In last month’s Risk, John Hull and Alan White used bond prices to calculate credit risk on derivative transactions. But for Robert Jarrow and Stuart Turnbull, a forex analogy is also essential.

Current practice in pricing and hedging credit-risky assets like derivatives has directly adapted recent innovations in interest rate risk management.¹ These make use of a new option pricing technology which takes as its inputs the term structure of default-free zero coupon bond prices and the term structure of default-free zero coupon bond price volatilities.²

These models can be very sophisticated, using multiple factors that require complex computational procedures and correspondingly complex computer software. But they are inadequate when credit risk is involved.

When applied to options on triple-A corporate debt, for example, the term structure of default-free zero coupon bond prices becomes the term structure of triple-A corporate debt; and the term structure of default-free zero coupon bond price volatilities becomes the term structure of triple-A corporate debt volatilities. This implies, of course, that triple-A corporate debt is default-free (regardless of the maturity) – a fact directly inconsistent with the evidence. Furthermore, and perhaps even more damaging, is the fact that a credit risk spread in this procedure implies the existence of fictitious arbitrage opportunities between default-free and credit-risky debt.³

This article will describe a new approach to the pricing and the hedging of credit-risky assets which is devoid of such difficulties.⁴ This approach takes as its inputs: (i) the default-free zero coupon bond prices, (ii) the credit-risky zero coupon bond prices, (iii) the default-free zero coupon bond price volatilities, and (iv) the credit-risky zero coupon bond price volatilities. This methodology is arbitrage-free, allows cross hedging between credit-risky and default-free term structures, and allows credit-risky assets (eg, long-term debt) to default with positive probability. The methodology can be used to price and hedge derivatives written on assets subject to credit risk; it can also be used to price and hedge derivatives subject to the additional risk that the writer might default. It is intuitive, simple to use, and in special cases it collapses to any prespecified interest rate option model desired – for example, Hull and White (1990) or Heath, Jarrow, Morton (1991, 1992). So, what’s the catch? As far as we can tell, there is none.

Credit risk arises in a financial contract between two parties whenever one or both of the parties may not fulfill the conditions of the contract due to limited financial resources. For example, corporate bonds may not pay their face value at maturity because the corporation is bankrupt, or the counterparty to a swap may default, terminating the swap’s future payments. In this light, we will be concerned with two types of credit-risky options. First, options where the underlying asset may default (eg, call provisions on corporate debt) and second, options where the writer may default (eg, the counterparty to a swap). Both types of credit risks are real, and both are important.

The basic insight of the approach is to show that pricing options on credit-risky assets is the same problem as pricing options on foreign currencies. Hence, the term the “forex analogy”. Since solutions to this later problem are well understood,⁵ the credit risk option problem is solved. All that will remain, then, is to fill in the details of this particular application of the forex option pricing technology.

To see the forex analogy, let us first consider a market situation where there are traded credit-risky zero coupon bonds of all maturities (called “XYZ” debt) and default-free zero-coupon bonds of all maturities.⁶ Let $v(t, T)$ be the time $t$ price of a promised dollar payment by XYZ corporation at time $T$ ($T > t$); and let $p_0(t, T)$ be the time $t$ price of a sure dollar payment at time $T$. These latter bonds are issued by the US government. We assume that XYZ corporation can default with positive probability, and therefore $v(t, T) < p_0(t, T)$.

Let us abstract for a moment, and think of XYZ debt as paying off, not in dollars, but in a hypothetical currency called “XYZ promised dollars” or simply “XYZS”. In this currency, XYZ debt is, of course, default-free. The difficulty here is that at maturity, however, an XYZ promised dollar may not be worth an actual dollar. This will be the case when XYZ corporation is in default. Thus, we can hypothesise the existence of a spot exchange rate $e(t)$ of dollars for XYZS. It is unity if XYZ is solvent, and less then unity if XYZ is bankrupt. Let $p_0(t, T)$ be the time $t$ price in XYZS of an XYZ promised dollar delivered at time $T$ for sure. This is the term structure of XYZ debt in XYZS. By construction, the dollar value of XYZ debt can be written as:

$$v(t, T) = p_0(t, T)e(T-t)$$

This tautological decomposition is the forex analogy. The left side is the dollar value of a foreign currency denominated bond. The right side is the foreign currency value of a foreign currency denominated bond multiplied by a spot exchange rate. Pricing and hedging options on credit-risky XYZ debt are, therefore, analogous to pricing and hedging options on a foreign currency bond in dollars.

An example will illustrate the application of the forex analogy to pricing credit risky options. The procedure follows the standard option pricing techniques as described in various textbooks.⁷

The simplest example to consider is a three-period economy (times 0, 1, 2) with two default-free zero coupon bonds and two zero coupon corporate bonds trading. The initial term structures, which are shown in table 1, are taken as given. Two lattices

<table>
<thead>
<tr>
<th>Table 1. Initial term structures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maturity</td>
</tr>
<tr>
<td>---------</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
</tbody>
</table>

⁴ See Ho and Lee (1986), Hull and White (1990), Heath, Jarrow and Morton (1991, 1992), Black, Derman and Toy (1990) for further elaboration.
⁵ See Jarrow and Turnbull (1990, 1992).
⁶ See Amin and Jarrow (1991) and references therein.
⁷ Although this is not true in practice, the problem of stripping out zeros from coupon bonds is well studied.
1. Default-free dollar term structure with pseudo-probabilities

\[
\begin{array}{c|c|c}
\text{Time} & 0 & 1 & 2 \\
\hline
r_{0.0901} & 1 & 1.10 \\
0.8658 & 1.075 & 1.05 \\
0.9302 & 1 \\
\hline
\end{array}
\]

T-bill prices

\[
\begin{array}{c|c|c}
T(0.02) & 1 \\
T(0.12) & 1 \\
\hline
\end{array}
\]

Referring to figure 1, the default-free bond which matures at \( t = 2 \) is assumed to have one of two possible values at \( t = 1 \), either

\[
p_0(1,2) = 0.9091 \quad (2a)
\]

which implies a one period rate of \( r_{1.1} = 1.10 \), or

\[
p_0(1,2) = 0.9524 \quad (2b)
\]

which implies a one period rate of \( r_{1.2} = 1.05 \). Using the standard no-arbitrage condition, the value of the two period bond is

\[
p_0(0,2) = \left( \frac{1}{2} \right) 0.9091 + \left( \frac{1}{2} \right) 0.9524 \cdot 1.075 = 0.8658
\]

which agrees with table 1. If we did not have agreement, we would have altered the values (2a) and (2b) until we reached agreement with the term structure of prices and volatilities. This type of forward induction argument is explained in Black, Derman and Toy (1990).

Standard interest rate options can be priced off the tree in figure 1 using the well-known risk neutrality argument. For example, consider a European call option on the two period default-free bond with exercise date 1 and exercise price (0.9302). The payoff to this option at time 1 is uncertain and equal to:

\[
\text{Max}[p_0(1,2) - 0.9302,0] = \begin{cases} 
0 & \text{if } p_0(1,2) = 0.9091 \\
0.0222 & \text{if } p_0(1,2) = 0.9524
\end{cases}
\]

Using the risk neutral valuation procedure, its time 0 price, denoted \( C_0(0) \) is given by:

\[
C_0(0) = E(\text{Max}[p_0(1,2) - 0.9302,0]) / r_0
\]

\[
= (1/2)(0.9524 - 0.9302) / 1.075 = 0.0103
\]

The default-free term structure is seen to be complete as we can create the above call synthetically. To review this construction, choose \( \alpha \) units of the default-free two period bond at time 0 and \( \beta \) units of a money market account at time 0 such that the time 1 payments to this portfolio equal the time 1 pay-outs to the call option:

\[
\alpha(0.9091) + \beta(1.075) = 0 \quad (4a)
\]

\[
\alpha(0.9524) + \beta(1.075) = 0.0222 \quad (4b)
\]

This implies that \( \alpha = 0.5127 \) and \( \beta = -0.4336 \). In words, purchase 0.5127 units of the default-free two period bond and borrow 0.4336 dollars at the spot rate. This portfolio duplicates the call option.

To avoid arbitrage, therefore, the value of the traded call at time 0 must be the initial cost of creating this portfolio:

\[
\alpha(0.8658) + \beta(1) = 0.0103 \quad (5)
\]

This is the same value, however, as given in expression (3). (As it should be.)

The first step in pricing credit-risky options is understanding the bankruptcy process for firm XYZ. Figure 2 describes the important components of this process. At time 0 it is solvent (by construction) and the payoff ratio is 1. At time 1 with pseudo-probability (1/4), XYZ goes bankrupt and pays off 50c to the dollar. If bankrupt at time 1, it stays bankrupt at time 2 and the pay-off ratio remains 50c. If not bankrupt at time 1, again with pseudo-
3. XYZ term structure in XYZs with pseudo-probabilities

<table>
<thead>
<tr>
<th>Time</th>
<th>0</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A)</td>
<td>0.6764</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>(B)</td>
<td>0.7955</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>(C)</td>
<td>0.8333</td>
<td>3/4</td>
<td>1</td>
</tr>
<tr>
<td>(D)</td>
<td>0.9099</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>(E)</td>
<td>0.9524</td>
<td>1/8</td>
<td></td>
</tr>
<tr>
<td>(F)</td>
<td>1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Process:

\[
\begin{bmatrix}
[p_1(0,2)] \\
[p_2(0,1)] \\
[p_3(1,2)] \\
[p_4(1,1)]
\end{bmatrix}
\]

4. XYZ term structure in dollars with pseudo-probabilities

<table>
<thead>
<tr>
<th>Time</th>
<th>0</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A)</td>
<td>0.6764</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>(B)</td>
<td>0.7955</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>(C)</td>
<td>0.8333</td>
<td>3/4</td>
<td>1</td>
</tr>
<tr>
<td>(D)</td>
<td>0.9099</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>(E)</td>
<td>0.9524</td>
<td>1/8</td>
<td></td>
</tr>
<tr>
<td>(F)</td>
<td>1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Bond prices:

\[
\begin{bmatrix}
[v(0,2)] \\
[v(1,2)] \\
[v(1,1)] \\
[v(2,2)]
\end{bmatrix}
\]

The second step is specifying the XYZ term structure in XYZs. Figure 3 gives this process. There are four branches to the tree at time 1 as there are four possible outcomes: spot interest rates move up or down and there is bankruptcy or no bankruptcy. The pseudo-probabilities are taken to be the products of the separate probabilities for each event, as they are assumed to be independent. The exact numbers in each node were selected so that (i) the XYZ dollar term structure given in figure 4 satisfies the standard no-arbitrage conditions, which are that the current bond prices equal their expected future values, appropriately discounted, and (ii) the current bond prices are consistent with the initial term structure of prices and volatilities.

Figure 4 is constructed by combining figures 2 and 3. At nodes B and C in figure 4 default has not occurred. The payoff to the one-period corporate bond which matures at time 1 is unity:

\[v(1, 1) = 1.\]

At nodes D and E default occurs. In the event of default it is assumed that bond holders receive 50 units on the dollar:

\[v(1, 1) = \frac{1}{2}.\]

Using the standard no-arbitrage condition

\[\mathbb{E}[v(1, 1)] / r_0\]

and the value of the one-period corporate bond is

\[v(0, 1) = \left(\frac{3}{4}\right)^{1/2} \frac{1}{2} + \left(\frac{1}{4}\right)^{1/2} \frac{1}{2} / 1.075\]

\[= 0.8140,\]

where \(1/4\) is the pseudo-probability of default occurring at \(t = 1\). The value given in expression (6) for the one-period corporate bond agrees with the figure in table 1. Had there been disagreement, we would have altered the pseudo-probability of default until agreement was reached.

We now want to determine the pseudo-probability of default occurring at \(t = 2\), given default did not occur at \(t = 0\), or \(t = 1\). At node B in figure 4 default has not occurred and the spot default-free rate is \(r_{11} = 1.10\). Using the standard no-arbitrage condition

\[\mathbb{E}[v(2, 1)] / r_{11}\]

gives

\[v(2, 1) = \left(\frac{3}{4}\right)^{1/2} \frac{1}{2} + \left(\frac{1}{4}\right)^{1/2} \frac{1}{2} / 1.10\]

\[= 0.7955,\]

which agrees with table 1. If there had been disagreement, we would have altered the pseudo-probability.*

Simple algebra shows that the XYZ dollar bond price divided by the default-free bond price equals the expected payoff to the credit-risky bond at maturity.

\[\mathbb{E}(e(2)) = v(2, 1) / p(0, 2) = 0.8658,\]

where \(1/4\) is the pseudo-probability of default occurring at \(t = 2\), given default has not occurred at \(t = 1\). At node C default has not occurred and the spot default-free rate is \(r_{12} = 1.05\). The value of the corporate bond is

\[v(1, 2) = \left(\frac{3}{4}\right)^{1/2} \frac{1}{2} + \left(\frac{1}{4}\right)^{1/2} \frac{1}{2} / 1.05\]

\[= 0.8333.\]

At node D default has occurred, so the payoff to the bond holder at \(t = 2\) is \(1/2\). Given a spot default free rate \(r_{11} = 1.10\), the value of the corporate bond is

\[v(1, 2) = \left(\frac{1}{2}\right) / 1.10\]

\[= 0.4545.\]

At node E default has occurred, the payoff to the bond holder at \(t = 2\) is \(1/2\). The spot rate for \(r_{12} = 1.05\) and the value of the corporate bond is:

\[v(1, 2) = \left(\frac{1}{2}\right) / 1.05\]

\[= 0.4762.\]

The value of the two-period corporate bond today is

\[v(0, 2) = \left(\frac{3}{4}\right)^{1/2} \frac{1}{2} + \left(\frac{1}{4}\right)^{1/2} \frac{1}{2} + \left(\frac{3}{4}\right)^{1/2} \frac{1}{2} + \left(\frac{1}{4}\right)^{1/2} \frac{1}{2} / 1.075\]

\[= 0.6764,\]

which agrees with table 1. If there had been disagreement, we would have altered the pseudo-probability.

Using the numbers \(0.7813 = 0.6764 / 0.8658\), and

\[\mathbb{E}(e(1)) = v(0, 1) / p(0, 1) = 0.8140 / 0.9302.\]
For a benchmark model to be of practical use, it must be applicable to pricing both options on Treasury bonds and options on corporate debt. A minimal requirement for such a benchmark model is that it be consistent with the absence of arbitrage.

This is a useful result. It provides a simple way to quantify the expected payoff per promised XYZ dollar at a future date.

Next, we consider pricing a European call option with exercise date 1 and exercise price (0.9302) on the two-period XYZ bond: a similar option to that priced in expression (3) but this time issued against XYZ debt. Its payoff at time 1 is given by:

$$\max[v(1,2) \cdot (0.9302), 0] = 0$$

under all circumstances.

By risk neutrality, its value, denoted $C_1(0)$, is given by

$$C_1(0) = \frac{\mathbb{E}(\max[v(1,2) \cdot (0.9302), 0])}{\tau_0} \quad (9)$$

The option on the credit-risky debt is worthless. This value differs from that given in expression (3) due to the credit risk of the underlying asset and the credit risk spread.

Next, consider a European call option with exercise date 1 and a reduced exercise price of (0.8000) on the two-period XYZ bond. Its value, denoted $C_r(0)$, is:

$$C_r(0) = \frac{\mathbb{E}(\max[v(1,2) \cdot (0.8000), 0])}{\tau_0} = \frac{(3/8)(0.8333 - 0.8000)}{1.075} \quad (10)$$

$$= 0.0116.$$ 

To create this call option synthetically, we need four assets, as there are four branches on the tree in figure 4. To see this construction, choose $\alpha$ units of XYZ debt $v(0,2)$, $\beta$ units of XYZ debt $v(0,1)$, $\gamma$ units of default-free debt $p_d(0,2)$, and $\delta$ units of a money market account such that

$$\begin{align*}
\alpha(0.7955) + \beta(1) + \gamma(0.9091) + \delta(1.075) &= 0 \\
\alpha(0.8333) + \beta(1) + \gamma(0.9524) + \delta(1.075) &= 0.0333 \quad (11) \\
\alpha(0.4545) + \beta(0.5) + \gamma(0.9091) + \delta(1.075) &= 0 \\
\alpha(0.4762) + \beta(0.5) + \gamma(0.9524) + \delta(1.075) &= 0
\end{align*}$$

The solution is:

$$\begin{align*}
\alpha &= 2.07 \\
\beta &= -1.4118 \\
\gamma &= -1.0374 \\
\delta &= 0.6588
\end{align*}$$

We are long 2.07 shares of the two-period XYZ debt, short 1.4118 units of the single-period XYZ debt, short 1.0374 units of the two-period government bond, and we purchase 0.6588 units of the money market account. The initial cost of constructing this portfolio is

$$\frac{\alpha}{\tau_0} + \beta + \gamma + \delta = 0.0116 \quad (12)$$

This equals the call's value in expression (10), as it should.

A similar process is involved where the credit risk corresponds not to the asset underlying the option but to the writer of the option. These are called "vulnerable" options. To analyse this case, suppose that XYZ writes the European call option described in expression (3). Note that this option is written on a Treasury bill, so there is no credit risk in the underlying asset. Its pay-off at time 1, $\max[p_0(1,2) - (0.9302), 0]$ is now the promised pay-off by XYZ. Its actual dollar value is, therefore:

$$\begin{align*}
e(1)\max[p_0(1,2) - (0.9302), 0] &= \\
\max[p_0(1,2) - (0.9302), 0] &= 0 \\
\text{if not bankrupt} \\
\frac{1}{2}\max[p_0(1,2) - (0.9302), 0] &= 0 \\
\text{if bankrupt}
\end{align*}$$

It only equals the promised pay-off if XYZ is not bankrupt, and the payoff ratio $e(1)$ is one.

Under risk neutrality, the current value, denoted $C_r(0)$, is easily calculated:

$$C_r(0) = \frac{\mathbb{E}(e(1) \cdot \max[p_0(1,2) - (0.9302), 0])}{\tau_0} = \frac{\mathbb{E}(e(1))\mathbb{E}[\max[p_0(1,2) - (0.9302), 0]]}{\tau_0} \quad (13)$$

Now the first term on the right-hand side is given in (8b) and the second term is the value of a non-vulnerable option which we calculated in equation (3). Therefore

$$C_r(0) = 0.875(0.0103) = 0.0090 \quad (13)$$

Notice that this value differs from both the option on default-free debt $C_0(0) = 0.0103$ and the option on credit-risky debt $C_r(0) = 0$.

Using expression (8), we can show that

$$C_r(0) = \frac{\mathbb{E}(v(0,2)) - \mathbb{E}(v(0,1))}{p_0(0,1)} \quad (14)$$

that is, the value of a vulnerable option is less than that of an option written by a riskless writer by exactly the factor $[(v(0,2) - v(0,1))/p_0(0,1)]$, the inverse of the credit risk spread.

This example readily generalises to multi-periods (discrete or continuous time) and multifactors. The only binding assumptions in the above analysis are that the bond markets are complete (ie, all risks can be hedged) and that there are no arbitrage.
trage opportunities. Both of these assumptions are reasonable approximations to the actual bond markets.

If one assumes that the bankruptcy process of XYZ corporation (under the pseudo-probabilities) is independent of the stochastic process generating the default-free term structure, then the following results can still be shown to apply. First,

$$v(t,T) = E_v(e(T))p_0(t,T)$$

(15)

where $E_v(.)$ is the time $t$ conditional expectation under the pseudo-probabilities.

Expression (15) states that the price of a credit-risky discount bond equals its discounted expected payoff at maturity. Given additional parametric assumptions upon the stochastic processes for the bankruptcy process ($e(t)$), this expression enables one to estimate the bankruptcy probabilities (per unit time) from market data.

Second, letting $C(t)$ be the time $t$ cashflow to a contingent claim, risk-neutral valuation readily implies:

$$C(t) = E_p[C(t)/B(t)]B(t)$$

(16)

where $B(t)$ is the time $t$ value of a money market account, initialised with a dollar investment at time 0. Expression (16) states that the contingent claim's value equals its discounted expected value under the pseudo-probabilities. These techniques can be easily extended to value American or exotic options.

For special cases – economies where the default-free term structure is Gaussian and the bankruptcy process is Poisson (under the pseudo-probabilities) – analytic solutions to expression (16) are available for various European options. For example, the value of a European call option with maturity $T$ and strike price $K$ written on a zero coupon corporate bond with maturity $M \geq T$ is

$$C(0;K) = \exp(-\lambda T)\left[ \exp(-\lambda (M - T)) + \exp(-\delta) [1 - \exp(-\lambda (M - T))] \right]C_0(0;K')$$

$$+ \left[ 1 - \exp(-\lambda T) \right] \exp(-\delta) C_0(0;K^*)$$

(17)

where $C_0(0,L)$ is the value of an European call option with strike price $L$ and maturity $T$ written on a zero coupon Treasury bill which matures at $M$.

$$C_0(0,L) = p_0(0,M) N(h) - L p_0(0,T) N(h - q)$$

$$h = \left\{ n[p_0(0,M)/L_p(0,T)] + q^2 / 2 \right\} / q$$

$$q^2 = (\sigma^2 / 2n^1)$$

$$\left[ \exp(-\eta T) - \exp(-\eta M) \right] \left[ \exp(2\eta T) - 1 \right]$$

$\eta$ is the reversion factor, $\sigma$ is the volatility of the default-free spot interest rate;

$$K' = K / \left\{ \exp(-\lambda (M - T)) + \exp(-\delta) [1 - \exp(-\lambda (M - T))] \right\}$$

$$K^* = K \exp(-\delta)$$

$\exp(-\lambda T)$ is the probability that default does not occur over the life of the option; $\exp(-\delta) < 1$ is the payment bondholders receive if default occurs; and $N(.)$ is the cumulative normal distribution function. Equation (17) can be interpreted as follows. The first term on the right-hand side is the expected value of the option at maturity, given default does not occur over the life of the option, and the second term is the expected value of the option at maturity given default in the underlying asset occurs at or before the maturity of the option. These formulas can be shown to collapse to those of Hull and White (1990) and Heath, Jarrow and Morton (1991, 1992) when there is no default risk.

Hull and White (1992) argue that interest rate option markets need a benchmark pricing model and suggest the Hull-White model, which assumes that interest rates are normally distributed. For a benchmark model to be of practical use, however, it must be applicable to pricing both options on Treasury bonds and options on corporate debt. A minimal requirement for such a benchmark model is that it be consistent with the absence of arbitrage. The Jarrow and Turnbull model meets all the requirements and it can be used across different types of interest rate markets. Unfortunately, if the Hull and White model is used to price options simultaneously in different types of interest rate markets, then in general their results will be inconsistent with the absence of arbitrage. Thus it does not satisfy the minimal requirement for a benchmark model.

Finally, expression (14) also generalises and it corresponds to options written by credit risky individuals, ie

$$C_s(t) = \frac{v(t,T)}{p_0(t,T)}$$

(18)

where $C_s(t)$ is the time $t$ value of a option written by a firm with risky debt ($v(t,T)$), and $C(t)$ is the time $t$ value of the same option written by an otherwise riskless writer. Expression (18) is a useful formula for the pricing of vulnerable options.

The model can be further extended to more complex and realistic bankruptcy processes; for example, the bankruptcy processes can be dependent on the history of the firm and the current level of interest rates. The model can also be extended to incorporate multiple credit classes, multiple term structures, and to multiple foreign currencies. It is a very rich model. The only limitation is that the more complex the model becomes, the more time-consuming it is to compute values.

Robert Jarrow is a professor at the Johnson Graduate School of Management at Cornell University, Ithaca, New York; Stuart Turnbull is a professor at the School of Business, Queen's University, Kingston, Canada. Both are directors of Jarrow Turnbull Derivative Securities, a risk management consultancy.
References


Heath, D, R Jarrow and A Morton, 1992, Bond pricing and the term structure of interest rates: a new methodology for contingent claims valuation, Econometrica 60 (1), pages 77–105


Hull, J and A White, 1990, Pricing interest rate derivative securities, Review of Financial Studies, 3(4)


Hull, J and A White, 1992, In the common interest, Risk March 1992, pages 64–68


Jarrow, RA and SM Turnbull, 1992a, Interest rate risk management in the presence of default risk, unpublished manuscript, Johnson Graduate School of Management

Jarrow, RA and SM Turnbull, 1992b, The pricing and hedging of options on financial securities subject to credit risk: the discrete time case, unpublished manuscript, Johnson Graduate School of Management

Jarrow, RA and SM Turnbull, May 1990, revised March 1992, Pricing options on financial securities subject to credit risk, unpublished manuscript, Johnson Graduate School of Management

