an equity extraction or a drop in home values, increases the risk to the lending institution.

A number of secular trends over the last two decades, including the increased efficiency of the refinancing process and the growth of the refinancing business, have made it much easier for homeowners to refinance their

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<sup>1</sup> See, for example, Danis and Pennington-Cross (2005), Downing, Stanton, and Wallace (2005), Gerardi, Shapiro, and Willen (2007), Doms, Furlong, and Krainer (2007), Bajari, Chu, and Park (2008), Bhardwaj and Sengupta (2008a), and Gerardi, Lehnert, Sherlund, and Willen (2008).

mortgages to take advantage of declining interest rates, increasing housing prices, or both. Consequences of these trends have been documented by Greenspan and Kennedy (2008, p. 120), who observe, “since the mid-1980s, mortgage debt has grown more rapidly than home values, resulting in a decline in housing wealth as a share of the value of homes.” They attribute most of this effect to discretionary equity extractions via home sales, “cash-out” refinancing (where the homeowner receives cash after the refinancing), and home-equity loans.

In this paper, we focus on a previously unstudied dimension of risk in the mortgage market: the interplay among the growth of the refinancing business, the decline in interest rates, and the appreciation of property values. Each of these three trends is systemically neutral or positive when considered in isolation, but when they occur simultaneously, the results can be explosive. We argue that during periods of rising home prices, falling interest rates, and increasingly competitive and efficient refinancing markets, cash-out refinancing is like a ratchet. It incrementally increases homeowner leverage as real-estate values appreciate without the ability to symmetrically decrease leverage by increments as real-estate values decline. This self-synchronizing “ratchet effect” can create significant systemic risk in an otherwise geographically and temporally diverse pool of mortgages.

The potential magnitude of the risk created due to the refinancing ratchet effect is most clearly illustrated through a hypothetical scenario in which all homeowners decide to keep their leverage at a level generally associated with extreme prudence and good lending practices, for example, a loan-to-value (LTV) of 80% for a conventional fully amortizing 30-year fixed-rate mortgage. Suppose the refinancing market is so competitive, i.e., refinancing costs are so low and capital is so plentiful, that homeowners are able to extract any equity above the minimum each month. In such an extreme case, cash-out refinancing has the same effect as if all mortgages were re-originated at the peak of the housing market. When home prices fall, as they must eventually, the ratchet “locks” because homeowners cannot easily unwind their real-estate positions and incrementally deleverage due to indivisibility and illiquidity. The unintentional synchronization of leverage during the market’s rise naturally leads to an apparent shift in regime during the market’s decline, in which historically uncorrelated defaults now become highly correlated.

Indivisibility and occupant-ownership of residential real-estate are two special characteristics of this asset class that make addressing this issue particularly challenging. The impact of indivisibility can be crystallized by comparing an investment in residential real estate with a leveraged investment in a typical exchange-traded instrument such as shares of common stock. While the latter is subject to both an initial margin requirement as well as a maintenance margin requirement, home mortgages only have a homeowner equity requirement that plays a role similar to that of an initial margin. It is hard to imagine that homeowners would willingly finance large capital purchases using short-term debt like margin accounts, and long-term debt may have become the standard method for financing home purchases precisely because of the indivisible nature of

the collateral. Furthermore, the occupant is almost always the sole equityholder in an owner-occupied residential property, and moral hazard concerns preclude the owner from reducing leverage by raising incremental capital via issuing equity to others.

These two special features of residential real estate may be viewed as market frictions or institutional rigidities that create an important asymmetry in the housing market which does not exist in most financial markets. While a leveraged investor may decide not to incrementally deleverage as prices decline due to optimistic expectations of a price reversal, indivisibility and occupant-ownership make incremental deleveraging impossible, even for those who wish to reduce their exposure to real estate. Therefore, the only option available to homeowners in a declining market is to sell their homes, recognize their capital losses, and move into less expensive properties that satisfy their desired LTV ratio. The enormous costs—both financial and psychological—of such a transaction make it a highly impractical and implausible response to addressing the issue raised in this paper.

We propose to gauge the magnitude of the potential risk caused by the refinancing ratchet effect by creating a numerical simulation of the U.S. housing and mortgage markets. By calibrating our simulation to the existing stock of real estate, and by specifying reasonable behavioral rules for the typical homeowner’s equity extraction decision—which satisfy common standards of prudence and good lending practices in the U.S.—our simulation can match some of the major trends in this market over the past decade. Based on the calibrated simulation and using a standard derivatives-pricing model, we construct an estimate of losses absorbed by mortgage lenders—banks, asset management firms, and government-sponsored enterprises (GSEs)—from the decline in real-estate prices and compare these estimates with the scenario of no equity extractions over the same period. Our simulation yields an approximate loss of \$1.7 trillion from the housing-market decline since June 2006 compared to a loss of \$330 billion if no equity had been extracted from U.S. residential real estate during the boom.

Of course, a simple response to the refinancing ratchet effect might be to eliminate non-recourse mortgages. If all mortgages were recourse loans and borrowers had uncorrelated sources of income, their income streams would create an extra level of protection for lenders and, therefore, distribute the risk in the mortgage system between lenders and borrowers more evenly. Instead, current legal procedures for foreclosure and obtaining deficiency judgments are complex and vary greatly from state to state. As discussed by Ghent and Kudlyak (2009, Table 1), while home mortgages are explicitly non-recourse in only 11 states, in certain populous states with recourse such as Florida and Texas, generous homestead-exemption laws can make it virtually impossible for lenders to collect on deficiency judgments because borrowers can easily shield their assets. Nevertheless, the risks and potential losses calculated according to the framework proposed in this paper must be borne by some combination of borrowers and lenders; from our systemic-risk perspective, the precise combination is of less consequence than the aggregate magnitude.

While we have attempted to construct as realistic a simulation as possible, we acknowledge at the outset that our approach is intended to capture “reduced-form” relations and is not based on a general-equilibrium model of households and mortgage lenders. Instead of relying on a stylized general-equilibrium model, we adopt a simple refinancing rule that seems to capture plausible behavior among U.S. homeowners over the recent past. Also, we do not model the supply of refinancing and the behavior of lenders, but rather assume that households can refinance as much as they wish at prevailing historical interest rates. While the plentiful supply of credit had been close to reality during the decade leading up to the peak of the housing market in June 2006, our motivation for this assumption is to isolate the impact of the refinancing ratchet effect. Lending behavior undoubtedly contributed to the magnitude of the Financial Crisis of 2007–2009, as did many other factors (see [Lo, 2012](#) for a review of the burgeoning crisis literature). An empirically accurate stochastic dynamic general-equilibrium model of the housing and mortgage markets that endogenizes these factors is a much more challenging undertaking and beyond the scope of this paper.

Our objective is not to explain the crisis, but rather to show that even in the absence of any dysfunctional behavior such as excessive risk-taking, fraud, regulatory forbearance, political intervention, and predatory borrowing and lending, large system-wide shocks can occur in the housing and mortgage markets. The refinancing ratchet effect is a considerably more subtle and complex form of systemic risk, arising from the confluence of three familiar and individually welfare-improving economic trends coupled with inherent frictions in the housing market. The simplicity of our simulation approach makes the refinancing ratchet effect more transparent, and the potential magnitude of its impact suggests that further attention is warranted.

We begin in [Section 2](#) with a brief review of the literature. We outline the design of our simulation and describe the results of the calibration exercise in [Section 3](#). We use these results in conjunction with a simple option-pricing model in [Section 4](#) to estimate the impact of mortgage refinancing on the aggregate risk of the U.S. mortgage market as home prices declined from 2006 to 2008. We provide some qualifications for and extensions of our results in [Section 5](#), and provide conclusions in [Section 6](#).

## 2. Literature review

Given the magnitude of the subprime mortgage crisis, a number of recent papers have attempted to trace its root causes. [Dell’Ariccia, Igan, and Laeven \(2012\)](#), [Demyanyk and Van Hemert \(2011\)](#), [Bhardwaj and Sengupta \(2008b\)](#), [Keys, Mukherjee, Seru, and Vig \(2008\)](#), and [Mian and Sufi \(2009\)](#) are only a few of the examples in this vast and growing literature. While the issues discussed in these papers, such as lax lending standards and the impact of institutional changes like securitization or the expansion of the subprime market, were certainly of primary importance in causing the recent crisis, none of these papers

have focused on the unique interplay between refinancing and systemic risk in the residential mortgage system that we examine in this paper.

The uncertain durations and credit risk of mortgages—due to prepayment or default by the borrower—make their risks different from other fixed-income products. The approach to modeling these risks can be divided into two categories: structural and reduced-form. Structural models focus on the underlying dynamics of the collateral value and the interest rates to arrive at a model of consumer behavior, while reduced-form models take a more statistical approach. [Kau, Keenan, Muller, and Epperson \(1992, 1995\)](#) and [Kau and Keenan \(1995\)](#) provide some early examples of the structural approach while [Schwartz and Torous \(1989\)](#), [Deng, Quigley, and Van Order \(2000\)](#), and [Deng and Quigley \(2002\)](#) take the reduced-form approach in their studies. [LaCour-Little \(2008\)](#) provides a recent review of this literature.

The earliest structural models adopted simplifying assumptions that yielded elegant closed-form solutions at the expense of certain stylized facts of the U.S. mortgage market that could not be captured by those assumptions. For example, consider the decision to default on a mortgage. The value of the underlying real estate is obviously the most important factor in driving this decision. However, while negative equity may be a necessary condition to trigger default, it is apparently not sufficient ([Foote, Gerardi, and Willen, 2008](#)), perhaps due to concerns such as moving costs, the desire to preserve reputational capital, default penalties, or even sentimental attachment to the home.<sup>2</sup> Similarly, homeowners seeking to refinance into a lower interest-rate mortgage when rates decline may be constrained by their financial circumstances or insufficient amounts of equity in their homes.<sup>3</sup>

Such complexities make complete modeling of risk in the residential mortgage system challenging. To avoid the possibility that our main message could be lost while dealing with these complexities, we have adopted a simple yet realistic behavioral rule that can be easily understood and allows us to focus on the main subject of our paper. Our approach for evaluating risk and pricing mortgage guarantees uses option-pricing technology that makes the analytical aspects of our approach closer to the structural models.

We argue that the increasing familiarity of borrowers with the refinancing process; the invention of new mortgage products; and the corresponding institutional, social, and political changes over the last decade contributed to an environment fertile for the type of risk that is the focus of this paper. Other researchers have studied and commented on this topic as well. For example, by comparing the refinancing decision of homeowners in the 1980s relative to the 1990s, [Bennett, Peach, and Peristiani \(2001\)](#) find evidence that over time, a combination of technological, regulatory, and structural changes has reduced the net

<sup>2</sup> [Stanton \(1995\)](#) and [Downing, Stanton, and Wallace \(2005\)](#) incorporate some of these effects into their models of mortgage termination.

<sup>3</sup> [Archer, Ling, and McGill \(1997\)](#) and [Peristiani, Bennett, Peach, and Raiff \(1997\)](#) consider the impact of household financial conditions such as income, credit history, and the amount of homeowner’s equity on the ability to refinance.

benefit needed to trigger a refinancing decision. They conjecture that homeowners' familiarity with the refinancing process and their increased financial sophistication are possible drivers behind this phenomenon.

Two examples of new mortgage products that enabled easier refinancing are the "subprime" and "Alt-A" mortgages. As Mayer and Pence (2008, p. 1) observe, "these new products not only allowed new buyers to access credit, but also made it easier for homeowners to refinance loans and withdraw cash from houses that had appreciated in value." They point out that "subprime mortgages are used a bit more for refinancing than home purchase" and "almost all subprime refinances are cash-out refinances" (Mayer and Pence, 2008, p. 10). Moreover, some of the more exotic products like non- or negative-amortization mortgages are contractual equivalents to dynamic strategies involving frequent cash-out refinancing to maintain a desired leverage ratio. These product innovations may have facilitated large-scale equity extractions by making refinancing significantly easier, cheaper, and virtually automatic.<sup>4</sup> The behavioral and social aspects of the decision to default on a residential mortgage is considered by Guiso, Sapienza, and Zingales (2009) using surveys of American households in late 2008 and early 2009. They find that households who have been exposed to defaults are more willing to default strategically, i.e., to default even though they can afford their mortgage payments. For example, individuals who know someone who defaulted strategically are 82% more likely to declare their intention to do so.

Perhaps a similar set of forces was at play during the most recent cash-out refinancing boom. Institutional changes, heightened competition, and technological advances made it easier and cheaper for consumers to engage in mortgage refinancing, and increased awareness of and familiarity with the refinancing process made it more popular. Even though many homeowners were undoubtedly aware of the potential dangers of equity extractions, the fact that many of their neighbors or co-workers were extracting equity from their homes made it more socially acceptable to do so at the height of the housing boom.

### 3. Simulating the U.S. mortgage market

Our main workhorse in this paper is a simulation of the U.S. residential mortgage system that attempts to capture first-order risks in this market. We simulate each home from the time it enters into the mortgage system and follow it as it ages and its mortgage is fully paid off. By listing a set of simple and reasonable rules, we try to calibrate our simulations to match the overall size and major trends in the U.S. housing and mortgage markets. To ensure that our simulation is computationally feasible given the computing power available to us, we simulate 1,000 paths for homes that enter the mortgage system in

a given month. Therefore, for each complete run of our simulations, we simulate approximately 1.1 million individual paths. For each path, we keep track of home value, interest rate, mortgage outstanding, and several option-based risk measures. The information is then aggregated to arrive at system-wide time series of interest such as total mortgage debt outstanding, total equity extracted, and various option-based risk metrics.

We describe the details of our simulation assumptions in Section 3.1. Our simulations depend on a number of parameters and for expositional clarity, we have summarized these parameters in Table 1. In particular, the specific rule that individuals follow in their refinancing decisions is a critical component of the simulations, and we describe the rule we use in Section 3.2. In Section 3.3, we report the results of our calibration exercise and specify the set of parameters to be used throughout the simulations.

#### 3.1. Simulation assumptions

In designing our simulation, we must balance the desire for realism against the availability of data and the tractability of the computations required. To that end, we make the following assumptions:

- (A1) Each house is purchased at an initial LTV ratio drawn from a distribution that is fixed through time and does not have any geographical dependency.
- (A2) All homes are purchased with conventional fixed-rate mortgages that are non-recourse loans with initial maturity drawn from a distribution that is fixed through time and does not have geographical dependency.
- (A3) The market value of homes follows a geometric random walk given by:

$$\log P_{i,t} - \log P_{i,t-1} = \beta_{rt} + N_{it}, \quad (1)$$

where  $\beta_{rt}$  is the cross-sectional common factor in home price appreciation for all homes in a given region  $r$  and  $N_{it}$  is the idiosyncratic component for each home and month. We calibrate  $\beta_{rt}$ ,  $r = 1, \dots, 10$ , to 10 distinct regional home price indexes and assume  $N_{it}$  to be serially uncorrelated normal random variables with a volatility that is constant through time and across all regions (see Table 1 for more details).

- (A4) We allow homeowners the possibility of engaging in "Cash-out refinancing" or "Rate refinancing" in each month.
- (A5) For Cash-out refinancing, we assume that the  $i$ th homeowner's decision is random with probability  $\text{REFI}_{i,t}$  which is a function only of the current equity in the home and the prevailing mortgage rate. In particular, we assume that the refinancing decision does not depend on factors such as the price and age of the home, or the time elapsed since any previous refinancing. We also assume that the homeowner will refinance into a new loan with the initial LTV ratio and maturity specified in Assumptions (A1) and (A2).
- (A6) The owners will engage in a Rate refinancing as soon as mortgage rates have fallen by more than the "Rate

<sup>4</sup> Many of these innovations may also have important tax or transaction-cost benefits to the borrower; hence, they may have been demand-driven rather than the result of overly aggressive mortgage lenders. In fact, these products may be essential for achieving optimal risk-sharing.

**Table 1**

Time series data used to calibrate a simulation of the U.S. housing and mortgage markets. See the Appendix for details.

Data item	Description
Home price appreciation	Prior to 1987, we assume that all homes grow at a rate specified by a single nationwide Home Price Index constructed using data from Robert Shiller prior to 1975Q1 and data from the FHFA for 1975Q4–1986Q4. After 1987, we use the ten individual series from the Standard and Poor's (S&P)/Case-Shiller Composite-10 Home Price Index to introduce geographical heterogeneity in our simulations
New homes entering the mortgage system	The number of new homes entering the mortgage system is calculated using data from the U.S. Census Bureau after 1963. We make some adjustments to take into account homes built by owners or by contractors. For years prior to 1963, we use a statistical approach outlined in the Appendix to backfill the data. Post-1987, we use the weights as given by the S&P/Case-Shiller Composite-10 Home Price Index to calculate the number of new homes in each of the ten regions
New home purchase price	We construct a time series of the average price of new homes using data from the U.S. Census Bureau since 1963. We backfill the data using our Home Price Appreciation index to January 1919. Finally, we use data from the 2007 American Housing Survey to create a distribution with 15 different price levels around the average series
Initial loan-to-value ratio	We assume that the initial loan-to-value ratios are uniformly distributed between 75% and 95%
Initial mortgage maturity	Based on the data from the 2007 American Housing Survey, 80% of mortgages are assumed to be 30-year fixed-rate and the remaining 20% are 15-year fixed-rate, all with standard amortization
Long-term risk-free rate	After February 1977, we use the yield on constant maturity 30-year Treasury bonds. For earlier periods, we use the annual long-term interest rate data collected by Robert Shiller and interpolate it to arrive at monthly series
Mortgage rates	For 30-year mortgages, we use the data available from Federal Home Loan Mortgage Corporation (Freddie Mac) for periods after April 1971. For earlier periods, we add 150 basis points (bps) to our Long-term risk-free rate and use the resulting time series. 150 bps is selected based on the average difference between these series in the post-1971 period. For 15-year mortgages, we use the data available from Freddie Mac since September 1991. For earlier periods, we subtract 46 bps from the 30-year mortgages to arrive at the 15-year series. 46 bps is the average difference between the two series in the post-1991 period
Home price volatility	Determines the volatility of individual home values around the mean given by the Home Price Index. The observed volatility of national home price indexes masks much of the idiosyncratic volatility of individual home prices. Fortunately, an estimate for the volatility of individual homes is produced in the process of estimating the repeated-sales index. Based on the data available from the FHFA, <sup>a</sup> we use 8% annual volatility in our study. Since this is central to all of our derivatives-related calculations, we also report results assuming for 6% and 10% annualized volatility
Rent yield	Determines the service flow, akin to dividend payouts from common stock, from home ownership. This parameter affects derivatives-related calculations. Motivated by Himmelberg, Mayer, and Sinai (2005), we use 4% annual yield in the base case, but also report results assuming values of 3% and 5% rent yield
Rates refinance threshold	Determines the minimum drop in mortgage rates needed to trigger a rates refinancing. We set this threshold to 2% in all simulations, but the simulation results are not very sensitive to this value
LTV refinance threshold	Determines the maximum level of LTV, beyond which homeowners cannot engage in cash-out refinancing. Given our assumption that the initial LTV is distributed between 75% and 95%, we set this parameter to 75%
Prepayment probability	Determines the propensity of individuals to pre-pay their mortgage. We use a value of 1 bps per month, but the simulation results are not very sensitive to this value

<sup>a</sup> See <http://www.fhfa.gov/Default.aspx?Page=87>. The relevant data are given in the sections "Purchase Only Indexes Volatility" and "All-Transactions Indexes Volatility."

refinance threshold" (RRT) from the existing mortgage rate. The new mortgage is assumed to have the same maturity as the existing mortgage, and the principal of the new mortgage is equal to the remaining value of the existing mortgage. Therefore, the homeowner will save in monthly payments due to the lower mortgage rate, but no equity is extracted.

- (A7) Homeowners' refinancing decisions are random and independent of each other, apart from the dependence explicitly parameterized in the refinancing rule.
- (A8) Once fully paid for, a home will not re-enter the housing market.
- (A9) We do not incorporate taxes or transaction costs explicitly into our simulations.

Given the central role that these assumptions play in our simulations and their interpretation, a few words about their motivation are in order.

Assumptions (A1) and (A2) determine the initial leverage and type of mortgages we assume for new homeowners. Here, we have assumed the initial LTV distribution did not

change throughout time and all mortgages were standard and fully amortizing. Of course, in the years leading up to the peak of the housing market in 2006, considerably more aggressive and exotic loans were made, including the now-infamous NINJA (no income, no job or assets) mortgages and many others with embedded options. Assumptions (A1) and (A2) are motivated by our desire for simplicity; we also wish to err on the side of caution with respect to default-related loss implications wherever possible.

Assuming that mortgages are non-recourse loans greatly simplifies our simulations because we do not need to model the dynamics of other sources of collateral. However, by assuming that lenders have no recourse to any other sources of collateral, our simulation may yield over-estimates of potential losses, and it may also over-simplify the behavior of borrowers (see Ghent and Kudlyak, 2009). To take on the more complex challenge of matching the mix of recourse and non-recourse loans in the mortgage system in our simulations, we would require information about the types of recourse that are permitted and the practicalities of enforcing deficiency judgments in each of the 50 states, as well as cross-



sectional and time-series properties of homeowner income levels, assets, and liabilities. While this task is beyond the scope of our current study, it is not insurmountable given sufficient time, resources, and access to financial data at the household level.

Assumption (A3) allows us to calibrate the price dynamics of our simulated housing stock. We introduce geographical heterogeneity in the mean home price appreciation rate,  $\beta_{rt}$ , but assume that the volatility of the idiosyncratic component is constant and use the estimated volatility as reported by the Federal Housing Finance Agency (FHFA) in our simulations (see Table 1 for more details). Once again, these assumptions are meant to err on the conservative side. For example, it is likely that home price volatility spiked in regions with sharp price declines, or after national price levels dropped; we ignore such spikes in our simulations.

The apparent inconsistency between our assumed dynamics (A3) and the smooth rise and fall in home price indexes deserves further discussion. First, note that our assumed dynamics are consistent with the standard weighted-repeat-sales index construction methodology (see, for example, Calhoun, 1996). While aggregate home price series certainly do not appear to be consistent with geometric Brownian motion—they are far too “smooth”—the common component  $\beta_{rt}$  does reflect the smoothness induced by aggregation. For our purposes, the volatility of the idiosyncratic term  $N_{it}$  is the key input into determining the value of the embedded put. As noted earlier, this volatility is calibrated according to FHFA volatility estimates.<sup>5</sup> Of course, the relative magnitude of the systematic and idiosyncratic volatility in home price returns has important implications for our results. The synchronization of homeowner leverage operates on homes that share a common factor, and the housing and mortgage markets are most susceptible to the ratchet effect when that common factor has experienced long periods of positive momentum. In a world where home prices contained little or no systematic risk, the ratchet effect would be weaker. However, such a world is both counterfactual and difficult to reconcile with common intuition regarding the influence of

local, regional, and macroeconomic factors that create common drivers in residential real estate.

Assumptions (A4)–(A6) are simple behavioral rules meant to encapsulate the economic deliberations of homeowners as they decide whether or not to refinance. Accordingly, implicit in these rules are many factors that we do not model explicitly, e.g., transactions costs, opportunity costs, homeowner characteristics such as income and risk preferences, macroeconomic conditions, and social norms. While it may be possible to derive similar rules from first principles (e.g., Stanton, 1995), the computational challenges may outweigh the benefits, especially from the perspective of producing estimates of potential losses for the aggregate housing sector.

Assumptions (A5) and (A6) outline the two polar opposites of our simulated refinancing activities—(A5) describes the situation where owners decide to increase their mortgage debt to extract equity from their homes while (A6) describes the situation where owners do not change the size of their mortgage debt but refinance to take advantage of declining interest rates. Clearly, a number of intermediate cases can be considered, but we focus only on these two extremes to delineate the boundaries that separate them.

Implicit in (A4)–(A6) is the assumption that the supply of credit to households is infinitely elastic at prevailing market rates, and it is motivated by our interest in measuring the impact of household refinancing behavior in and of itself. The complexities of consumer credit markets warrant a separate simulation study focusing on just those issues.

Assumption (A7) requires some clarification because the refinancing rules in (A5) and (A6) imply that refinancing decisions are not independent across households. Assumption (A7) simply states that there are no *other* sources of dependence (e.g., peer pressure and social norms arising from the refinancing activity of neighbors). The only channel through which refinancing decisions are correlated across households in our simulation is through interest rates and home prices via the behavioral rules in (A5) and (A6). Remarkably, this single source of commonality is sufficient to generate an enormous amount of synchronized losses when home prices decline. Finally, Assumption (A8) is motivated primarily by the desire for simplicity, and can easily be amended to allow fully paid houses to re-enter the real-estate market.

Ignoring issues such as relocation or renting vs. owning is not likely to affect our estimates of aggregate risk and losses. For example, consider the case of an individual who decides to rent after selling for \$200,000 a home that was recently purchased for \$100,000 with a down payment of \$15,000. Assuming a 0% interest rate for simplicity, this fortunate individual has taken \$115,000 of equity out of the housing market. However, the new buyer of this home will likely borrow all but 10–20% of the purchase price. For the purpose of measuring aggregate risk, this transaction is virtually identical to a cash-out refinancing by the original homeowner.

Assumption (A9) is a standard simplification but is not equivalent to the usual “perfect markets” assumption where taxes and transactions costs are assumed to be

<sup>5</sup> To the extent that  $\beta_{rt}$  induces a smooth time-varying expected return, this can be addressed by the mean-reverting diffusion processes in Lo and Wang (1995). The implications for option-pricing analysis are particularly straightforward (only the drift is affected by mean reversion, implying that the option-pricing formula is unchanged but the estimated volatility must be adjusted for serial correlation). In our analysis, we use the idiosyncratic volatility of each home as estimated by the FHFA and therefore no adjustment is required. Another extension is to consider price dynamics that reflect the U.S. real-estate “bubble.” However, developing a precise definition of a bubble is not a simple task. For example, while some studies concluded that real estate prices were too high in 2004–2006 (Shiller, 2006), other studies came to the opposite conclusion (McCarthy and Peach, 2004; Himmelberg, Mayer, and Sinai, 2005). Even ex post, estimating the appropriate “price correction” is not obvious, as Wheaton and Nechayev (2007) illustrate. This lack of consensus underscores the empirical challenges in identifying stable relations between prices and the most obvious fundamentals (in particular, see Gallin, 2004, 2006). But to the extent that a “bubble” refers, instead, to an impending tail event, this case can easily be accommodated by assuming a jump component in the stochastic process of the Home Price Index, and then using Merton’s (1976) jump-diffusion option-pricing model to price the embedded put.

zero. In fact, assuming away market frictions may seem particularly incongruous in the context of a simulation of refinancing activity, which some consider to be driven largely by transactions costs. Assumption (A9) does not assert that these frictions do not exist, but merely that we do not model their impact on behavior explicitly. Instead, our behavioral rules for the homeowner's refinancing decision implicitly incorporate these costs into our simulation in a "reduced-form" manner.

With these assumptions in place, we can now turn to the specific inputs of the simulation. Since our simulations depend on a relatively long list of input parameters and time series, a summary of all of them is provided in Table 1. Due to space limitations, we have relegated more detailed information to the Appendix. For three of our parameters—"Rates refinance threshold," "LTV refinance threshold," and "Prepayment probability" (see Table 1 for definitions)—we were unable to find appropriate data to calibrate their behavior over time. In lieu of formal calibration, we set these parameters to plausible values, and have conducted a series of sensitivity analyses that confirm the robustness of our findings to perturbations around these values.

### 3.2. Parameterization of the refinancing probability

The path each home follows is driven by factors such as the evolution of mean home prices, mortgage rates (MR), and the realization of idiosyncratic home price movement around the mean home price, as well as the owners' refinancing decisions as described in Assumptions (A5) and (A6). The main driver of our simulation results is  $REFI_{i,t}$  (see Assumption (A5)), which determines the probability that homeowner  $i$  may participate in a cash-out refinancing in month  $t$ . We assume that  $REFI_{i,t}$  has the following functional form:

$$REFI_{i,t} = (LTV_{i,t} < 75\%)[\text{Base refinancing rate} + (MR_t < MR_{i,0}) \times \text{Refinancing intensity}(t)]. \quad (2)$$

Our motivation for selecting this particular characterization requires some discussion. As noted earlier, our object in this paper is to construct a simple yet realistic simulation that matches the size and growth of the U.S. residential mortgage system and to use that to study the potential risk caused by the refinancing ratchet effect alone. This objective reduces the burden on us to have a rule in place that is plausible for the behavior of owners. The particular characterization proposed here is simple, yet it has a number of intuitively plausible properties. First, its assumed form ensures that owners do not participate in a cash-out refinancing unless they have at least 25% equity in their home. Given the assumed distribution for the initial LTV, this constraint ensures that individuals participate in cash-out refinancing only after they have had time to build some equity above their initial equity level. For those owners who satisfy this LTV constraint, the refinancing intensity has two parts. One part, given by the "Base refinancing rate," is constant through time and independent of the rate on the outstanding mortgage relative to the prevailing market rate. The second component, given by "Refinancing

intensity( $t$ )," is active when the rate on the current mortgage,  $MR_{i,0}$ , is above the prevailing rate of  $MR_t$ . This second component can be a function of time. In fact, in some of our simulations we assume that refinancing intensity increases through time perhaps due to technological change, consumer familiarity, or other such factors. Ultimately, the ability of this model to capture the main drivers of refinancing trends will be judged by the success in reproducing the calibration time series. We turn to this issue in the next section.

### 3.3. Calibration exercise

Our goal is to calibrate the parameters of our simulation to closely resemble critical aspects of the U.S. residential mortgage system as captured by the following two historical time series:

1. Outstanding mortgage volume. We use the value of residential mortgage liabilities as reported in the Federal Reserve *Flow of Funds Accounts*. These data are available at a quarterly frequency from 1951Q4 to 2008Q4, and annually from 1945 to 1951.
2. Equity Extractions. We use the series produced by Greenspan and Kennedy (2005), which is available at a quarterly frequency from 1968Q1 to 2008Q4.

The calibration of our simulation consists of specifying a base refinancing rate and a refinancing intensity function that can reproduce the above two series as closely as possible. Since the time series used in these calibrations are non-stationary, traditional measures such as correlation and  $R^2$  may be misleading indicators of goodness-of-fit. A simpler alternative is to compute the mean of the quarterly absolute deviations between the simulated and actual series as a percentage of the actual quarterly values:

$$\text{Mean absolute deviation} \equiv \frac{1}{T} \sum_{k=1}^T \frac{|\text{Simulated}_t - \text{Actual}_t|}{\text{Actual}_t}. \quad (3)$$

We begin with a base refinancing rate of 0.1% per month and assume that the refinancing intensity is constant over the entire sample period. By varying the level of the refinancing intensity function, we try to achieve a low level for the Mean Absolute Deviation (MAD) for both our calibration series. Table 2 contains the MAD results of this calibration exercise for three time periods: 1980–2008, 1990–2008, and 2000–2008. The results suggest that a refinancing intensity level of 4.00% achieves the lowest level of MAD across both calibration reference series during the 2000–2008 period, which is the most relevant period for our purposes.

Fig. 1 depicts the entire time series produced by our simulations for the combination of input parameters selected. While our simulations capture the massive growth in the amount of mortgages outstanding and cumulative equity extractions after 2000 very well, they fall behind the calibration series between the mid-1980s and the late 1990s. However, since our main focus in this paper is to evaluate risk in the mortgage system in the

**Table 2**

Summary of Mean Absolute Deviations (MAD), defined in (3), between the results produced by our simulation approach and the calibration reference series for Total mortgages outstanding and cumulative equity extractions in the U.S. housing market.

Cash-out refinancing takes place according to the probabilistic rule given in (2) where the Base refinancing rate is 0.1% per month and the refinancing intensity is constant and given by the first element of each row. The time series of Total mortgages outstanding is compared with the Total mortgage liability series from *Flow of Funds Accounts*; the time series of Cumulative equity extractions is compared with the series produced by Greenspan and Kennedy (2005). The MAD is reported for three different time periods to prove additional details about the success of the calibration procedure.

Uniform	MAD of mortgages outstanding (%)			MAD of cumulative equity extractions (%)		
	80–08	90–08	00–08	80–08	90–08	00–08
2.00%	24.39	23.78	21.82	33.57	32.31	26.82
2.25%	22.78	21.50	18.84	31.00	28.99	22.64
2.50%	21.07	19.15	15.88	28.26	25.49	18.42
2.75%	19.78	17.26	13.39	26.16	22.72	14.96
3.00%	18.46	15.44	11.06	24.07	20.07	11.69
3.25%	17.54	14.09	9.33	22.71	18.23	9.47
3.50%	16.46	12.58	7.42	21.37	16.48	7.75
3.75%	15.72	11.55	6.20	20.52	15.48	7.13
4.00%	15.12	10.72	5.51	19.89	14.76	7.22
4.25%	14.58	10.07	5.25	19.28	14.25	7.90
4.50%	14.32	9.74	5.32	19.13	14.15	8.76

years leading up to the Financial Crisis of 2007–2009, the lack of fit in earlier periods is not as problematic.

The refinancing intensity levels of 4.00% per month may seem excessively high, but note this level is only relevant for homes that meet both the LTV and the mortgage rate conditions in (2). To develop further intuition for this aspect of our simulation, we computed the fraction of homes in our simulation that meet both conditions in (2). Fig. 2(a) shows the time series of the percentage of homes that meet the LTV condition of (2) and Fig. 2(b) provides the corresponding time series for the percentage of homes that meet the Mortgage rate condition. Fig. 2(c) contains the time series for the percentage of homes that meet both conditions; such homes are candidates for potential cash-out refinancing. It can be seen that there are only a few periods—for example, the early and late 1990s and the period between 2001 and 2005—during which a large fraction of homes meets both constraints and for which the assumed 4.00% refinancing intensity represents the actual likelihood of cash-out refinancing.

Based on the goodness-of-fit metrics reported in Table 2 and the full time series shown in Fig. 1, we believe that our simulation under refinancing rule (2)—where the refinancing intensity is constant through time at the level of 4.00%—is properly calibrated to assess the impact of refinancing on the systemic risk of the U.S. residential mortgage market. We adopt this specification in our analysis of such risks in Section 4. While this rule implies a uniform probability of cash-out refinancing, we have studied two alternative rules in which the refinancing intensity curve is either linearly increasing in time or where the refinancing intensity undergoes a discrete break in 1988 (as motivated by Bennett,

Peach, and Peristiani, 2001). The results based on these refinancing rules are provided in the Appendix.

#### 4. Options-based risk analysis

Armed with a properly calibrated simulation of the U.S. residential mortgage market, we now turn to assessing the systemic risk posed by the refinancing ratchet effect. Given our assumption that all mortgages in our simulations are non-recourse loans—collateralized only by the value of the underlying real estate—the homeowner has a guarantee or put option that allows him to put or “sell” the home to the lender at the remaining value of the loan if the value of the home declines below the outstanding mortgage. Such guarantees can be evaluated using derivatives-pricing theory as described in Merton (1977) and Merton and Bodie (1992), and can be applied to quantify macro-level risks as described in Gray, Merton, and Bodie (2006, 2007a,b, 2008) and Gray and Malone (2008).

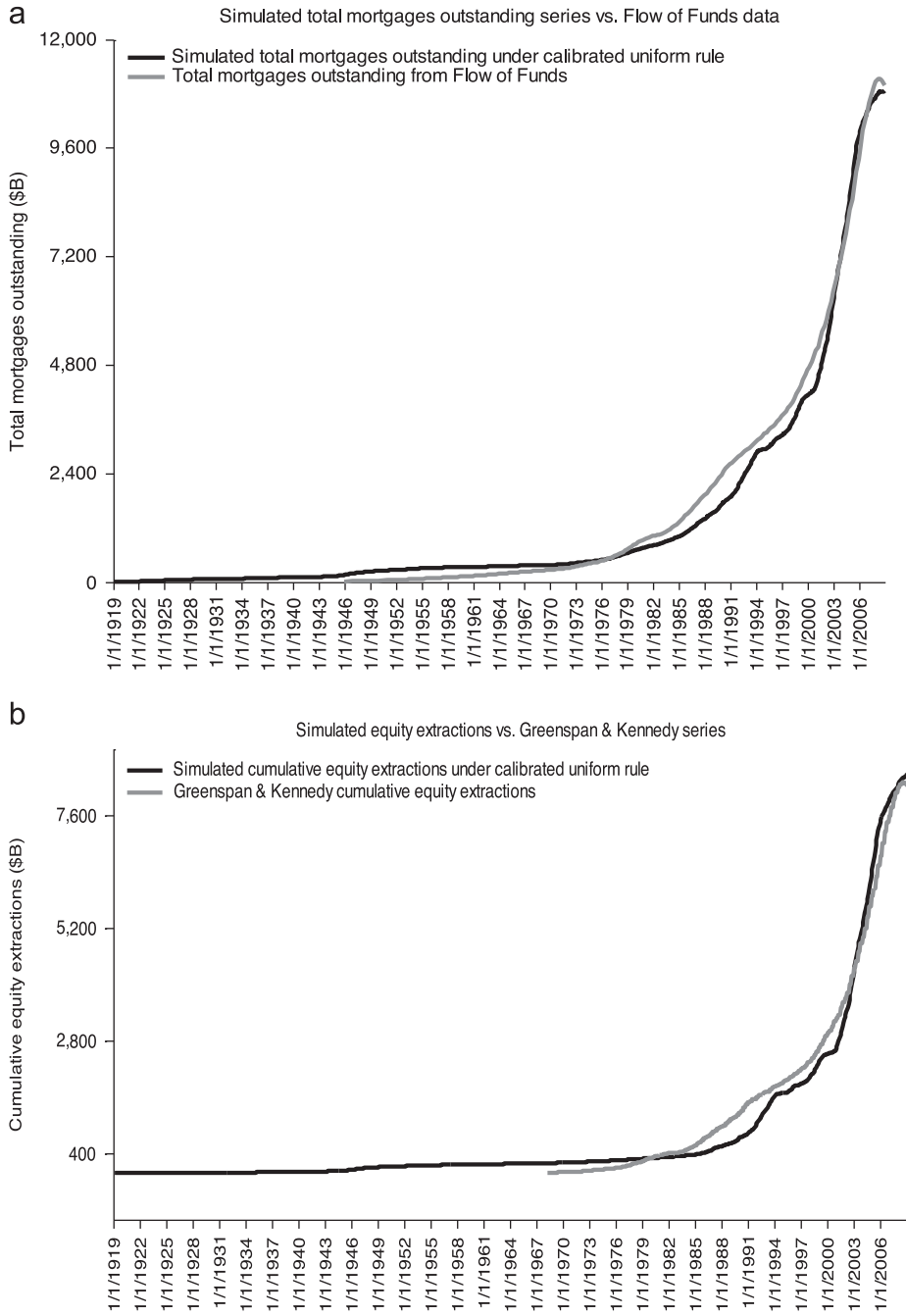
As mortgages are placed in various structured products like collateralized mortgage obligations and then sold and re-sold to banks, asset-management firms, or GSEs (see Fig. 3), the ultimate entities exposed to these guarantees may be masked. However, it is clear that all mortgage lenders must, in the aggregate, be holding the guarantees provided to all homeowners. Therefore, we can circumvent the complexities of these intermediate transactions—those in the dotted box of Fig. 3—and use the aggregate value of the guarantees and their various risk metrics to evaluate the overall risk in the mortgage system. As discussed earlier, to the extent that some owners may be liable for the deficiency in their collateral value through recourse, those owners share some of the burden of the loss caused by a decline in home prices. Therefore, the economic loss and various risk metrics estimated in this section should be viewed as the amount of economic loss or the risk exposure for the lenders and the subset of borrowers that are legally responsible via recourse mortgages.

##### 4.1. The aggregate value of mortgage put options

We measure the value of the guarantee embedded in each non-recourse mortgage as the value of a put option written on the underlying real estate. Since Merton's (1977) analysis of deposit insurance, the use of derivatives-pricing models to value guarantees has become standard. Such an approach is forward-looking by construction, providing a consistent framework for estimating potential losses based on current market conditions—in particular, the price and volatility of the guaranteed asset—rather than historical experience. Of course, derivatives-pricing models do require additional assumptions, e.g., complete markets and a specific stochastic process (one that is consistent with completeness such as geometric Brownian motion). We adopt a discrete-time version of these assumptions in (A10)

(A10) Housing-price dynamics can be approximated by a discrete-time geometric random walk represented by a recombining binomial tree, and markets

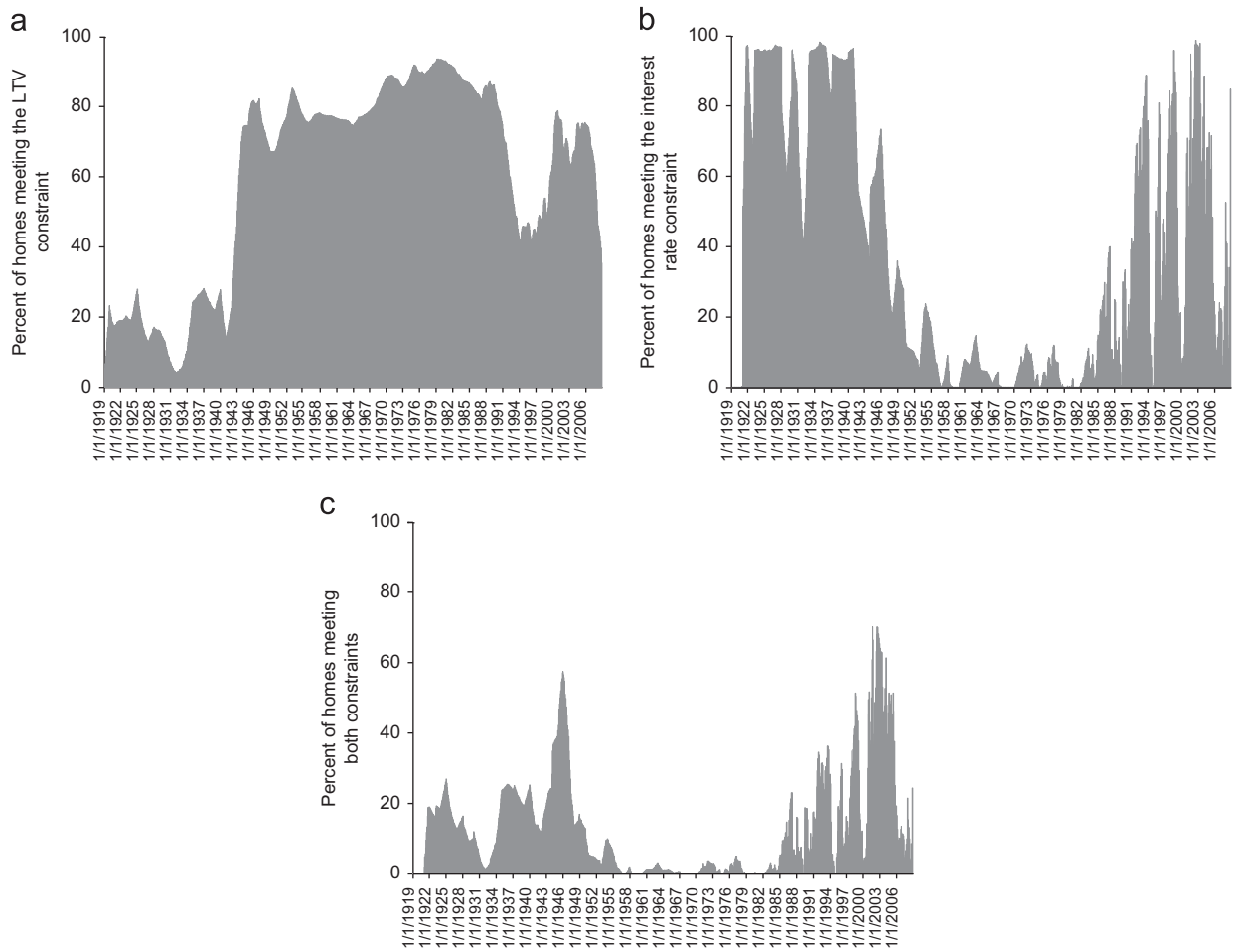




**Fig. 1.** A comparison of Total mortgages outstanding and Cumulative equity extractions produced by our simulation and Total mortgage liability series from *Flow of Funds Accounts* data and the Cumulative equity extractions series of [Greenspan and Kennedy \(2005\)](#). Cash-out refinancing takes place according to the probabilistic rule given in (2), where the Base refinancing rate is 0.1% per month and the refinancing intensity is 4.00%. The data refer to the U.S. residential housing market. (a) Total mortgages outstanding and (b) cumulative equity extractions.

are dynamically complete so options on property values can be priced by no-arbitrage arguments alone.

Under (A10), we model the guarantee in non-recourse mortgages as a “Bermuda” put option—an option that can be exercised at certain dates in the future, but only on



**Fig. 2.** Simulated time series of the percentage of homes meeting the (a) LTV condition in (2); (b) the MR condition in (2); (c) both conditions. The results are based on the optimized parameters (see Table 2) with the base refinancing rate set to 0.1% per month and the refinancing intensity equal to 4.00% per month.

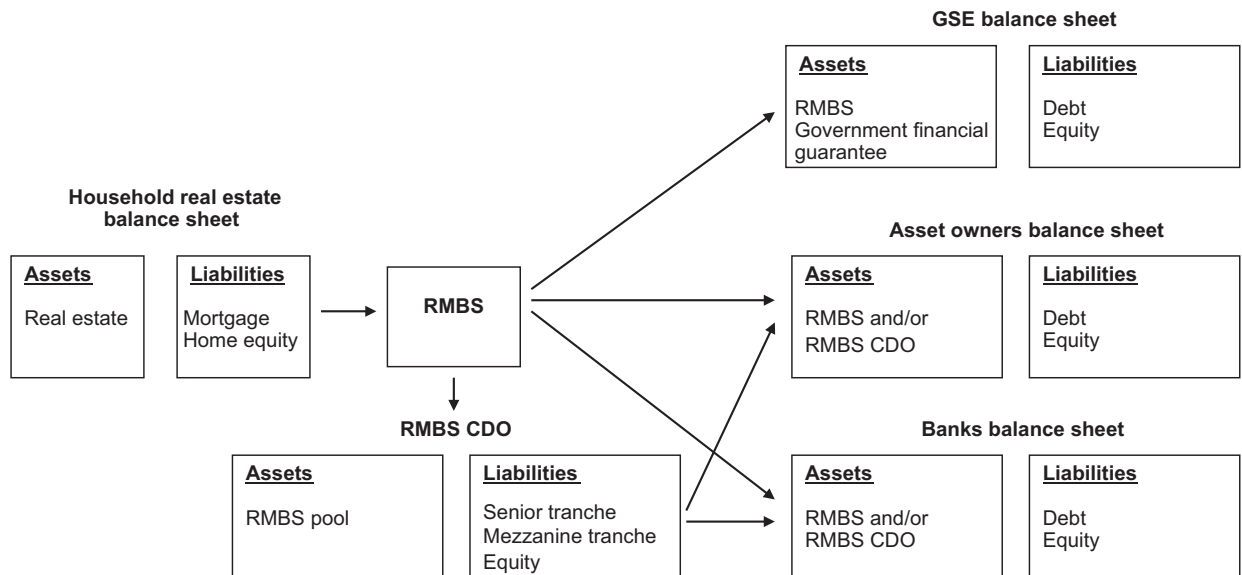
those fixed dates—and we set these exercise dates to be once a month, just prior to each mortgage payment date.<sup>6</sup> The exercise price is the amount of the outstanding loan, which declines over time due to the monthly mortgage payments. Before we can implement this option-pricing model, we must determine the volatility of the underlying asset on which the option is written, as well as any “dividend yield” that may affect the value of that asset. We set these two parameters to the values reported in Table 1. In each run of our simulation, we calculate the value of the put option and various risk metrics related to the embedded option in each mortgage. We then aggregate these results to construct a bottom-up estimate of the overall value of the put options and corresponding risk exposures in the system.

<sup>6</sup> We use the Cox-Ross-Rubinstein (see Cox and Rubinstein, 1985) binomial tree algorithm to price these options, and implement it in Matlab (Version 7.2) using the Financial Derivatives Toolbox (Version 4.0) and the functions: `crrtimespec`, `crrsens`, `crrtree`, `instopt-stock`, `intenvset`, and `stockspec`. See <http://www.mathworks.com> for documentation and additional details.

Fig. 4 shows the simulated time series for the aggregate value of put options for the cases of no-cash-out vs. cash-out refinancing using our calibrated uniform refinancing rule, and Table 3 contains the numerical values for each quarter between 2005Q1 and 2008Q4. During normal times, homeowners’ equity absorbs the first losses from a decline in residential real-estate prices (see Fig. 3).

However, the process of equity extraction causes the size of this buffer to decrease, resulting in a larger portion of the losses transferred to the equity-holders and debt-holders of various mortgage-lending entities (through the complex risk redistribution methods shown in the dotted section of Fig. 3). Our simulations show that with the downturn in residential real estate in 2007 and 2008, the value of the guarantees extended to homeowners by mortgage lenders increased substantially.<sup>7</sup> In particular,

<sup>7</sup> Note that negative correlation between volatility and prices has been documented in several asset classes (see, for example, Bekaert and Wu, 2000 for the equities case). To the extent that this negative correlation holds in real-estate markets as well, our volatility parameter—which is an approximate long-term average—is likely to



**Fig. 3.** Residential mortgage-backed security (RMBS), interlinked balance sheet of entities backed by the underlying real estate, based on Gray, Merton, and Bodie (2008). Intermediate risk redistributions—through, for example, RMBS and collateralized debt obligations (CDOs)—will be ignored in our simulations.

by the end of 2008Q4, the total put value of the guarantee embedded in mortgages was \$1.7 trillion under the cash-out refinancing simulation, as compared to \$330 billion under the no-cash-out refinancing simulation.

#### 4.2. U.S. mortgage system delta, gamma, and vega

The overall level of risk in the mortgage system can be calculated based on the sensitivities of the value of mortgages' embedded put options to changes in the level or volatility of home prices. While the exact value of these risk metrics depends on the particular model used for option pricing, the nature of risk in the mortgage system transcends the specifics of the models. For example, regardless of the exact model, the value of the guarantees increases as the value of the collateral declines. Using the language of option pricing, the delta of the mortgage guarantees is positive. Furthermore, the rate of the increase is itself increasing, or in the option language, the gamma is positive.

Fig. 5 and Table 3 report these metrics for the simulation based on the uniform refinancing rule (we provide these metrics for alternative refinancing rules in the Appendix). As reported in Table 3, in the first quarter of 2005, we estimate that the aggregate value of all embedded put options would increase by \$18.17 billion for each 1% drop in home prices. By the last quarter of 2008, this sensitivity almost doubled to \$38.13 billion for each 1% drop in home values. This large increase is due to the large gamma of these embedded options, as reported in Table 3. For the same simulation, the estimated gamma was \$573.79 million per 1% drop in home values in the first quarter of 2005,

which increased to \$801.13 million for each 1% drop in home values by the last quarter of 2008. The size and increase in the gammas of these options indicate substantial nonlinearity in the risk of the mortgage system that may need to be accounted for in systemic risk measurement and analysis. Table 3 contains delta and gamma estimates for simulations without cash-out refinancing as well.

Another aspect of risk in the mortgage system can be measured by estimating the sensitivity of the value of embedded options to an increase in home price volatility, also known as the option's "vega." Based on our calculations, we estimate that the total value of the embedded put options in non-recourse mortgages would increase by approximately \$70–\$80 billion for each 1% increase in home price volatility in the years leading up to the crisis. While Fig. 5 shows a large increase in vega over time, during the recent crisis this measure of risk first increased and then declined. Portfolios of options can exhibit such counterintuitive behavior because of the nonlinearity of these metrics. For example, in the Black-Scholes model, the vega of options way in or out of the money is low, but is quite high for options near the money. These nonlinearities can give rise to the effects shown here for the U.S. mortgage system.

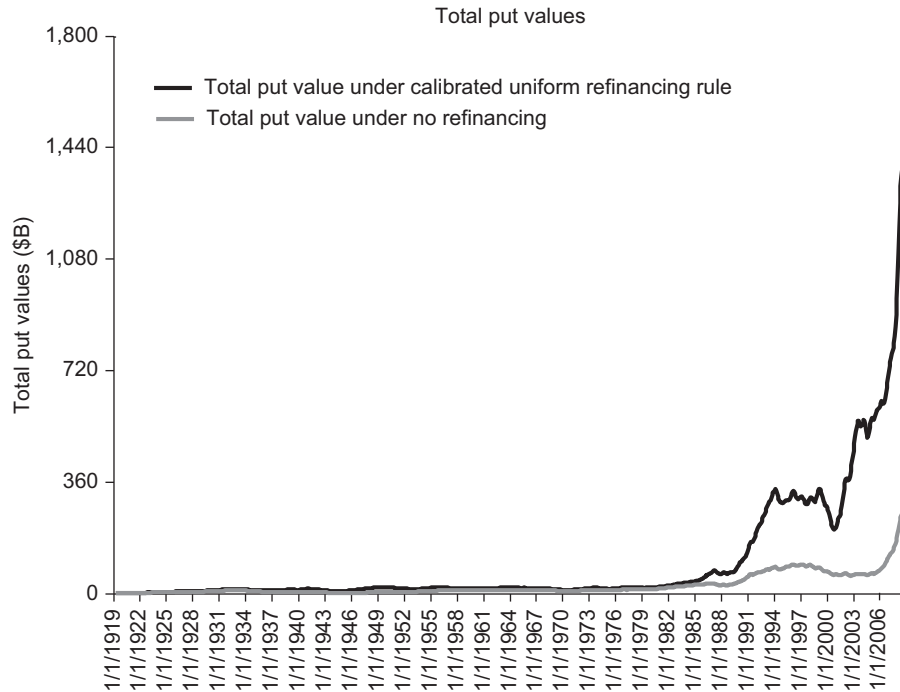
#### 4.3. Sensitivity to model parameters and the refinancing rule

The accuracy of the simulation results of Sections 4.1 and 4.2 depends, of course, on the values of the various parameters of our simulations, as well as the assumed form of the behavioral refinancing intensity function. We have conducted a series of sensitivity analyses that we will summarize in this section.

We first consider the estimates for the aggregate value of the put options in non-recourse mortgage loans under the two alternative refinancing rules. As reported in Table 4, the results are remarkably stable across different

(footnote continued)

underestimate the realized volatility during a market downturn, which, in turn, will underestimate aggregate losses.



**Fig. 4.** Simulated time series of the aggregate value of total guarantees extended to U.S. homeowners by mortgage lenders for cash-out and no-cash-out refinancing scenarios. For the cash-out refinancing case, refinancing takes place according to probabilistic rule (2) in which the base refinancing rate is 0.1% per month and the Refinancing intensity is constant over time and equal to 4.00%.

**Table 3**

Simulated time series of the aggregate value and sensitivities of total guarantees extended to homeowners by mortgage lenders for cash-out and no-cash-out refinancing scenarios for each quarter from 2005Q1 to 2008Q4 (put values are in \$billions, deltas are in \$billions per 1% decline in home prices, gammas are in \$millions per 1% decline in home prices, and vegas are in \$billions per 1% increase in home price volatility). For the cash-out refinancing case, refinancing takes place according to probabilistic rule (2) in which the base refinancing rate is 0.1% per month and the refinancing intensity is constant over time and equal to 4.00%.

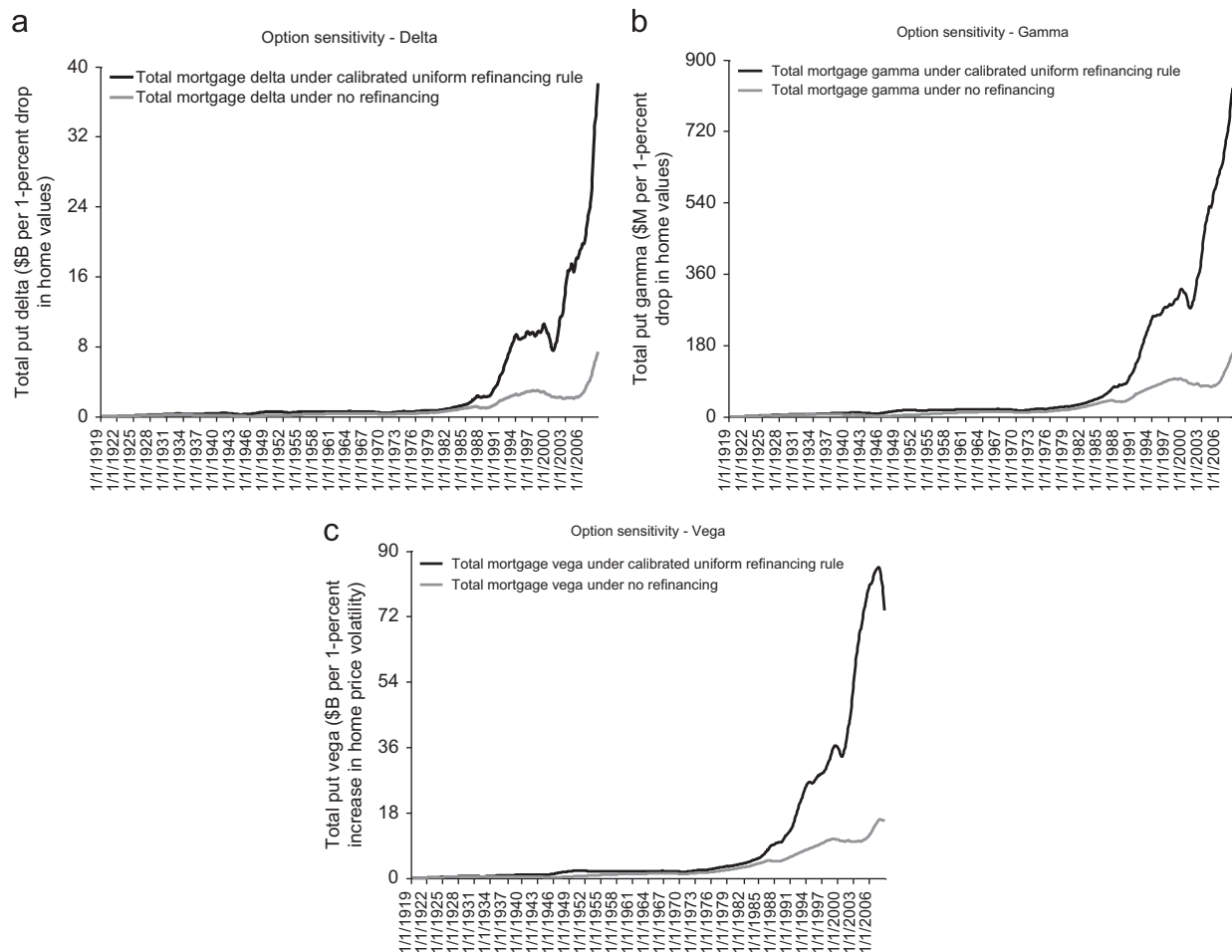
Date	No cash-out				Cash-out			
	Put value	Delta	Gamma	Vega	Put value	Delta	Gamma	Vega
Mar-05	64.90	2.24	79.32	10.67	566.60	18.17	573.79	74.64
Jun-05	65.70	2.27	80.11	10.84	568.80	18.30	580.83	76.22
Sep-05	69.20	2.37	82.70	11.18	592.30	18.93	598.38	78.24
Dec-05	74.20	2.51	86.67	11.62	601.30	19.26	610.92	79.73
Mar-06	81.50	2.70	91.48	12.09	621.10	19.79	624.81	80.87
Jun-06	87.10	2.87	96.71	12.55	611.70	19.72	630.83	80.94
Sep-06	100.90	3.23	105.41	13.36	644.90	20.52	647.87	81.94
Dec-06	114.90	3.57	113.41	14.06	698.70	21.77	673.15	83.48
Mar-07	126.80	3.86	120.11	14.55	748.40	22.90	695.70	84.39
Jun-07	137.30	4.14	127.12	15.08	782.80	23.74	715.13	85.05
Sep-07	153.30	4.52	135.97	15.72	831.20	24.81	735.34	85.44
Dec-07	178.90	5.05	145.70	16.14	951.00	27.14	770.51	85.57
Mar-08	221.80	5.82	155.67	16.21	1185.10	31.18	812.91	84.18
Jun-08	252.40	6.35	161.10	16.12	1345.20	33.70	829.32	81.74
Sep-08	278.40	6.76	164.30	16.10	1465.40	35.24	823.54	78.97
Dec-08	330.20	7.42	164.96	15.62	1727.20	38.13	801.13	73.75

refinancing rules. This stability is likely due to the fact that each of these rules is calibrated to match the overall size and growth in the U.S. residential mortgage system by matching our two reference series (see the Appendix).

To gauge the sensitivity of our simulations to the rent yield and home price volatility assumptions, we

performed additional simulations for rent yields of 3% and 5%, and home price volatilities of 6% and 10%. To conserve space, we have reported only the resulting estimates for the total put value under these parameter values in Table 5. These results show that in the fourth quarter





**Fig. 5.** Simulated time series of the sensitivities of the aggregate value of total guarantees extended to homeowners by mortgage lenders for cash-out and no-cash-out refinancing scenarios. Panel (a) plots the sensitivity to a 1% drop in home prices, Panel (b) plots the rate of change of (a) with respect to home prices, and Panel (c) plots the sensitivity to a 1% increase in home price volatility. For the cash-out refinancing case, refinancing takes place according to probabilistic rule (2) in which the base refinancing rate is 0.1% per month and the refinancing intensity is constant over time and equal to 4.00%.

**Table 4**

Simulated time series of the aggregate value and sensitivities of total guarantees extended to homeowners by mortgage lenders for cash-out and no-cash-out refinancing scenarios for each quarter from 2005Q1 to 2008Q4 (put values are in \$billions, deltas are in \$billions per 1% decline in home prices, gammas are in \$millions per 1% decline in home prices, and vegas are in \$billions per 1% increase in home price volatility) for three refinancing rules: Uniform (4.00%), Linear (4.50%), Uniform with break (3.75% before 1988; 4.25% from 1988 onward). See Table 2, Tables A.4 and A.5 of the Appendix for details on how these rules are calibrated.

Date	Uniform (base case)				Linear				Uniform with break			
	Put value	Delta	Gamma	Vega	Put value	Delta	Gamma	Vega	Put value	Delta	Gamma	Vega
Mar-05	566.60	18.18	573.79	74.64	578.10	18.45	578.63	75.21	588.30	18.82	591.95	76.94
Jun-05	568.60	18.30	580.83	76.22	578.80	18.56	586.04	76.82	586.20	18.85	597.22	78.33
Sep-05	592.30	18.93	598.38	78.24	603.10	19.21	603.99	78.94	610.90	19.49	614.44	80.39
Dec-05	601.30	19.26	610.92	79.73	612.10	19.55	617.21	80.52	617.80	19.78	626.14	81.79
Mar-06	621.10	19.79	624.81	80.87	631.20	20.06	631.21	81.64	636.60	20.27	638.94	82.84
Jun-06	611.70	19.72	630.83	80.94	621.40	19.99	637.12	81.71	626.90	20.20	644.63	82.86
Sep-06	644.90	20.53	647.87	81.94	654.60	20.80	654.33	82.82	659.10	20.99	661.77	83.87
Dec-06	698.70	21.78	673.15	83.49	707.90	22.04	678.76	84.26	712.20	22.21	685.50	85.24
Mar-07	748.40	22.90	695.70	84.39	756.70	23.13	699.87	85.01	761.40	23.31	707.30	86.05
Jun-07	782.80	23.75	715.13	85.05	789.30	23.92	717.79	85.53	793.60	24.11	726.16	86.62
Sep-07	831.20	24.81	735.34	85.44	837.90	24.99	737.92	85.86	842.60	25.19	745.96	86.96
Dec-07	951.00	27.15	770.51	85.57	955.80	27.24	770.24	85.76	961.80	27.50	780.43	86.96
Mar-08	1185.10	31.19	812.91	84.18	1190.90	31.27	812.12	84.27	1196.60	31.54	822.13	85.48
Jun-08	1345.20	33.71	829.32	81.74	1352.70	33.79	827.43	81.77	1358.50	34.08	838.22	82.97
Sep-08	1465.40	35.24	823.54	78.97	1472.30	35.30	821.47	78.97	1478.70	35.61	832.92	80.09
Dec-08	1727.20	38.14	801.13	73.75	1733.70	38.16	797.50	73.65	1742.90	38.54	811.56	74.71

**Table 5**

Simulated total value of guarantees extended to homeowners by mortgage lenders (in \$billions) for various values of home price volatility (Vol) and rent yield (RY) under the Uniform (4%) refinancing rule from 2005Q1 to 2008Q4.

Date	Vol=6%			Vol=8%			Vol=10%		
	RY=3%	RY=4%	RY=5%	RY=3%	RY=4%	RY=5%	RY=3%	RY=4%	RY=5%
Mar-05	225.00	430.60	729.30	346.70	566.60	859.50	489.30	719.60	1007.40
Jun-05	223.60	430.40	732.30	346.40	568.60	866.20	491.10	725.10	1018.70
Sep-05	236.10	450.90	762.10	362.50	592.30	899.00	511.50	753.10	1056.00
Dec-05	239.90	457.30	772.70	368.30	601.30	912.50	519.90	765.20	1073.00
Mar-06	252.70	475.30	795.90	383.40	621.10	937.50	537.60	787.40	1100.10
Jun-06	248.20	465.90	781.20	378.00	611.70	923.90	531.70	778.20	1087.80
Sep-06	270.80	497.30	820.60	403.90	644.90	963.90	560.70	813.40	1128.80
Dec-06	307.20	548.30	885.30	445.60	698.70	1029.30	607.40	870.30	1195.50
Mar-07	343.20	596.40	943.60	485.60	748.40	1087.30	651.10	921.80	1253.80
Jun-07	369.00	629.70	982.90	514.20	782.80	1126.50	682.30	957.60	1293.40
Sep-07	407.20	677.40	1038.00	555.10	831.20	1180.80	725.60	1006.70	1347.10
Dec-07	504.90	797.50	1175.40	657.20	951.00	1314.80	831.80	1126.80	1478.50
Mar-08	706.50	1035.40	1440.00	862.20	1185.10	1571.40	1040.40	1358.40	1728.00
Jun-08	858.70	1200.90	1612.60	1012.00	1345.20	1737.30	1188.30	1513.70	1887.60
Sep-08	981.20	1326.80	1737.70	1129.90	1465.40	1856.80	1301.80	1628.50	2001.40
Dec-08	1241.20	1599.20	2014.40	1381.60	1727.20	2122.60	1545.80	1880.00	2256.00

of 2008, the simulated loss estimates range from a low of \$1241 billion (3% rent yield, 6% volatility) to a high of \$2256 billion (5% rent yield, 10% volatility). As volatility increases, or as the rent yield increases, *ceteris paribus*, the embedded guarantee becomes more valuable. While rent yields may be relatively stable over time, it can be argued that home price volatility is more variable. In particular, as the national home price index reached its peak in June 2006 and began to decline, home price volatility is likely to have increased significantly beyond historical levels, which implies that our estimates for the aggregate put value may underestimate actual losses. Tables A.6–A.8 in the Appendix provide similar sensitivity analyses for the estimated delta, gamma, and vega measures for the aggregate put. We have conducted a number of other sensitivity analyses but due to space limitations, the results are provided in the Appendix. Overall, we have found the magnitudes of the results to be remarkably robust to variations in assumptions and parameters. As noted earlier, this stability is likely due to the fact that each of these rules is calibrated to match the overall size and growth of the U.S. residential mortgage system as captured by our two reference series.

## 5. Discussion

In this section, we present a number of qualifications, extensions, and implications of our simulation of the U.S. residential housing market. In Section 5.1, we contrast the heuristic nature of our simulations to traditional general-equilibrium analysis. We acknowledge in Section 5.2 that we have not modeled the behavior of lenders in our simulations. We distinguish between market risk and systemic risk in Section 5.3. In Section 5.4 we observe that the welfare implications of the recent financial crisis, and the events leading up to it, are not yet fully understood.

### 5.1. Heuristic vs. general-equilibrium analysis

Our simulations are based on a number of simplifying assumptions. While we have attempted to err on the side of lower implied losses whenever possible, some assumptions may have the opposite effect, e.g., assuming that all mortgages are non-recourse loans. Incorporating more realistic features of the housing market such as adjustable-rate and negative-amortization mortgages with teaser rates, NINJA loans, and regional differences in the U.S. residential real-estate market, bankruptcy laws, and homeowner asset and income dynamics, may increase the accuracy of the simulation.

However, our analysis is not designed to capture feedback effects among all endogenous variables such as home prices, interest rates, household income, and borrowing and lending behavior. Therefore, standard comparative-statics questions, such as “How much would home prices have risen if the Fed had not cut interest rates from 2000 to 2003?”, are not addressed in our simulations. Instead, our narrower reduced-form focus has been to gauge the magnitude of the refinancing ratchet effect on mortgage lenders. A more formal general-equilibrium analysis of these markets would begin with optimizing households from which the demand for housing and mortgages are derived, aggregated, and equilibrated with optimizing home builders and mortgage lenders that supply the homes and mortgages, respectively, to households. While computable general-equilibrium models have become considerably more sophisticated in recent years (see, for example, Dixon and Rimmer, 2002), the dynamic and stochastic nature of the demand and supply decisions are sufficiently complex—even for a single agent—that constructing a true stochastic dynamic general-equilibrium model of the entire U.S. housing market seems computationally impractical. Nevertheless, some useful insights may be gleaned from considering special cases of such optimizing behavior and equilibrium, e.g., Pliska (2006), Fortin,

Michelson, Smith, and Weaver (2007), and Agarwal, Driscoll, and Laibson (2008), which may be worth pursuing further.

### 5.2. Lending behavior

Any analysis of the Financial Crisis of 2007–2009 would not be complete without some discussion of the behavior of mortgage lenders and associated businesses. Our simulations assume that all household demand for mortgages and refinancing is satisfied at prevailing historical rates, i.e., the supply of funds to borrowers is infinitely elastic at all times. While this may have been a reasonable approximation to reality during the decade prior to the peak of the housing market in 2006, our motivation for this simplifying assumption is to gauge the impact of the refinancing ratchet effect in isolation. However, supply shocks certainly must have had an impact on systemic risk in recent years as well. Therefore, an important open question is how lenders behaved during the course of our simulations, and what economic or behavioral forces led them to engage in such behavior.

A tractable and empirically plausible model of lending behavior is beyond the scope of our current simulation, and it deserves a separate set of simulation studies in its own right (one possible starting point is Thurner, Farmer, and Geanakoplos, 2009). However, it is not difficult to speculate about the factors those simulations might include. In addition to modeling the behavior of banks, which are the traditional sources of home loans, such a simulation must also account for a host of financial innovations that have emerged only recently, including securitized debt (e.g., CDOs and CDO-squareds), credit default swaps and related insurance products, Internet-based marketing of consumer-finance products, the growth of the “shadow banking industry” and illiquidity, and the globalization of financial markets. Rajan (2006), Gorton (2008, 2009), Brunnermeier (2009), and Gorton and Metrick (2012) provide overviews of some of these developments. In addition, these simulations must incorporate the impact of rating agencies, GSEs, and broader government policies in promoting cheap financing for would-be homeowners, as well as the increasing competition for yield among asset-managers and asset-owners. Collectively, these developments contributed to the enormous supply of funds available to homeowners during the past decade, but further analysis is needed before we can determine the relative importance of each.

The challenge in constructing a simulation with all of these features is the fact that there is precious little history on which to calibrate many of the parameters. In contrast to typical simulations that assume a statistically stationary environment, simulating the supply of funds for residential real-estate purchases involves the historically unique financial innovations described above. This simulation may provide a clue as to the magnitude of the current crisis, as well as its apparent uniqueness in recent history. The mechanism discussed in this paper is surely relevant when comparing the impact of housing-price crashes across countries. As discussed in Hubbard and Mayer (2009), many countries experienced similar housing-price growth driven by

comparable trends in real interest rates. In a country where cash-out refinancing is easier or more common—perhaps because of familiarity or other social characteristics—a larger portion of the increase in homeowner’s equity is extracted by the owner. This would, in turn, cause more synchronization in homeowners’ leverage and more severe losses for lenders in the wake of home-price declines.

More importantly, the main thrust of our analysis is that the refinancing ratchet effect is a wholly separate mechanism that operates irrespective of the supply of credit, and one that must be considered a potential source of systemic risk in its own right.

### 5.3. Market risk vs. systemic risk

While the \$1.7 trillion figure seems imposing, large financial losses do not necessarily imply significant systemic risk. For example, on April 14, 2000, the Center for Research in Security Prices (CRSP) value-weighted stock market index (excluding dividends) declined by 6.63%, implying an aggregate one-day loss of approximately \$1.04 trillion to corporate America. While certainly unfortunate, this event was not particularly memorable, nor was it a cause for national alarm or emergency government intervention. Market risk is distinct from systemic risk; the latter arises when large financial losses affect important economic entities that are unprepared for and unable to withstand such losses, causing a cascade of failures and widespread loss of confidence. This element of surprise lies at the heart of the recent financial crisis. The fact that the three conditions that cause the refinancing ratchet effect—rising home prices, falling interest rates, and easy access to refinancing opportunities—are individually innocuous and are often viewed as signs of economic growth and prosperity creates the element of surprise. Therefore, not only is the magnitude of losses caused by the refinancing ratchet effect large, but these losses are also more likely to be unexpected, resulting in systemic risk to the financial system.

### 5.4. Welfare implications

Although much has already been written about the Financial Crisis of 2007–2009, its welfare implications for homeowners, lenders, and intermediaries are not yet fully understood. While many homeowners have been adversely affected by rising interest rates, foreclosures, and falling property values, there are other satisfied and solvent homeowners who are homeowners only because of the business practices, government policies, and economic circumstances that contributed to the refinancing ratchet effect. Eliminating or otherwise restricting these business practices and policies may benefit some groups, but it will no doubt disadvantage others. Moreover, as discussed above, we have not attempted to model the supply side of the refinancing industry, which no doubt contributed to the growth of home prices, leverage ratios, and systemic risk. Many have criticized the role of securitization, insurance, and financial innovation in creating the crisis, but during the decade leading up to the peak of the housing market in 2006, these developments were responsible for the low-interest-rate

and easy-credit environment that was so conducive to global economic growth and the “ownership society.” Any policy recommendations with respect to the Financial Crisis of 2007–2009 must balance these myriad trade-offs between individual and institutional stakeholders.

## 6. Conclusion

During periods of rising home prices, falling interest rates, and increasingly competitive and efficient refinancing markets, cash-out refinancing is like a ratchet, incrementally increasing homeowner leverage as real-estate values appreciate without the ability to symmetrically decrease leverage by increments as real-estate values decline. Using a numerical simulation calibrated to the basic time-series properties of the U.S. residential housing market, we show that this ratchet effect is capable of generating the magnitude of losses suffered by mortgage lenders during the Financial Crisis of 2007–2009. During normal times, and in the absence of cash-out refinancing, the cross-sectional distribution of leverage among homeowners is relatively heterogeneous, with newer homeowners more highly leveraged than those who have had the opportunity to build more equity. Heterogeneity of leverage in the cross section implies fewer correlated defaults among borrowers and lower systemic risk.

However, during periods of falling interest rates and rising home prices, most homeowners will have an incentive to refinance. If the refinancing market is so competitive and efficient that homeowners refinance frequently, this pattern of behavior has an effect on systemic risk similar to the one that would occur if these homeowners all purchased their homes at the same time, at peak prices, with newly issued mortgages at the highest allowable LTV ratios. A coordinated increase in leverage among homeowners during good times will lead to sharply higher correlations in defaults among those same homeowners in bad times. Our simulations show that this effect alone is enough to generate \$1.7 trillion in losses for mortgage-lending institutions since June 2006.

These observations have important implications for risk management practices and regulatory reform. The fact that the refinancing ratchet effect arises only when three market conditions are simultaneously satisfied demonstrates that the recent financial crisis is subtle and may not be attributable to a single cause. Moreover, a number of the activities that gave rise to these three conditions are likely to be ones that we would not want to sharply curtail or outright ban because they are individually beneficial. While excessive risk-taking, overly aggressive lending practices, procyclical regulations, and political pressures surely contributed to the recent problems in the U.S. housing market, our simulations show that even if all homeowners, lenders, investors, insurers, rating agencies, regulators, and policy-makers behaved rationally, ethically, and with the purest of motives, financial crises could still occur. Therefore, we must acknowledge the possibility that no easy legislative or regulatory solutions may exist. As Reinhart and Rogoff (2008a,b) have shown, financial crises occur on a regular basis throughout the world and are often tied to economic

growth, capital inflows, and financial liberalization and innovation. Successfully managing systemic risk will require flexible, creative, and well-trained professionals who understand the fundamental drivers of such risk, not static rules meant to prevent history from repeating.

## Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version at <http://dx.doi.org/10.1016/j.jfineco.2012.10.007>.

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