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8.1 Credit Default Swaps (CDS)

We work with a tenor structure \( \{ t = T_i < \cdots < T_j = T \} \). Here, \( \tau \) is a default time and the filtration \( \mathcal{G}_t := \mathcal{F}_t \vee \sigma(\tau) \) contains the additional information on \( \tau \), as defined in (7.3).

A Credit Default Swap (CDS) is a contract consisting in

- A premium leg: the buyer is purchasing protection at time \( t \) against default at time \( T_k, k = i + 1, \ldots, j \), and has to make a fixed spread payment \( S^i_j \) at times \( T_{i+1}, \ldots, T_j \) between \( t \) and \( T \) in compensation.

The discounted value at time \( t \) of the premium leg is

\[
V^p(t, T) = \mathbb{E} \left[ \sum_{k=i}^{j-1} S^i_j \delta_k \mathbb{1}_{\{ \tau > T_{k+1} \}} \exp \left( - \int_t^{T_{k+1}} r_s \, ds \right) \mid \mathcal{G}_t \right] \\
= \sum_{k=i}^{j-1} S^i_j \delta_k \mathbb{E} \left[ \mathbb{1}_{\{ \tau > T_{k+1} \}} \exp \left( - \int_t^{T_{k+1}} r_s \, ds \right) \mid \mathcal{G}_t \right]
\]
\[ S_t^{i,j} = S_t^{i,j} \sum_{k=i}^{j-1} \delta_k P(t, T_{k+1}) = S_t^{i,j} P(t, T_i, T_j), \]  

(8.1)

where \( \delta_k = T_{k+1} - T_k \),

\[ P(t, T_k) = 1_{\{\tau > t\}} \mathbb{E} \left[ \exp \left( - \int_t^{T_k} (r_s + \lambda_s) ds \right) \mid \mathcal{F}_t \right], \quad 0 \leq t \leq T_k, \]

is the defaultable bond price with maturity \( T_k \), \( k = i, \ldots, j-1 \), see Lemma 7.3, and

\[ P(t, T_i, T_j) = \sum_{k=i}^{j-1} \delta_k P(t, T_{k+1}) \]

is the (default) annuity numéraire, cf. e.g. Relation (??) in Privault (2014),

For simplicity we have ignored a possible accrual interest term over the time interval \([T_k, \tau]\) when \( \tau \in [T_k, T_{k+1}] \) in the above value of the premium leg.

- **A protection leg:** the seller or issuer of the contract makes a compensation payment \( 1 - \xi_{k+1} \) to the buyer in case default occurs at time \( T_{k+1} \), \( k = i, \ldots, j-1 \), where \( \xi_{k+1} \) is the **recovery rate**.

The value at time \( t \) of the protection leg is

\[ V^d(t, T) := \mathbb{E} \left[ \sum_{k=i}^{j-1} 1_{(T_k, T_{k+1})}(\tau)(1 - \xi_{k+1}) \exp \left( - \int_t^{T_{k+1}} r_s ds \right) \mid \mathcal{G}_t \right], \]

(8.2)

where \( \xi_{k+1} \) is the recovery rate associated with the maturity \( T_{k+1} \), \( k = i, \ldots, j-1 \).

In the case of a non-random recovery rate \( \xi_k \) the value of the protection leg becomes

\[ \sum_{k=i}^{j-1} (1 - \xi_{k+1}) \mathbb{E} \left[ 1_{(T_k, T_{k+1})}(\tau) \exp \left( - \int_t^{T_{k+1}} r_s ds \right) \mid \mathcal{G}_t \right]. \]

The spread \( S_t^{i,j} \) is computed by equating the values of the premium (8.1) and protection (8.2) legs, *i.e.* from the relation

\[ V^p(t, T) = S_t^{i,j} P(t, T_i, T_j) \]
Credit Valuation

\[
= \mathbb{E} \left[ \sum_{k=i}^{j-1} \mathbbm{1}_{(T_k, T_{k+1}]}(\tau)(1 - \xi_{k+1}) \exp \left( - \int_t^{T_{k+1}} r_s ds \right) \mid \mathcal{G}_t \right],
\]

which yields

\[
S_t^{i,j} = \frac{1}{P(t, T_i, T_j)} \sum_{k=i}^{j-1} \mathbb{E} \left[ \mathbbm{1}_{(T_k, T_{k+1}]}(\tau)(1 - \xi_{k+1}) \exp \left( - \int_t^{T_{k+1}} r_s ds \right) \mid \mathcal{G}_t \right].
\]

The spread \( S_t^{i,j} \), which is quoted in basis points per year and paid at regular time intervals, gives protection against defaults on payments of $1. For a notional amount \( N \) the premium payment will become \( N \times S_t^{i,j} \).

In the case of a constant recovery rate \( \xi \) we find

\[
S_t^{i,j} = \frac{1 - \xi}{P(t, T_i, T_j)} \sum_{k=i}^{j-1} \mathbb{E} \left[ \mathbbm{1}_{(T_k, T_{k+1}]}(\tau) \exp \left( - \int_t^{T_{k+1}} r_s ds \right) \mid \mathcal{G}_t \right],
\]

and if \( \tau \) is constrained to take values in the tenor structure \( \{ t = T_i, \ldots, T_j \} \), we get

\[
S_t^{i,j} = \frac{1 - \xi}{P(t, T_i, T_j)} \mathbb{E} \left[ \mathbbm{1}_{(t,T)}(\tau) \exp \left( - \int_t^{\tau} r_s ds \right) \mid \mathcal{G}_t \right].
\]

The buyer of a Credit Default Swap (CDS) is purchasing protection at time \( t \) against default at time \( T_k, k = i + 1, \ldots, j \), by making a fixed payment \( S_t^{i,j} \) (the premium leg) at times \( T_{i+1}, \ldots, T_j \). On the other hand, the issuer of the contract makes a payment \( 1 - \xi_{k+1} \) to the buyer in case default occurs at time \( T_{k+1}, k = i, \ldots, j - 1 \).

The contract is priced in terms of the swap rate \( S_t^{i,j} \) (or spread) computed by equating the values \( V^d(t, T) \) and \( V^p(t, T) \) of the protection and premium legs, and acts as a compensation that makes the deal fair to both parties. Recall that from (8.3) and see Lemma 7.3 we have

\[
S_t^{i,j} = \frac{1}{P(t, T_i, T_j)} \sum_{k=i}^{j-1} \mathbb{E} \left[ \mathbbm{1}_{(T_k, T_{k+1}]}(\tau)(1 - \xi_{k+1}) \exp \left( - \int_t^{T_{k+1}} r_s ds \right) \mid \mathcal{G}_t \right] + \frac{1}{P(t, T_i, T_j)} \sum_{k=i}^{j-1} \mathbb{E} \left[ (\mathbbm{1}_{\{T_k < \tau\}} - \mathbbm{1}_{\{T_{k+1} < \tau\}})(1 - \xi_{k+1}) \exp \left( - \int_t^{T_{k+1}} r_s ds \right) \mid \mathcal{G}_t \right] - \frac{1}{P(t, T_i, T_j)} \sum_{k=i}^{j-1} \mathbb{E} \left[ (1 - \xi_{k+1}) \left( \exp \left( - \int_t^{T_k} \lambda_s ds \right) - \exp \left( - \int_t^{T_{k+1}} \lambda_s ds \right) \right) \mid \mathcal{G}_t \right]
\]
\[
\times \exp \left( - \int_t^{T_k+1} r_s ds \right) \mid F_t \right].
\]

Estimating a deterministic failure rate

In case the rates \( r(s) \), \( \lambda(s) \) and the recovery rate \( \xi_{k+1} \) the above spread can be written as

\[
S_{i,j}^t P(t, T_i, T_j) = \mathbbm{1}_{\{\tau > t\}} \sum_{k=i}^{j-1} (1 - \xi_k) \exp \left( - \int_t^{T_k+1} r(s) ds \right) \times \left( \exp \left( - \int_t^{T_k} \lambda_s ds \right) - \exp \left( - \int_t^{T_k+1} \lambda_s ds \right) \right).
\]

Given that

\[
P(t, T_i, T_j) = \sum_{k=i}^{j-1} (T_{k+1} - T_k) P(t, T_{k+1}), \quad t \in [T_i, T_j],
\]

we can write

\[
S_{i,j}^t \sum_{k=i}^{j-1} (T_{k+1} - T_k) \exp \left( - \int_t^{T_k+1} (r(s) + \lambda(s)) ds \right)
\]

\[
= \mathbbm{1}_{\{\tau > t\}} \sum_{k=i}^{j-1} (1 - \xi_k) \exp \left( - \int_t^{T_k+1} r(s) ds \right) \left( \exp \left( - \int_t^{T_k} \lambda_s ds \right) - \exp \left( - \int_t^{T_k+1} \lambda_s ds \right) \right).
\]

In particular, when \( r(t) \) and \( \lambda(t) \) are written as in (7.6) and assuming that \( \xi_k = \xi, \ k = i, \ldots, j \), we get, with \( t = T_i \) and writing \( \delta_k = T_{k+1} - T_k, \ k = i, \ldots, j - 1 \),

\[
S_{i,j}^t \sum_{k=i}^{j-1} \delta_{k+1} \exp \left( - \sum_{p=i}^{k} \delta_p (r_p + \lambda_p) \right)
\]

\[
= \mathbbm{1}_{\{\tau > t\}} (1 - \xi) \sum_{k=i}^{j-1} \exp \left( - \sum_{p=i}^{k} \delta_p (r_p + \lambda_p) \right) (1 - \exp(-\delta_k \lambda_k)).
\]

Assuming further that \( \lambda_k = \lambda, \ k = i, \ldots, j \), we have

\[
S_{i,j}^t \sum_{k=i}^{j-1} \delta_k \exp \left( - \sum_{p=i}^{k} \delta_p r_p - \lambda \sum_{p=i}^{k} \delta_p \right)
\]

\[
= \mathbbm{1}_{\{\tau > t\}} (1 - \xi) \sum_{k=i}^{j-1} \exp \left( - \sum_{p=i}^{k} \delta_p \right) (1 - \exp(-\delta_k \lambda_k)).
\]

(8.4)
Credit Valuation

\[
= (1 - \xi) \sum_{k=i}^{j-1} (1 - \exp(-\lambda \delta_k)) \exp \left( - \sum_{p=i}^{k} \delta_p r_p - \lambda \sum_{p=i}^{k} \delta_p \right),
\]

which can be solved numerically for \(\lambda\), cf. Sections 4 and 5 of Castellacci (2008) for the JP Morgan model.

Note that, as \(\lambda\) tends to \(\infty\), the ratio

\[
\frac{S^i_j \sum_{k=i}^{j-1} \delta_k \exp \left( - \sum_{p=i}^{k} \delta_p r_p - \lambda \sum_{p=i}^{k} \delta_p \right)}{(1 - \xi) \sum_{k=i}^{j-1} (1 - e^{-\lambda \delta_k}) \exp \left( - \sum_{p=i}^{k} \delta_p r_p - \lambda \sum_{p=i}^{k} \delta_p \right)}
\]

converges to \(S^i_j \delta_k / (1 - \xi) \leq 1\), while it tends to \(+\infty\) as \(\lambda\) goes to 0. Therefore the equation (8.4) admits a numerical solution as we normally have \(S^i_j \delta_k / (1 - \xi) \leq 1\) under standard market conditions.

### 8.2 Collateralized Debt Obligations (CDO)

Consider a portfolio consisting of \(N = j - i\) bonds with default times \(\tau_k \in (T_k, T_{k+1}]\), \(k = i, \ldots, j - 1\), and recovery rates \(\xi_k \in [0, 1]\), \(k = i + 1, \ldots, j\).

A synthetic CDO is a structured investment product constructed by splitting the above portfolio into \(n\) ordered tranches numbered \(i = 1, 2, \ldots, n\), where tranche \(n^0 i\) represents a percentage \(p_i\%\) of the total portfolio value. We let

\[
\alpha_l = p_1 + p_2 + \cdots + p_l, \quad l = 1, 2, \ldots, n,
\]

with \(\alpha_n = p_1 + p_2 + \cdots + p_n = 100\%\) and \(\alpha_0 = 0\).

The tranches are ordered according to increasing default risk, tranche \(n^0 1\) being the riskiest one (“equity tranche”), and tranche \(n^0 n\) being the safest one (“senior tranche”), while the intermediate tranches are referred to as “mezzanine tranches”. In practice losses occur first to the “equity” tranches, next to the “mezzanine” tranche holders, and finally to “senior” tranches.
CDOs can attract different types of investors.

- Unfunded investors (usually for the higher tranches) are receiving premiums and make payments in case of default.
- Funded investors (usually in the lower tranches) are investing in risky bonds to receive principal payments at maturity, and they are the first in line to incur losses.
- A CDO can also be used as a Credit Default Swap (CDS) for the “short investors” who make premium payments in exchange for credit protection in case of default.

The market for synthetic CDOs has been significantly reduced since the 2006-2008 subprime crisis.

Synthetic CDOs are based on $N = j - i$ bonds that can potentially generate a cumulative loss

$$L_t := \sum_{l=i}^{j-1} (1 - \xi_{l+1}) \mathbb{1}_{\{\tau_l \leq t\}} \in [0, N],$$

at time $t \in [T_i, T_j]$, based on the default time $\tau_l$ and recovery rate $\xi_{l+1}$ of each involved CDS, $k = i, \ldots, j - 1$, with $N = j - i$.

When the first loss occurs, tranche $n^1$ is the first in line, and it loses the amount

$$L^1_t = L_t \mathbb{1}_{\{L_t \leq p_1 N\}} + Np_1 \mathbb{1}_{\{L_t > p_1 N\}} = N \min(L_t / N, p_1).$$

In case $L_t > p_1 N$, then tranche $n^2$ takes the remaining loss up to the amount $Np_2$, that means the loss $L^2_t$ of tranche $n^2$ is

$$L^2_t = (L_t - Np_1) \mathbb{1}_{\{p_1 N < L_t \leq (p_1 + p_2) N\}} + Np_2 \mathbb{1}_{\{L_t > (p_1 + p_2) N\}}$$

$$= (L_t - Np_1) \mathbb{1}_{\{p_1 N < L_t \leq \alpha_2 N\}} + Np_2 \mathbb{1}_{\{L_t > \alpha_2 N\}}$$
Credit Valuation

\[
(L_t - Np_1)^+ \mathbb{1}_{\{L_t \leq \alpha_2 N\}} + Np_2 \mathbb{1}_{\{L_t > \alpha_2 N\}}
= \min((L_t - Np_1)^+, Np_2)
= \max(\min(L_t, Np_1 + Np_2) - Np_1, 0)
= \max(\min(L_t, N\alpha_2) - Np_1, 0).
\]

By induction, the potential loss taken by tranche \(n^{\circ}i\) is given by

\[
L^i_t = (L_t - N\alpha_{i-1})^+ \mathbb{1}_{\{ \alpha_{i-1} N < L_t \leq \alpha_i N \}} + Np_i \mathbb{1}_{\{L_t > \alpha_i N\}}
= \min((L_t - N\alpha_{i-1})^+, Np_i)
= \max(\min(L_t, N\alpha_i) - N\alpha_{i-1}, 0),
\]

with \(\alpha_i = p_1 + p_2 + \cdots + p_i, i = 1, 2, \ldots, n\).

In the end, tranche \(n^{\circ}n\) will take the loss

\[
L^n_t = (L_t - N\alpha_{n-1})^+ \mathbb{1}_{\{ \alpha_{n-1} N < L_t \}} = (L_t - N\alpha_{n-1})^+.
\]

Fig. 8.2: A Titanic-style representation of cumulative tranche losses.

The CDO tranche \(n^{\circ}l, l = 1, 2, \ldots, n\), can be decomposed into:

- A premium leg: the short investor in tranche \(n^{\circ}l\) is purchasing protection at time \(t\) against default at time \(T_k, k = i + 1, \ldots, j\), by making fixed payments \(S^l_{i,j}\) at times \(T_{i+1}, \ldots, T_j\) between \(t\) and \(T\) in compensation. This premium can also be received by the unfunded investor.

The discounted value at time \(t\) of the premium leg for the tranche \(n^{\circ}l\) is

\[
V^p_l(t, T) = \mathbb{E} \left[ \sum_{k=i}^{j-1} S_{i,k} \delta_{k}(Np_l - L^l_{T_{k+1}}) \exp \left( - \int_{t}^{T_{k+1}} r_s ds \right) \bigg| G_t \right]
\]

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The spread which yields

\[ S_l^j = \sum_{k=i}^{j-1} \delta_k \mathbb{E} \left[ (Np_l - L^l_{T_{k+1}}) \exp \left( - \int_t^{T_{k+1}} r_s ds \right) \bigg| \mathcal{G}_t \right] (8.5) \]

\( l = 1, 2, \ldots, N, \) where the premium spread \( S_l^j \) is quoted as a proportion of the compensation \( Np_l - L^l_{T_{k+1}} \) and paid at each time \( T_{k+1} \) until \( k = j - 1 \) or \( L^l_{T_{k+1}} = 100\% \), whichever comes first, with \( \delta_k = T_{k+1} - T_k, \)

\( k = i, \ldots, j - 1. \)

- A protection leg: the short investor receives protection against default from the premium leg, which can also be paid by the unfunded investors. Noting that at each default time \( \tau_k \in (T_k, T_{k+1}] , \) \( k = i, \ldots, j - 1, \) the loss \( L^l_{T_k} \) taken by tranche \( n^o l \) jumps by the amount \( \Delta L^l_{T_k} = L^l_{T_k} - L^l_{T_{j-1}}, \) the value at time \( t \) of the protection leg is

\[ V_l^p(t, T) = \mathbb{E} \left[ \sum_{k=i}^{j-1} \mathbb{1}_{[T_k, T_{j}]}(\tau_k) \Delta L^l_{T_k} \exp \left( - \int_t^{\tau_k} r_u du \right) \bigg| \mathcal{G}_t \right] \]

\[ = \mathbb{E} \left[ \int_{T_i}^{T_j} \exp \left( - \int_t^s r_u du \right) dL^l_s \bigg| \mathcal{G}_t \right] \]

\[ = \mathbb{E} \left[ \exp \left( - \int_t^{T_j} r_u du \right) L^l_{T_j} - \exp \left( - \int_t^{T_i} r_u du \right) L^l_{T_i} \bigg| \mathcal{G}_t \right] \]

\[ + \mathbb{E} \left[ \int_{T_i}^{T_j} r_u \exp \left( - \int_t^s r_u du \right) L^l_s ds \bigg| \mathcal{G}_t \right] \]

\[ = \mathbb{E} \left[ \exp \left( - \int_t^{T_j} r_u du \right) L^l_{T_j} \bigg| \mathcal{G}_t \right] + \mathbb{E} \left[ \int_{T_i}^{T_j} r_u \exp \left( - \int_t^s r_u du \right) L^l_s ds \bigg| \mathcal{G}_t \right], \]

where we applied integration by parts on \( [T_i, T_j] \) and used the fact that \( L^l_{T_i} = 0. \)

The spread \( S_l^j \) paid by tranche \( n^o l \) is computed by equating the values \( V_l^p(t, T) = V_l^d(t, T) \) of the protection and premium legs in (8.5) and (8.6), which yields

\[ S_l^j = \frac{\mathbb{E} \left[ \int_{T_i}^{T_j} \exp \left( - \int_t^s r_u du \right) dL^l_s \bigg| \mathcal{G}_t \right]}{\sum_{k=i}^{j-1} \delta_k \mathbb{E} \left[ (Np_l - L^l_{T_{k+1}}) \exp \left( - \int_t^{T_{k+1}} r_s ds \right) \bigg| \mathcal{G}_t \right]} \]

\[ = \frac{\mathbb{E} \left[ \exp \left( - \int_t^{T_j} r_u du \right) L^l_{T_j} \bigg| \mathcal{G}_t \right] + \mathbb{E} \left[ \int_{T_i}^{T_j} r_u \exp \left( - \int_t^s r_u du \right) L^l_s ds \bigg| \mathcal{G}_t \right]}{\sum_{k=i}^{j-1} \delta_k \mathbb{E} \left[ (Np_l - L^l_{T_{k+1}}) \exp \left( - \int_t^{T_{k+1}} r_s ds \right) \bigg| \mathcal{G}_t \right]} \]

\[ \geq 0, \]

\( l = 1, 2, \ldots, n. \)
Expected tranche loss

The expected cumulative loss can be computed by linearity as

\[
\mathbb{E}[L_t | M = m] = \sum_{l=i}^{j-1} \mathbb{E} \left[ (1 - \xi_{l+1}) \mathbb{1}_{\{\tau_l \leq t\}} | M = m \right]
\]

\[
= \sum_{l=i}^{j-1} (1 - \xi_{l+1}) \mathbb{P}(\tau_l \leq t | M = m)
\]

\[
= \sum_{l=i}^{j-1} (1 - \xi_{l+1}) \Phi \left( \frac{\Phi^{-1}(\mathbb{P}(\tau_l \leq t)) + a_km}{\sqrt{1 - a_k^2}} \right),
\]

by (6.5), and the expected cumulative loss can be written as

\[
\mathbb{E}[L_t] = \int_{-\infty}^{\infty} \mathbb{E}[L_t | M = m] \phi(m) dm = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \mathbb{E}[L_t | M = m] e^{-m^2/2} dm.
\]

The situation is different for the expected loss of tranche \(n^\circ k\) is written as the expected value

\[
\mathbb{E}[L_t^k] = \mathbb{E} \left[ \min((L_t - N\alpha_{k-1})^+, Np_k) \right], \quad k = 1, 2, \ldots, n.
\]

of the nonlinear function \(f_k(x) := \min((x - N\alpha_{k-1})^+, Np_k)\) of \(L_t\).

The expected tranche loss \(\mathbb{E}[L_t^k] \ n^\circ k\ can be estimated by the Monte Carlo method when the default times are generated according to (6.8).

In order to compute expected tranche losses we can use the fact that the cumulative loss \(L_t\) is a discrete random variable, with for example
\[
P\left(L_t = N - \sum_{k=i}^{j-1} \xi_{k+1}\right) = P(\tau_i \leq t, \ldots, \tau_{j-1} \leq t),
\]
and
\[
P(L_t = 0) = P(\tau_i > t, \ldots, \tau_{j-1} > t),
\]
which require the knowledge of the joint distribution of the default times \(\tau_i, \ldots, \tau_{j-1}\).

If the \(\tau_k's\) are independent and identically distributed with common cumulative distribution function \(F_\tau\) and \(a_k = a, \xi_k = \xi, k = i+1, \ldots, j\), then the cumulative loss \(L_t\) has a binomial distribution given \(M\), given by
\[
P(L_t = (1 - \xi)k \mid M) = \binom{N}{k} (1 - P(\tau \leq T \mid M))^{N-k}(P(\tau \leq T \mid M))^k
\]
\[
= \binom{N}{k} \left(1 - \Phi\left(\frac{\Phi^{-1}(F_\tau(T)) - aM}{\sqrt{1-a^2}}\right)\right)^{N-k} \left(\Phi\left(\frac{\Phi^{-1}(F_\tau(T)) - aM}{\sqrt{1-a^2}}\right)\right)^k,
\]
k = 0, 1, \ldots, N. The expected loss of tranche \(n^k\) can then be expressed as
\[
E[L_t^k] = \int_{-\infty}^{\infty} E[f_k(L_t) \mid M = m] \phi(m)dm
\]
\[
= \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} E[f_k(L_t) \mid M = m] e^{-m^2/2} dm,
\]
k = 1, 2, \ldots, n, where \(E[f_k(L_t) \mid M = m]\) is computed either by the Monte Carlo method, from the distribution of \(L_t\).

In Vašiček (01 Dec 2002), the tranche loss has been approximated by a Gaussian random variable for very large portfolios with \(N \to \infty\).

The \(\alpha\)-percentile loss of the portfolio can be estimated as
\[
E[L_t \mid M = m] = \sum_{k=i}^{j-1} (1 - \xi_{k+1}) \Phi\left(\frac{\Phi^{-1}(P(\tau_k \leq T)) - a_k\Phi^{-1}(\alpha)}{\sqrt{1-a_k^2}}\right),
\]
where \(m = \Phi^{-1}(\alpha)\).

Such (Gaussian) Merton Merton (1974) and Vasiccek Vašiček (01 Dec 2002) type models have been implemented in the Basel II recommendations on Banking Supervision (2005). Namely in Basel II, banks are expected to hold capital in prevision of unexpected losses in a worst case scenario, according to the Internal Ratings-Based (IRB) formula.
Credit Valuation

\[
j^{-1} \sum_{k=i} (1 - \xi_{k+1}) \left( \Phi \left( \Phi^{-1}\left(\mathbb{P}(\tau_k \leq T)\right) - a_k \Phi^{-1}(\alpha) \right) \right) - \mathbb{P}(\tau_k \leq T),
\]

where the confidence level is set at \( \alpha = 0.999 \) i.e. \( m = \Phi^{-1}(0.999) = 3.09 \), cf. Relation (2.4) page 10 of Aas (2005). Recall that the function

\[ x \mapsto \Phi \left( \frac{\Phi^{-1}(x) + a_k \Phi^{-1}(\alpha)}{\sqrt{1 - a_k^2}} \right) \]

always lies above the graph of \( x \) when \( a_k < 0 \), as in the next figure.

![Figure 8.4: Internal Ratings-Based formula.](https://www.ntu.edu.sg/home/nprivault/indext.html)

### 8.3 Credit Valuation Adjustment (CVA)

Credit Valuation Adjustments (CVA) aim at estimating the amount of capital required in the event of counterparty default, and are specially relevant to the Basel III regulatory framework. Other credit value adjustments (XVA) include the DVA, FVA, KVA, and MVA. The purpose of XVAs is also to take into account the future value of trades and their associated risks. The real-time estimation of XVA measures is generally highly demanding from a computational point of view.

**Net Present Value (NPV) of a CDS**

We work with a tenor structure \( \{t = T_i < \cdots < T_j = T\} \). Let

\[
\Pi(T_i, T_j) := \text{protectionleg} - \text{premiumleg} = V^d(t, T) - V^p(t, T),
\]

denote the difference between the remaining protection and premium legs from time \( T_i \) until time \( T_j \), where the values \( V^d(t, T) \) and \( V^p(t, T) \) of the premium and protection legs are given by (8.1) and (8.2). We have
\[ \Pi(T_l, T_j) := \text{protection - premium} \]
\[ = \mathbb{E} \left[ \sum_{k=l}^{j-1} \mathbb{1}_{(T_k, T_{k+1})}(\tau)(1 - \xi_{k+1}) \exp \left( - \int_t^{T_{k+1}} r_s ds \right) \mid \mathcal{G}_{T_l} \right] \]
\[ - \mathbb{E} \left[ \sum_{k=l}^{j-1} S^{i,j}_t \delta_k \mathbb{1}_{\{\tau > T_{k+1}\}} \exp \left( - \int_t^{T_{k+1}} r_s ds \right) \mid \mathcal{G}_{T_l} \right] \]
\[ = (1 - \xi) \mathbb{E} \left[ \sum_{k=l}^{j-1} \mathbb{1}_{(T_k, T_{k+1})}(\tau) \exp \left( - \int_t^{T_{k+1}} r_s ds \right) \mid \mathcal{G}_{T_l} \right] \]
\[ - \mathbb{E} \left[ \sum_{k=l}^{j-1} S^{i,j}_t \delta_k \mathbb{1}_{\{\tau > T_{k+1}\}} \exp \left( - \int_t^{T_{k+1}} r_s ds \right) \mid \mathcal{G}_{T_l} \right] \]
\[ = \mathbb{E} \left[ \sum_{k=l}^{j-1} \left( (1 - \xi) \mathbb{1}_{(T_k, T_{k+1})}(\tau) \exp \left( - \int_t^{T_{k+1}} r_s ds \right) \right. \right. \]
\[ \left. \left. - \delta_k \mathbb{1}_{\{\tau > T_{k+1}\}} \exp \left( - \int_t^{T_{k+1}} r_s ds \right) \right) \mid \mathcal{G}_{T_l} \right] \]

Note that we have \( \Pi(t, T_j) = 0 \) by definition of the spread \( S^{i,j}_t \).

The Net Present Value (NPV) at time \( T_l \) of the CDS is the conditional expected value

\[ \text{NPV}(T_l, T_j) := \mathbb{E} \left[ \Pi(T_l, T_j) \mid \mathcal{G}_{T_l} \right] \]
\[ = \mathbb{E} \left[ \sum_{k=l}^{j-1} \mathbb{1}_{(T_k, T_{k+1})}(\tau)(1 - \xi_{k+1}) \exp \left( - \int_t^{T_{k+1}} r_s ds \right) \mid \mathcal{G}_{T_l} \right] \]
\[ - \mathbb{E} \left[ \sum_{k=l}^{j-1} S^{i,j}_t \delta_k \mathbb{1}_{\{\tau > T_{k+1}\}} \exp \left( - \int_t^{T_{k+1}} r_s ds \right) \mid \mathcal{G}_{T_l} \right] \]
\[ = (1 - \xi) \sum_{k=l}^{j-1} \mathbb{E} \left[ \mathbb{1}_{(T_k, T_{k+1})}(\tau) \exp \left( - \int_t^{T_{k+1}} r_s ds \right) \mid \mathcal{G}_t \right] - S^{i,j}_t \sum_{k=l}^{j-1} \delta_k P(t, T_{k+1}) \]
\[ = \sum_{k=l}^{j-1} \left( (1 - \xi) \mathbb{E} \left[ \mathbb{1}_{(T_k, T_{k+1})}(\tau) \exp \left( - \int_t^{T_{k+1}} r_s ds \right) \mid \mathcal{G}_t \right] - S^{i,j}_t \delta_k P(t, T_{k+1}) \right) \]

of the difference between the values at time \( T_l \) of the remaining protection and premium legs from time \( T_l \) until time \( T_j \).

In addition to the credit default time \( \tau \) we introduce a second stopping time \( \nu \) as the possible default time of the party providing the protection leg.
The Net Present Value $\text{NPV}(\nu, T_j)$ is estimated when default occurs at time $\nu$.

i) If $\text{NPV}(\nu, T_j) > 0$ then a payment is due from the party providing the protection leg, and only a fraction $\eta \text{NPV}(\nu, T_j)$ of this payment is recovered, where $\eta \in [0,1]$ is the recovery rate of the party providing protection in the CDS.

ii) On the other hand, if $\text{NPV}(\nu, T_j) < 0$ then the original fee payment $-\text{NPV}(\nu, T_j)$ is still due.

As a consequence, in the event of default at time $\nu$, the net present value of the CDS at time $\nu$ is

$$
\eta \text{NPV}(\nu, T_j) \mathbb{1}_{\{\text{NPV}(\nu, T_j) > 0\}} + \text{NPV}(\nu, T_j) \mathbb{1}_{\{\text{NPV}(\nu, T_j) < 0\}}
$$

$$
= \eta (\text{NPV}(\nu, T_j))^+ - (\text{NPV}(\nu, T_j))^-
$$

$$
= \eta (\text{NPV}(\nu, T_j))^+ - (- \text{NPV}(\nu, T_j))^+
$$

$$
= \eta (\text{NPV}(\nu, T_j))^+ + (\text{NPV}(\nu, T_j) - (\text{NPV}(\nu, T_j))^+)
$$

$$
= \text{NPV}(\nu, T_j) - (1 - \eta)(\text{NPV}(\nu, T_j))^+. 
$$

(8.8)

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After discounting the cash flow (8.8) from time $T_j$ to time $\nu$, we find that the total payoff from time $t$ to time $T_j$ in the event of default at time $\nu < T_j$ is

$$
\Pi(T_t, \nu) + \exp\left(-\int_T^\nu r_s ds\right) \left(\eta (\text{NPV}(\nu, T_j))^+ - (- \text{NPV}(\nu, T_j))^+\right)
$$

$$
= \Pi(T_t, \nu) + \exp\left(-\int_T^\nu r_s ds\right) \left(\text{NPV}(\nu, T_j) - (1 - \eta)(\text{NPV}(\nu, T_j))^+\right)
$$

$$
= \Pi(T_t, T_j) - (1 - \eta) \exp\left(-\int_T^\nu r_s ds\right) (\text{NPV}(\nu, T_j))^+,
$$

since

$$
\Pi(T_t, T_j) = \Pi(T_t, \nu) + \exp\left(-\int_T^\nu r_s ds\right) \text{NPV}(\nu, T_j).
$$

More generally, the total payoff from time $t$ to time $T_j$ under counterparty risk is given as

$$
\Pi^D(T_t, T_j) = \mathbb{1}_{\{T_j < \nu\}} \Pi(T_t, T_j)
$$

$$
+ \mathbb{1}_{\{T_t < \nu \leq T_j\}} \left( \Pi(T_t, \nu) + \exp\left(-\int_T^\nu r_s ds\right) \left(\eta (\text{NPV}(\nu, T_j))^+ - (- \text{NPV}(\nu, T_j))^+\right) \right)
$$

$$
= \mathbb{1}_{\{T_j < \nu\}} \Pi(T_t, T_j)
$$
\[ + \mathbb{1}_{\{T_l < \nu \leq T_j\}} \left( \Pi(T_l, T_j) - (1 - \eta) \exp \left( - \int_{T_l}^{\nu} r_s ds \right) (\text{NPV}(\nu, T_j))^+ \right) \]

\[ = \Pi(T_l, T_j) - \mathbb{1}_{\{T_l < \nu \leq T_j\}} (1 - \eta) \exp \left( - \int_{T_l}^{\nu} r_s ds \right) (\text{NPV}(\nu, T_j))^+ , \quad (8.9) \]

cf. Brigo and Chourdakis (2009), Brigo and Masetti (2006). As a consequence of (8.9), we derive the following result.

**Proposition 8.1.** The price at time \( T_l \) of the payoff \( \Pi^D(T_l, T_j) \) under counterparty risk is given by

\[
\mathbb{E} \left[ \Pi^D(T_l, T_j) \mid \mathcal{F}_{T_l} \right] = \mathbb{E} \left[ \Pi(T_l, T_j) \mid \mathcal{F}_{T_l} \right] - (1 - \eta) \mathbb{E} \left[ \mathbb{1}_{\{T_l < \nu \leq T_j\}} \exp \left( - \int_{T_l}^{\nu} r_s ds \right) (\text{NPV}(\nu, T_j))^+ \mid \mathcal{F}_{T_l} \right].
\]

The quantity

\[
(1 - \eta) \mathbb{E} \left[ \mathbb{1}_{\{T_l < \nu \leq T_j\}} \exp \left( - \int_{T_l}^{\nu} r_s ds \right) (\text{NPV}(\nu, T_j))^+ \mid \mathcal{F}_{T_l} \right]
\]

is called the (positive) Counterparty Risk (CR) Credit Valuation Adjustment (CVA).

**Exercises**

Exercise 8.1 Credit default swaps. Estimate the first default rate \( \lambda_1 \) and the associated default probability in the framework of (8.4), based on CDS market data, cf. also Castellacci (2008).

Exercise 8.2 We work with a tenor structure \( \{ t = T_i < \cdots < T_j = T \} \). Let

\[
\sum_{k=i}^{j-1} \mathbb{E} \left[ \mathbb{1}_{\{T_k, T_{k+1}\}}(\tau)(1 - \xi_{k+1}) \exp \left( - \int_{T_k}^{T_{k+1}} r_s ds \right) \mid \mathcal{G}_t \right]
\]

\[
= \sum_{k=i}^{j-1} \mathbb{E} \left[ \left( \mathbb{1}_{\{T_k < \tau\}} - \mathbb{1}_{\{T_{k+1} < \tau\}} \right)(1 - \xi_{k+1}) \exp \left( - \int_t^{T_{k+1}} r_s ds \right) \mid \mathcal{G}_t \right]
\]

\[
= \mathbb{1}_{\{\tau > t\}} \sum_{k=i}^{j-1} \mathbb{E} \left[ (1 - \xi_{k+1}) \left( e^{-\int_t^{T_k} \lambda_s ds} - e^{-\int_t^{T_{k+1}} \lambda_s ds} \right) e^{-\int_t^{T_{k+1}} r_s ds} \mid \mathcal{F}_t \right]
\]

\[
= \mathbb{1}_{\{\tau > t\}} (1 - \xi) \sum_{k=i}^{j-1} e^{-\int_t^{T_k} \lambda_s ds} \mathbb{E} \left[ e^{-\int_t^{T_k} \lambda_s ds} - e^{-\int_t^{T_{k+1}} \lambda_s ds} \mid \mathcal{F}_t \right]
\]

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\[ \mathbb{1}_{\{\tau > t\}} (1 - \xi) \sum_{k=i}^{j-1} P(t, T_{k+1}) (Q(t, T_k) - Q(t, T_{k+1})) , \]

denote the discounted value at time \( t \) of the protection leg, where

\[ P(t, T_k) = \exp \left( - \int_t^{T_k} r_s ds \right) = e^{-r_k(T_k-t)}, \quad k = i, \ldots, j, \]

is a deterministic discount factor, and

\[ Q(t, T_k) = \mathbb{E} \left[ \exp \left( - \int_t^{T_k} \lambda_s ds \right) \bigg| \mathcal{F}_t \right] \]

is the survival probability. Let

\[ VP(t, T) = S_t^{i,j} \sum_{k=i}^{j-1} \delta_k \mathbb{E} \left[ \mathbb{1}_{\{\tau > T_{k+1}\}} \exp \left( - \int_t^{T_{k+1}} r_s ds \right) \bigg| \mathcal{G}_t \right] \]

\[ = S_t^{i,j} \sum_{k=i}^{j-1} \delta_k \mathbb{E} \left[ \mathbb{1}_{\{T_{k+1} < \tau\}} \exp \left( - \int_t^{T_{k+1}} r_s ds \right) \bigg| \mathcal{G}_t \right] \]

\[ = 1_{\{\tau > t\}} S_t^{i,j} \sum_{k=i}^{j-1} \delta_k \mathbb{E} \left[ \exp \left( - \int_t^{T_{k+1}} \lambda_s ds \right) \exp \left( - \int_t^{T_{k+1}} r_s ds \right) \bigg| \mathcal{F}_t \right] \]

\[ = 1_{\{\tau > t\}} S_t^{i,j} \sum_{k=i}^{j-1} \delta_k P(t, T_{k+1}) Q(t, T_{k+1}), \]

denote the discounted value at time \( t \) of the premium leg, where \( \delta_k := T_{k+1} - T_k, \quad k = i, \ldots, j - 1. \)

a) By equating the protection and premium legs, find the value of \( Q(t, T_{i+1}) \) with \( Q(t, T_i) = 1 \), and derive a recurrence relation between \( Q(t, T_{j+1}) \) and \( Q(t, T_i), \ldots, Q(t, T_j) \).

b) For a given underlying asset, retrieve the corresponding CDS spreads \( S_t^{i,j} \) and discount factors \( P(t, T_i), \ldots, P(t, T_n) \), and estimate the corresponding survival probabilities \( Q(t, T_i), \ldots, Q(t, T_n) \).