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PRICING DEFAULT RISK IN MORTGAGES

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I. Introduction

Since the seminal work of Black and Scholes [2], option pricing theory has been applied to a wide variety of problems. Recently, a number of researchers have employed such techniques in analyzing housing finance problems. Dunn and McConnell [8] examine the pricing of default-free, GNMA mortgage-backed securities. Cunningham and Hendershott [7] study the borrower's default option, while Buser and Hendershott [4] consider the prepayment option.

This paper examines the valuation of fixed rate mortgages (FRMs) and the pricing of insurance against default on such mortgages. Both the mortgage and the insurance are treated as compound European puts. A put is the right, but not the obligation, to turn over an asset to another party for a specified payment, and being a European put indicates that this can only occur at a specified expiration date. The mortgage contract, and hence the insurance on it, fit into a European option framework because no rational borrower would ever choose to default until a payment is due. They are compound options in the sense of Geske [10] because at each payment date prior to the last one, the borrower either defaults or purchases a new option to default at the next payment date by making the scheduled payment.

These observations suggest a natural approach to the problem. Since the current value of the mortgage is affected by options to default in the future, the problem must be solved working backwards in time with the value of later options feeding into the earlier ones, so that the process builds on itself in a recursive fashion. Using familiar arguments from option pricing theory, the value of any of the assets in the model can be expressed as the solution to a partial differential equation (PDE), where the terms of the contract yield the appropriate terminal conditions. Standard numerical procedures can then be used to produce the value of the mortgage and the insurance under various economic conditions.

While the model is very general in most aspects, we have chosen to ignore the borrower's option to prepay the loan. This is done to isolate the default option and its relationship with the mortgage insurance. A complete model would integrate the work in this paper with previous work done on the prepayment option. Kau, Keenan, Muller, and Epperson [11] have preliminary results on such a model.

The organization of the paper is as follows. The model is specified and the fundamental PDE for the valuation of assets is developed. Next, the mortgage and insurance contracts are discussed within the context of the model. Simulation results are then reported and interpreted. The paper concludes with a summary and with suggestions for future research.

II. The Model

The two underlying sources of uncertainty in valuing a mortgage are the house itself and the term structure of interest rates. The house, $H(t)$, follows the stochastic differential equation

$$\frac{dH}{H} = \alpha dt + \sigma_1 dz_1 \tag{1}$$

where α is the total expected return to holding the house. The process is one of proportional growth in the house's value being disturbed by a stochastic term representing Brownian motion. Note that this process has an absorbing barrier at zero, which means that if $H(t)$ is ever zero it remains zero thereafter.

The return to owning the house comes in two parts, as price appreciation and as a service flow from using the house over time. We model the service flow as $sHdt$. Since the holder of an option on the house has no claim to the service flow, the relevant stochastic process for the option is

$$\frac{dH}{H} = (\alpha - s)dt + \sigma_1 dz_1 \tag{2}$$

where $\alpha-s$ is the expected price appreciation on the house. For a discussion of this in the context of dividends on a stock, see Merton [12].

The other source of uncertainty is in future interest rates. Consider the value P(t,T) of a pure discount bond at time t paying one dollar at time T. We assume the Local Expectations Hypothesis (LEH)

$$\frac{E[dP(t,T)]}{P(t,T)} = r(t)dt \tag{3}$$

which essentially serves to prevent there being any risk premiums in the term structure. For a discussion of the LEH, see Cox, Ingersoll, and Ross [5]. Note that one important implication of the LEH is that the spot rate r(t) incorporates all information known at time t about future interest rates.

If we assume that the spot rate follows some stochastic process

$$dr(t) = \mu(r)dt + \sigma(r)dz \tag{4}$$

it is not surprising to find that the formal solution of (4) for a discount bond is

$$P(t,T) = E\left[e^{-\int_t^T r(s)ds}\right] \tag{5}$$

What is perhaps more remarkable is that the solution to this problem arising from stochastic processes must also be the solution to the following PDE:

$$\tfrac{1}{2}\,\sigma(r)^2 P_{rr} + \mu(r)P_r - rP - P_t = 0 \tag{6}$$

$$P(T,T) = 1 \tag{7}$$

which has an entirely deterministic form.

The actual interest-rate mechanism employed here is

$$d\,\ln(r(t)) = \gamma(\ln\theta - \ln(r(t)))dt + \sigma_2 dz_2 \tag{8}$$

which has the property that the spot interest rate drifts toward the long-term interest rate θ. Note that as with the stochastic process for the house, this process has an absorbing barrier at r=0. For a discussion of this interest rate process, see Brennan and Schwartz [3].

With the stochastic processes specified as discussed above, the PDE for the valuation of assets solely a function of the house price and the interest rate takes the form

$$\begin{aligned} &\tfrac{1}{2}\,\sigma_1^{\,2} r^2 X_{rr} + \rho\sigma_1\sigma_2 rHX_{rH} + \tfrac{1}{2}\,\sigma_2^{\,2} H^2 X_{HH} \\ &+ r(\gamma\ln(\theta/r) + \tfrac{1}{2}\,\sigma_2^{\,2})X_r + (r-s)HX_H \\ &+ X_t - rX = 0 \end{aligned} \tag{9}$$

where

$$dz_1(t)dz_2(t) = \rho dt \tag{10}$$

and X denotes the value of the relevant asset. The derivation of (9) follows from standard arguments in finance. See, for instance, Cox, Ingersoll, and Ross [6].

To use (9) to value either the mortgage or the insurance, terminal conditions must be specified. The terms of the contract provide the appropriate conditions. As explained in the introduction, the value of either option is dependent on the value of future options, so the valuation must proceed from the expiration date of the mortgage backwards in time.

The following notation is useful.

- M: the mortgage payment.
- n: the expiration date of the mortgage contract.
- $G(i,j)$: the value at time i of the default put option with expiration date j whose terms are explained later.
- $S(i,j)$: the value at time i of certain mortgage payments in every period from j to n.
- $I(i,j)$: the value at time i of the insurance contract expiring at time j whose terms are explained later.

The position of the borrower at time n is

$$H(n) + G(n,n) - M \tag{11}$$

where

$$G(n,n) = \max\,[0, M-H(n)] \tag{12}$$

That is, the borrower holds the house and has an obligation to make the payment M; but he also has a put option on the house $G(n,n)$ allowing him to sell the house to the lender for M if he wishes. Note that the put is exercised only if $M > H(n)$.

At any earlier payment date i the borrower holds a corresponding position

$$H(i) + G(i,i) - S(i,i) \tag{13}$$

where the default put takes the compound form

$$G(i,i) = \max\,[G(i,i+1),\ S(i,i) - H(i)] \tag{14}$$

with $S(i,i)$ defined recursively as

$$S(i,i) = S(i,i+1) + M \tag{15}$$

and

$$S(n,n) = M \tag{16}$$

Having recursively defined the terminal conditions, we can use (9) to value G and S at any time. The procedure is as follows. Use (9), (12), and (16), to compute the value of $G(n-1,n)$ and $S(n-1,n)$. Then use these along with (9), (14), and (15), to compute $G(n-2,n-1)$ and $S(n-2,n-1)$. Continue in this fashion backwards in time to the beginning of the contract.

Turning to the insurance problem we find

$$I(n,n) = \min\ [M-H(n), \phi M] \tag{17}$$

which indicates that the insurer pays the difference between the defaulted house's value and the mortgage payment, up to a specified fraction ϕ of the unpaid balance. In earlier periods

$$I(i,i) = \begin{cases} I(i,i+1) & \text{if } S(i,i) - H(i) < G(i,i+1) \\ \max\ [0, \min[B(i) - H(i), \phi B(i)]] & \text{if } S(i,i) - H(i) > G(i,i+1) \end{cases} \tag{18}$$

where $B(i)$ is the unpaid balance prior to payment at i, calculated as

$$B(i) = \frac{(1+\bar{r})^n - (1+\bar{r})^{i-1}}{(1+\bar{r})^n - 1} L \tag{19}$$

with $\bar{r}$ being the contract rate and L the amount of the loan. While the recursive formula (18) seems somewhat complicated, the intuition is as simple as (17). The first equation says that if the borrower does not default, the insurance is rolled over and the second defines the insurer's liability if the borrower does default.

Two notes are in order here. First, since we have chosen to ignore the prepayment option, it is possible that because interest rates have fallen, a person may choose to default when the value of the house exceeds the unpaid balance. Second, due to the lack of symmetry in the interests of the borrower and the lender, there are discontinuities in the terminal conditions. Unlike the former anomaly, this peculiarity does not disappear when prepayments are allowed.

The contract rate in (19) is not exogenous but must be set by arbitrage considerations at the origination of the contract, time 0. It must be the case that the value of the assets each party gives up at time 0 is equal to the value of the assets received. Therefore, the contract rates must be adjusted so that this condition is satisfied. Note that this means the insurance can be paid for as part of the up-front fees, over time through a higher contract rate, or by some combination of the two.

III. The Simulations

The PDE (9) has been simulated using an explicit finite difference method. See [1] and [9] for details on such procedures. For the problem to be well-specified, boundary conditions must be imposed as well as terminal conditions. Because r=0 and H=0 serve as absorbing barriers, these boundary conditions take the form of (9) degenerating into a PDE in the single variable H along the r=0 axis and into a PDE in the single variable r along the H=0 axis. Since the case at the origin $(r,H) = (0,0)$ is self-evident, as are the cases when $r \rightarrow \infty$ or $H \rightarrow \infty$, the problem is closed.

Our simulations produce the value of the default option and the insurance for a number of different scenarios. We vary both the loan-to-value ratio and the specification of the standard deviation terms in (1) and (8). In all simulations the value of the house at origination is forty thousand dollars and the initial spot interest rate is 10 percent. Table 1 lists the values of the other parameters held constant across simulations.

Table 1

Parameter Values

ρ	= .25
s	= .05
θ	= .10
γ	= .07
ϕ	= .20
$\bar{r}$	= .10

These parameter values are in line with those commonly used in the literature. See [3], [4], and [7]. The contract rate is held constant for ease of exposition, so we implicitly assume that the arbitrage considerations discussed previously are satisfied by adjusting the points charged up front.

Table 2 lists the different specifications for σ_1 and σ_2. Table 3 reports the value of the right to default, and Table 4 reports the value of the insurance.

Table 2

Scenarios

	I	II	III	IV
σ_1	.02	.04	.06	.10
σ_2	.03	.07	.10	.15

Table 3

Value of the Default Option in Dollars

LTV Ratio	I	II	III	IV
80%	1309	1716	2247	3516
85%	1621	2094	2714	4195
90%	2811	3049	3360	4876

Table 4

Value of the Insurance in Dollars

LTV Ratio	I	II	III	IV
80%	234	254	287	384
85%	473	515	580	765
90%	697	713	742	1158

The simulations agree with the standard results from option theory and economic intuition. That is, the options increase in value as the magnitudes of the underlying variances increase and as the loan-to-value ratio increases. Note also that the value of the insurance is substantially below the value of the default option. The major reason for this is that the insurance is only on the top twenty percent of the loan.

IV. Conclusion

This paper has analyzed the value of default insurance in a model with stochastic interest rates. While the model and the results derived from it are interesting in their own right, this work is only part of an ongoing effort by a number of researchers to apply the techniques of option theory to mortgage-related problems.

There are numerous directions for future research. Even within the context of the relatively simple FRM, there is much to do. A complete model of the FRM would include a treatment of default, prepayment (for both financial and nonfinancial reasons), transaction costs, and a general specification of the term structure of interest rates. After that there are the more exotic mortgage instruments such as adjustable rate mortgages, growing equity mortgages, price level adjusted mort-gages, and a host of others to consider. The results in this paper illustrate the usefulness of option theory in analyzing various aspects of the FRM and suggest that further attempts to apply option theory to more complex mortgage instruments would prove fruitful.

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