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TREASURY AND CAPITAL MARKETS:
PRICING AND RISK METRICS GUIDE

LINEAR INTEREST RATE SERIES

Part 3: Multicurrency CSAs

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CONTENTS

EXECUTIVE SUMMARY

Financial markets have changed considerably since the global financial crisis in 2008, with regulatory reform and structural changes to the derivative market. This has resulted in increased collateralization of trades and a move to centralized clearing of vanilla trades in order to mitigate counter-party default risk. This has brought about dramatic changes in how derivatives are fundamentally priced, with collateral choices having an impact on the discounting curves used in derivative valuations.

Multicurrency Credit Support Annex's (CSAs) allow the collateral poster to choose collateral from a list of eligible currencies and securities. Each of these different currencies and types of collateral will have a different impact on derivative valuation. Given that each CSA is unique, there is a lack of transparency in the market around the valuation of multicurrency CSAs. It is common to see valuation discrepancies between counterparties, even for quite simple trades.

We hope you find this paper useful for better understanding the optionality on multicurrency CSAs. For more information on how we can help with your risk management, please contact us at capitalmarkets@finastra.com or visit us at finastra.com.

Cheapest to Deliver (CTD) Collateral Optionality

> "While in some jurisdictions there is no optionality on the posting of collateral, in others there is standard practice – e.g. Europe – so having a robust valuation method is paramount."

Pedro Porfirio
Global Head of Treasury and Capital Markets, Finastra

The purpose of this paper is to explain the nature of optionality on multicurrency CSAs, the various mathematical methods of valuation for this optionality in the dealer street and the relative advantages/disadvantages of each of these approaches.

For ease of exposition, let us consider a multicurrency CSA with cash collateral only. The choice of which currency collateral to post affects the return received on the posted collateral. A rational collateral poster would always post cash in the highest-yielding currency, which could vary over the life of the trade. This would yield the highest rate of return on posted collateral and is known as the cheapest to deliver collateral option. The highest-yielding cash collateral is obtained by comparing the yields in other currencies after converting them to a common base currency (having adjusted for cross-currency basis swap spreads).
The decision as to the optimal currency to post is dynamic and is a function of market at any point in time.

A key issue to consider is collateral substitutability. There are CSAs where collateral cannot be substituted because the collateral optionality is worthless. There are other CSAs where collateral can only be substituted with the consent of the other counterparty. This has less optionality but there is still a benefit to the collateral poster of posting the highest yielding collateral. There are two distinct cases to be considered here: i) Positive MTM reduces and the collateral giver may request that specific assets are to be returned; ii) Negative MTM becomes more negative, in which case outright collateral must be posted and there is explicit collateral optionality to be considered here.

It is important that a bank has systems in place to be able to monetize the cheapest to deliver option by identifying the cheapest to deliver option at any point in time.

Understanding Cheapest to Deliver Optionality at Intrinsic Value

The simplest approach for valuing collateral optionality is to assume the current OIS forwards and cross- currency basis forwards will be realized, and hence build a blended curve (called the "CTD curve") by taking the maximum forward rate amongst the deliverable set on each date over the life of the trade. This makes sense in that it emulates the collateral posting strategy that maximizes the rate of return on collateral to the collateral poster at each future discretized period. This approach values collateral optionality at intrinsic value and systematically underestimates collateral optionality (due to attaching zero value to the time value associated to the collateral switch option).

In the discussion below, we will make the following assumptions:

a. Interest rates are deterministic and hence no model for the evolution of the yield curve will be used
b. Bilateral CSA is in place which means that either counterparty could be asked to post collateral
c. Only cash collateral can be posted
d. No transaction costs
e. Zero Threshold and Zero Minimum Transfer Amount on the CSA (hence we have perfect collateralization)
f. Multiple cash currencies can be posted as collateral which may be different to the underlying transaction payment currency

The following are the steps to producing an intrinsic value CTD curve:

1. Select the time step width for the yield curve. e.g. quarterly

2a. Collateral posted in currency XXX is remunerated at OIS_{XXX}, which translates using the XXXUSD cross currency basis into a synthetic USD rate at a future time period t_i:

$$OIS_{USD}^{XXX}(t_i, t_{i+1}) = OIS_{XXX}(t_i, t_{i+1}) + XCCY\ Basis_{XXXUSD}(t_i, t_{i+1})$$ [1]

where:

$OIS_{XXX}(t_i, t_{i+1})$ = Forward OIS in currency XXX for fixing at t_i and maturity t_{i+1}

$XCCY\ Basis_{XXXUSD}(t_i, t_{i+1})$ = Forward OIS in currency XXX for fixing at t_i and maturity t_{i+1}. This can be inferred from a piecewise constant cross-currency basis curve which is calibrated to market quotes of spot starting cross currency basis swaps.

$OIS_{XXX}(t_i, t_{i+1})$ = Synthetic Forward OIS in currency USD for fixing at t_i and maturity t_{i+1}.

The poster of collateral would want to choose a currency XXX that has the highest equivalent synthetic USD rate and is the cheapest to deliver collateral. The calculation above is performed for each collateral currency XXX and for each distinct future time period t_i.

2b. At any future time point, one can switch from one collateral cash currency to another. The optimal choice will depend on the OIS_{XXX} and $XCCY\ Basis_{XXX/USD}$ rates at that future time point and for each currency XXX. Hence, the collateral option time value is a function of OIS_{XXX} volatility and the $XCCY\ Basis_{XXX/USD}$ volatility.

3. Under the assumption of zero cross-currency basis volatility and zero OIS volatility, the CTD forward rate at future time period t_i:

$$OIS_{USD}^{CTD}(t_i, t_{i+1}) = \underset{\{XXX\}}{MAX}[OIS_{USD}^{XXX}(t_i, t_{i+1})]$$ [2]

The calculation above is performed for each future time period $[t_i, t_{i+1}]$. Hence the CTD function OIS_{USD}^{CTD} is piecewise constant on each interval $[t_i, t_{i+1}]$.

1. Masaaki Fujii, Yasufumi Shimada , Akihiko Takahashi; A Note on the Construction of Multiple Swap Curves with and without Collateral; FSA Research Review Vol.6 (March 2010).
2. Vladimir Sankovich, Qinghua Zhu; Collateral option valuation made easy; Risk.Net October 2015.

4. The CTD discount curve is given by the following:

$$DF_{USD}^{CTD}(T) = \exp\left\{-\left(\prod_{i=0}^{N-1}\left(1 + OIS_{USD}^{CTD}(t_i, t_{i+1})\right)\right)\right\}$$ [3]

where:

$DF_{USD}^{CTD}(T)$ = CTD discount rate in USD to future time T.
$OIS_{USD}^{CTD}(t_i, t_{i+1})$ = CTD rate in USD for the interval $[t_i, t_{i+1}]$.
N-1 = number of time steps in the CTD algorithm up to future time T.

5. There are a number of practical considerations to be noted here. $XCCY\ Basis_{XXXUSD}$ is the cross-currency basis spread on OIS vs. OIS cross currency swaps, which are not quoted in the market. The Libor vs Libor cross- currency basis swaps are quoted in the market. In order to obtain the OIS vs OIS cross-currency swap you would need to adjust the Libor vs. Libor cross-currency basis spreads by the OIS vs. Libor basis in each currency. In practice, this means that you need to bootstrap your OIS and Libor curves simultaneously (so called "dual bootstrapping") and then you bootstrap the forward $XCCY\ Basis_{XXXUSD}$ curves.

The key advantage of the intrinsic value approach for CTD collateral is that its simplicity means calculation is easy and also numerically very fast. As a result, this was the approach followed by most banks initially post 2008 as this valuation issue caught the attention of market practitioners.

The key disadvantages of the intrinsic value approach for CTD collateral are: a) This approach consistently underestimates the value of the long collateral switch value as the time value is marked at zero. The value of the time value on the switch option in major banks' trading books today can be significant. b) There may be erratic changes in the model implied risk as changes in the cross-currency market and OIS levels move. This in turn forces changes in the cheapest to deliver collateral currency across the term structure. The instability of hedges led practitioners to start considering recognizing the time value of the switch option in valuations. c) Risk number will not be accurate.

From a practical standpoint, all trades that should be discounted using this blended CTD curve should be appropriately tagged and associated within trade bookings to this blended CTD curve.

3. Vladimir Piterbarg; Cooking with Collateral Risk; Risk (August 2012); p58-63.

Valuing Cheapest to Deliver Optionality at Full Option Value

Mathematically, the exact calculation of the CTD discount factor to t involves evaluating the following expectation:

$$DF_{CTD}(t) = E[\exp\left(-\int_0^t max_{i=1,2\ldots N}(r_i(s))ds\right)]$$ [4]

where:

$DF_{CTD}(t)$ = cheapest to deliver collateral curve discount rate to future time t.
$r_i(s)$ = instantaneous short rate of cross-currency basis swap adjusted funding rate in collateral currency i at future time s.
N = number of eligible collateral currencies in the basket.

The existence of a switch option introduces path dependency in the calculation of CTD discount factors. An idea is to evaluate this expectation by jointly simulating the funding rates of each eligible collateral currency within the basket under a certain distributional assumption and having calibrated the model parameters to some market observable prices (if any). This approach suffers from the main drawback that it introduces a numerical-intensive scheme like Monte Carlo simulation in the construction of a discounting curve, which is numerically inefficient and makes this approach impractical. This led market practitioners to develop a number of semi-analytical approximations to evaluate the expectation in equation [4] above.

In Piterbarg (2012), the expectation in equation [4] is evaluated in the following manner:

$$DF_{CTD} \approx \exp\left(-E_o\left(\int_0^t max_{i=1,2\ldots N}(r_i(s))ds\right)\right)$$ [5]

Antonov and Piterbarg (2014) improve the result in [5] by deriving an efficient approximation based on a conditional independence approach. This approach has been tested to work well for the simple case of only two collateral switch currencies but has shown to numerically inefficient as one increases the number of possible switch currencies. The other disadvantage of the approach in [5] is that one would be unable to calibrate model parameters to liquidly traded instruments and only empirical estimation from historical time series is possible.

We advocate the semi-analytical approach for CTD valuation in Sankovich and Zhu (2015). The key model features here are:

1. The aim of this piece of work is to find a semi-analytical approximation to the integral $\int_0^t max_{i=1,2\ldots N}\, r_i(s)ds$ without resorting to a numerical intensive scheme such as Monte Carlo simulation. A natural assumption for a distributional assumption for $max_{i=1,2\ldots N}\, r_i(s)$ is a Gaussian distribution. However, one would expect the variable $max_{i=1,2\ldots N}\, r_i(s)$ to exhibit significant positive skewness. As a consequence, the authors use a quadratic function of normal random variables which captures the higher moments of the random variable $max_{i=1,2\ldots N}\, r_i(s)$.

2. The coefficients of this quadratic function are obtained using moment matching. This requires an estimation of the first three moments of the integral $\int_0^t max_{i=1,2\ldots N}\, r_i(s)ds$. The authors use the Linear Gaussian Model's (LGM) joint normal dynamics for the instantaneous funding short rates for each collateral currency. This requires a good approximation to be found for the distribution of the maximum of N normal random variables and also a good approximation for the dynamics of the maximum of N normal random variables needs to be found. This approach allows computation of the integral $\int_0^t max_{i=1,2\ldots N}\, r_i(s)ds$ analytically.

3. The LGM dynamics of each of the instantaneous funding short rates for each collateral currency are specified by:

$$dr_i(t) = K_i(t)[\theta_i(t) - r_i(t)]dt + \sigma_i(t)dW_i(t)$$ [6]

where:

$r_i(t)$ = instantaneous cross currency adjusted funding short rate for collateral currency i.
$K_i(t)$ = time dependent mean reversion of short rate for collateral currency i.
$\theta_i(t)$ = time dependent long-term short rate for collateral currency i. These parameters are chosen to match the forward cross currency adjusted OIS curves in each collateral currency i.
$\sigma_i(t)$ = time dependent cross currency adjusted funding short rate volatility for collateral currency i.

$$< dW_i, dW_j >= \rho_{ij}dt$$

ρ_{ij} = correlation between the Brownian motion driving short rate i vs short rate j.
W_i = Brownian motion under the domestic risk neutral measure of the trade being priced.

4. Antonov A and V Piterbarg; Collateral Choice Option Valuation; SSRN eLibrary.
5. Clark CE; The greatest of a finite set of random variables; Operations Research 9(2), p145-162.
6. Blinnikov S and Moessner, Expansions for nearly Gaussian distributions, Supplement Series 130, p193-205.

> It is important that a bank has systems in place to identify the cheapest to deliver option at any point of time to monetize the opportunity fully.

Pedro Porfirio
Global Head of Treasury and
Capital Markets, Finastra

4. A historically well-known method of approximating the maximum of N Gaussian random variables is detailed in Clark (1961). This method is based on the observation that the maximum of the two Gaussian random variables is known analytically. Clark's method involves choosing two variables from the set, calculating the maximum of the two variables analytically, and then the maximum of the two variables is approximated using a Gaussian random variable that matches the first two moments of the true distribution. The two original Gaussian variables are then replaced with this new approximated Gaussian random variable, which is jointly Gaussian distributed with the remaining variables in the set. This procedure is implemented in an iterative fashion until all the variables in the set have been used up.

   One of the disadvantages of Clark's approach is that the approximation of the max of two normals as another normal random variable can be relatively inaccurate, since the true distribution of the max of two normals is positively skewed. As the number of random variables in the collateral set increases, this approximation error gets larger. This led the authors to consider extending Clark's approach by incorporating the higher moments of the max of two random variables into the algorithm.

5. The authors use a well-known asymptotic expansion of any arbitrary distribution in terms of the Gaussian density and a power series weighted by the higher moments of the actual distribution known as the Gram-Charlier expansion (see Appendix A).

6. The authors have derived an approximation for the terminal distribution of N Gaussian random variables at any time $t>0$. However, due to the path dependence of the CTD option, the knowledge of these terminal distributions is not sufficient. To compute the values of the discount factors requires the knowledge followed by $X_t = \max(r_i(t))$. The first three moments of the time integral $Y_t = \int_0^t X_s ds$ are estimated and then is approximated with a quadratic function of the standard Gaussian distribution.

7. This leads to the following result for Y_t and the CTD discount factor for maturity t:

$$Y_t = \int_0^t X_s ds = a(t)z^2 + b(t)z + c(t), z \sim N(0,1) \quad [7]$$

$$DF(t) = E[\exp(-Y_t)] = \frac{\exp\left(\frac{b^2(t)}{2(1+2a(t))} - c(t)\right)}{\sqrt{1+2a(t)}} \quad [8]$$

where:

The coefficients of the quadratic form are chosen so that the first three moments of $\int_0^t X_s ds$ are matched. The coefficients a, b, c satisfy:

$4a^3 - 6va + k = 0$
$b^2 = v - 2a^2$
$c = \mu - a$
μ = mean of $\int_0^t X_s ds$
v = variance of $\int_0^t X_s ds$
k = third central moment of $\int_0^t X_s ds$

In order to have a sensible discount factor, it requires $0 < a < \sqrt{v/2}$ and hence $\frac{k}{v^{\frac{3}{2}}} < 2\sqrt{2}$. In order to make sure these conditions are satisfied the authors suggest setting $a = \sqrt{v/2}$.

8. Calibrating this model would require a liquid market in OIS volatility, cross-currency basis volatility and also the correlation between cross currency basis adjusted OIS rates. These markets do not exist and hence empirical estimation of model parameters is required. Let $f_i(t,T)$ be the instantaneous forward rate to time T of the i the cross currency adjusted funding rate. In the LGM model described in [5], the volatility of $f_i(t,T)$ is:

$$\sigma_{f_i}(t,T) = \exp\left(-\int_t^T K_i(s)ds\right)\sigma_i(t,T) \quad [9]$$

$$< df_i \,, df_j >= \rho_{i,j} dt \quad [10]$$

We can further simplify the model by assuming K_i and σ_i are constant, then $\sigma_{f_i}(t,T) \exp(-K_i(T-t))\sigma_i$. For any given $\sigma_{f_i}(t,T_1)$ and $\sigma_{f_i}(t,T_2)$ we can calculate K_i and σ_i as:

$$K_i = -\frac{ln\sigma_{f_i}(t,T_1) - ln\sigma_{f_i}(t,T_2)}{T_1 - T_2} \quad [11]$$

$$\sigma_i = e^{K_i(T_1 - t)}\sigma_{f_i}(t,T_1) \quad [12]$$

In order to estimate the $\sigma_{f_i}(t,T_1)$ and $\sigma_{f_i}(t,T_2)$, we build a cross currency adjusted OIS time series for each historical data and then compute the standard deviation of the time series of these instantaneous forward rates.

9. **The approach of Sankovich and Zhu has the main advantage of being able to compute the option-adjusted discount factors for all maturities analytically** given the empirically estimated model parameters. The authors have compared the results with analytic with Monte Carlo simulation and have found relatively close agreement. This gives credibility that the analytic model assumptions are reasonable.

APPENDIX A: GRAM-CHARLIER EXPANSION

Sankovich and Zhu show that using the characteristic function techniques (Blinnikov & Moessner 1998) it is possible to show that a distribution that is known to fall off faster than exp $(-\frac{x^2}{4})$ can be approximated by the following series:

$$G(x) \approx \frac{1}{\sqrt{2\pi v}} \exp\left(-\frac{(x-\mu)^2}{2v}\right)\left[1 + \frac{k}{3!v^{\frac{3}{2}}} H_3\left(\frac{x-\mu}{\sqrt{v}}\right)\right] \quad [1]$$

where:

μ = mean of the distribution $G(x)$
v = variance of the distribution $G(x)$
k = third cumulant of the distribution $G(x)$
$H_3(x) = x^3 - 3x$

Sankovich and Zhu use this expansion to approximate the distribution of the maximum of two (correlated) Gaussian variables, and propose the following expression for the joint density of X_1 = max (r_1, r_2) and r_3:

$$p_{X_1,r_3}(x,y) = \varphi^{(2)}_{X_1,r_3}(x,y) + \varphi_{r_3}(y)(G_{X_1}(x) - \varphi X_1(x)) \quad [2]$$

where:

φ = normal density function
φ^2(x,y) = bivariate normal density
$G_{X_1}(x)$ = Gram-Charlier adjusted density of the maximum of r_1 and r_2 as given in [1]

Knowing the moments of r_1, r_2 and r_3 and their correlation matrix, Clark (1961) shows how the exact expressions for the moments of the distribution of X_1 and the correlation between X_1 and r_3 can be derived. The authors use Clark's results to generate the joint pdf of X_1 and r_3 as given by [2]. This pdf is then used to calculate the moments of X_2 =max (X_1, r_3) which in turn will be used to generate the joint pdf of X_2 and r_4 and so on until all variables in the original set have been used up.

The authors then derive expressions for the first three moments of X_i, $i > 1$, which are given by the following integral:

$$M_i^m = E[X_i^m] = \iint \max\big(X_{i-1}(x), r_{i+1}(y)\big)^m \, p_{X_{i-1},r_{i+1}}(x,y)\,dxdy$$

Given the form of the pdf in [2] Sankovich and Zhu represent the moments M_i^m as the sum of two terms: one given by Clark's bivariate normal approximation and an adjustment induced by the Gram-Charlier expansion. Thus, for any $i > 1$ and m =1,2,3 we have M_i^m= $M_i^{m,Clark}$ + $M_i^{m,Adj}$ with the adjustment terms given by:

$$M_i^{1,Adj} = \frac{k_{X_{i-1}}}{6v_{X_{i-1}}}\big(B - \mu_{X_{i-1}}\big)C$$

$$M_i^{2,Adj} = \frac{k_{X_{i-1}}}{3v_{X_{i-1}}}\big(A^2 + B^2 - B\mu_{X_{i-1}} + v_{X_{i-1}}\big)C$$

$$M_i^{3,Adj} = \frac{k_{X_{i-1}}}{2v_{X_{i-1}}}[\big[3A^2B + B^3 - \mu_{X_{i-1}}(A^2 + B^2) + 2Bv_{X_{i-1}}\big]C + 2v_{X_{i-1}}\varphi\left(\frac{\mu_{X_{i-1}} - \mu_{r_{i+1}}}{\sqrt{v_{X_{i-1}} + v_{r_{i+1}}}}\right)$$

where:

$\mu_{r_{i+1}}$ = mean of r_{i+1}
$\mu_{X_{i-1}}$ = = mean of X_{i-1}
$v_{r_{i+1}}$ = variance of r_{i+1}
$v_{X_{i-1}}$ = variance of X_{i-1}
$k_{X_{i-1}}$ = third moment of the distribution of X_{i-1}

$$A = \sqrt{\frac{v_{X_{i-1}} v_{r_{i+1}}}{v_{X_{i-1}} + v_{r_{i+1}}}}$$

$$B = \frac{u_{X_{i-1}} v_{r_{i+1}} + \mu_{r_{i+1}} v_{X_{i-1}}}{v_{X_{i-1}} + v_{r_{i+1}}}$$

$$C = \frac{1}{\sqrt{v_{X_{i-1}} + v_{r_{i+1}}}}\varphi\left(\frac{u_{X_{i-1}} - u_{r_{i+1}}}{\sqrt{v_{X_{i-1}} + v_{r_{i+1}}}}\right)$$

$\varphi(x)$ = cumulative normal density function

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About the author

Pedro Porfirio leads the global field and customer engagement with capital markets customers and prospects. Based in London, Pedro drives the growth of the company's entire capital markets business line spanning treasury, capital markets, and investment management. Pedro joined Finastra from Calypso Technology where he worked as Chief Product Officer, and brings over 25 years' experience in banking and technology. Pedro holds an aerospace engineering degree from ITA in Brazil and an MBA from University of Michigan.

Contact: **Pedro.Porfirio@finastra.com**

Pedro Porfirio
Global Head of Treasury & Capital Markets, Finastra

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Corporate Headquarters
4 Kingdom Street
Paddington
London W2 6BD
United Kingdom
T: +44 20 3320 5000

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