Consistent pricing of Standard and Other CSAs: different accounting viewpoints

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Executive summary

1. Classic Pricing Theory
   - Interest rate ambiguities
   - Difficulties with market “basis”

2. SCSA Pricing Theory
   - Consistent mono-currency and cross-currency markets of hedges with OIS discounting
   - Offshore/Onshore basis

3. Credit and Funding Extensions
   - CVA, DVA, FVA
   - CDS-Bond basis
Part 1 : Classic Pricing Theory
– A price diffuses in real world probability space as:
\[ dV(t) = \sum_i \Sigma_i(t) dB_i(t) + \mu V(t) dt \]

– There exists \( j = 1, \ldots, d \) hedge instruments:
\[ dA_j(t) = \sum_i \Sigma_i A_j(t) dB_i(t) + \mu A_j(t) dt \]
\[ \Sigma_i(t) = \sum_j h_j(t) \Sigma_i A_j(t) \]
\[ h_j(t) = \sum_k Q_{j,k}(t) \Sigma_k V(t) \]

– The hedged products diffuses as:
\[ dV(t) - \sum_j h_j(t) dA_j(t) = \left( \mu V(t) - \sum_j h_j(t) \mu A_j(t) \right) dt \]

– There should be no arbitrage:
\[ dV(t) - \sum_j h_j(t) dA_j(t) = r(t) \left( V(t) - \sum_j h_j(t) A_j(t) \right) dt \]

– Hence:
\[ \mu V(t) = r(t) V(t) dt + \sum_j h_j(t) (\mu A_j(t) - r(t) A_j(t)) dt \]
Can be rewritten:

\[ dV(t) = \sum_i \Sigma^V_i(t) dB^*_i(t) + r(t)V(t) \, dt \]

\[ dB^*_i(t) = dB_i(t) + \sum_j Q_{j,i}(t) \left( \mu^A_j(t) - r(t)A_j(t) \right) \, dt \]

- \( B^* \) doesn’t depend on \( V \! \)
- Change of probability measure where \( B^* \) is a Brownian motion: risk-neutral probability

\[ V(t) e^{-\int^t r(s) \, ds} \] is a martingale, hence

\[ V(t) = \mathbb{E} \left[ \sum_\phi \phi e^{-\int_t^T \phi \, r(s) \, ds} \right] \]
Classic Theory (3/9): Mono-Currency Market

- Liquid Zero-Coupon Bond
  - LIBOR textbook formula:
    \[ L(t; T_1, T_2) = \frac{1}{T_2 - T_1} \left( \frac{P(t, T_1)}{P(t, T_2)} - 1 \right) \]
  - one interest rate curve per currency
  - no remaining degree of freedom, everything is mark to market

- Theory consistent with independent markets in each currency, but…
One cannot fit both foreign swaps and cross-currency swaps with one single foreign curve.

One then distinguishes one discount curve and one projection curve: foreign zero-coupon bond are not supposed to be liquid anymore!

- Only domestic zero-coupon bonds supposed to be liquid
- Foreign bank accounts are defined by currency parity:
  - Foreign bank accounts $e^{\int_{t}^{s} r_f(s) \, ds}$ are assets
  - Then $X_{f/d}(t) e^{\int_{t}^{s} (r_f(s) - r_d(s)) \, ds}$ are martingales
  - Hence FX drift in risk-neutral probability

\[
d X_{f/d}(t) = - (r_f(t) - r_d(t)) \, d t + [\ldots] \, d \bar{B}(t)
\]
How are computed foreign forward LIBOR?
- Take the standalone mono-currency curve as projection curve? Not consistent in the classical theory, but finally close to the currency buckets theory
- Calibrate simultaneously the discount and the projection curves to fit xccy and monoccy swaps? Consistent in the classical theory, finally close to case of non-deliverable currency
- Can you accept different pricing hypothesis for mono-ccy and xccy? What about mono-ccy swaps hedges for xccy swaps: priced as in mono-ccy or as in xccy?
- What is the free bank account rate if it depends on your choice for domestic currency?
Classic Theory (6/9): Tenor Basis

- Basis swaps between OIS, LIBOR/1M, LIBOR/3M, LIBOR/6M, LIBOR/12M: one needs to introduce one projection curve per index
- Zero-coupon bonds are not supposed to be liquid anymore in any currency!
- Again, what is the discount curve to be used?
Different default risks for different banks come with different funding rates for each bank. The standard pricing theory using a risk-free rate for bank account can’t fit reality!

Two strategies to mitigate default risk

- Use Credit Support Annex
- Price and risk managed default risk in (residual) unsecured positions
Classic Theory (8/9): One Currency

- **Keeping the Standard Pricing Theory, the only hypothesis that has a chance to be globally consistent is:**
  - Impose a Standard CSA in one currency, e.g. USD, for whatever product
  - Consistent pricing methodology imposed to anyone is then to suppose one bank account in USD remunerated at market overnight rate
- **One can then omit the CSA formula and can simply recycle the usual pricing mechanics**
- **Hard to believe:**
  - In practice, everybody knows bank accounts in various banks and currencies are not consistent with the preceding hypothesis
  - One could not run his simpler mono-currency swap market with Standard CSA in its related currency, ignoring other currencies
Classic Theory (9/9): Conclusion

⇒ Risk-free rate concept anymore accurate enough
⇒ Risk-free rate based on strong hypothesis of market in stable equilibrium state, resulting somehow weak theory
⇒ Need to re-think the hypothesis of the theory, still using the same hedging ideas

⇒ Translation:
  ⇒ Risk-free rate: SCSA remuneration rate
  ⇒ Fair value: Benchmark values (TOTEM, Collateral margin calls, live trades)
Part 2: Standard CSA Pricing
Standard CSA Theory (1/12): Introduction

- Standard CSA in each currency separately for each mono-currency market
- Standard CSA in USD for cross-currency trades
- Possible to net collateral flows avoiding Herstatt effect
- Re-hypothecation of collateral
- How can this be consistent?
  - From the collateral pricing paradigm, we see that the bank account disappears from pricing result (but still convexity effects)
  - Isn’t it possible to build a theory directly without bank account?
We consider only products with Standard CSA in currency buckets: for derivatives to be manufactured by banks, and for liquid instruments used as hedges for those derivatives.

When pricing a derivative, cash posted in hedges collaterals will emulate the usual bank account, and compensates the collateral of the derivative.

Any product is a position to market risk only, not an investment.

- e.g. if one buys a zero-coupon bond at a given price, the counterparty immediately has to post back the price as collateral: there is no cash transfer at inception! Only margin calls depending on market moves.

Instead of using currency parity, we use tomorrow-next contracts.

SCSA solve all ambiguities about discounting.
For a chosen domestic currency ‘d’, there exists a probability space called risk-neutral, such that:

- The domestic value of a product with SCSA in domestic currency diffuses like:

\[ dA_d(t) = \tilde{\Sigma}_A_d(t) \cdot dB_d(t) + \rho_d(t)A_d(t)\,dt \]

- The spot exchange rate for a foreign currency ‘f’ diffuses like:

\[ \frac{dX_{f/d}(t)}{X_{f/d}(t)} = \tilde{\sigma}_{X_{f/d}}(t) \cdot dB_d(t) - y_{f/d}(t)\,dt \]

- The foreign value of a product with SCSA in a foreign currency ‘f’ diffuses like:

\[ dX_{f/d}(t) = X_{f/d}(t) \left( \tilde{\Sigma}_A_f(t) + A_f(t)\tilde{\sigma}_{X_{f/d}}(t) \right) \cdot dB_d(t) + \left( r_f(t) - y_{f/d}(t) \right) X_{f/d}(t)A_f(t)\,dt \]

Notations: Explicit the lambda
- Overnight Rate in currency ‘c’:
- Tom-Next spread defined at time ‘t’:
  - Pay at time t+dt
  - Receive at time t+dt
Standard CSA Theory (4/12): Changes in Pricing Theorem (2/2)

- No « bank account » or « default-free counterparty » or « defaultable average counterparty » with kind of « risk-free rate »
  - No need for stable equilibrium of market hypothesis: weaker hypothesis

- No constraint between overnight rates of different currencies because of cross-currency swaps, instead we have introduced the actively traded « tom-next » contract

- No liquid zero-coupon bonds

- Not one numéraire, instead martingales are built depending on the currency of the SCSA:

  - Domestic SCSA: \( A_d(t) e^{-\int^t r_d(s) \, ds} \)
  - Foreign SCSA: \( X_{f/d}(t) A_f(t) e^{-\int^t r_f(s) \, ds + \int^t y_{f/d}(s) \, ds} \)
As a concrete example, HJM framework can be extended with:
- Gaussian dynamic of forward Overnight Rates in all currencies
- Gaussian dynamic of instantaneous forward rates in cross-currency discount curves
- Gaussian dynamic of forward LIBOR in all currencies
- Lognormal dynamic of spot exchange rates

Rather “different” than “complex”, markets uses more complex maths
Standard CSA Theory (6/12): HJM Formula

\[
\begin{align*}
\frac{d x(t, T)}{X_{f/d}(t)} &= \sum_{r_a}(t, T) \cdot d \tilde{B}(t) + \sigma_{x_{f/d}}(t, T) \cdot d \tilde{B}(t) + \nu_{x_{f/d}}(t, T) \cdot d t \\
\frac{d x(t, T)}{X_{f/d}(t)} &= \sum_{r_b}(t, T) \cdot d \tilde{B}(t) + \sigma_{x_{f/d}}(t, T) \cdot d \tilde{B}(t) + \nu_{x_{f/d}}(t, T) \cdot d t \\
\frac{d L_{t, X}(t, T_F)}{X_{f/d}(t)} &= \sum_{L_{t, X}}(t, T_F) \cdot d \tilde{B}(t) + \nu_{L_{t, X}}(t, T_F) \cdot d t \\
\end{align*}
\]

\[
\begin{align*}
\mu_{r_a}^d(t, T) &= \sum_{r_a}(t, T) \cdot \int_t^T \sum_{r_a}(t, u) \cdot d u \\
\mu_{r_b}^d(t, T) &= \sum_{r_b}(t, T) \cdot \left( \int_t^T \sum_{r_b}(t, u) \cdot d u - \sigma_{x_{f/d}}(t) \right) \\
\mu_{x_{f/d}}^d(t, T) &= \sum_{x_{f/d}}(t, T) \cdot \left( \int_t^T \sum_{x_{f/d}}(t, u) \cdot d u - \sigma_{x_{f/d}}(t) \right) \\
\nu_{x_{f/d}}^d(t) &= -\gamma_{f/d}(t) = -(r_{f/d}(t) - r_{d}, t')) \\
\mu_{L_{t, X}}^d(t, T_F) &= \sum_{L_{t, X}}(t, T_F) \cdot \int_t^T \sum_{r_a}(t, u) \cdot d u \\
\mu_{L_{t, X}}^d(t, T_F) &= \sum_{L_{t, X}}(t, T_F) \cdot \left( \int_t^T \sum_{r_b}(t, u) \cdot d u - \sigma_{x_{f/d}}(t) \right)
\end{align*}
\]
• With HJM we have set the dynamic for:
  – All mono-currency overnight and LIBOR indices with SCSA in local currency
  – All foreign exchange rates against domestic currency
  – All foreign discount factors with SCSA in domestic currency

• The following should be computed from the SCSA theory with the above dynamic:
  – Forward overnight or LIBOR indices with SCSA in non-local currency, including foreign indices with SCSA in domestic currency as for liquid cross-currency swaps
  – Discount factors in any currency with SCSA in non-local which is not domestic currency

<table>
<thead>
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<th>Free and Constrained quantities</th>
<th>Discount</th>
<th>Forward Overnight</th>
<th>Forward LIBOR</th>
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<td>EUR</td>
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<tr>
<td>SCSA EUR</td>
<td>Constr</td>
<td>Constr</td>
<td>Free</td>
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Standard CSA Theory (8/12): Convexity (2/5)

• **Expectation**

\[ X_{f/d}(t)P_{f/d}(t,T_P)L_{f/d}(t,T_F) = \mathbb{E} \left[ X_{f/d}(T_P)L_{f/d}(t,T_F)e^{-\int_0^{T_P} r_d(s)\,ds} \right] \]

• **Related known expectations:**

\[ X_{f/d}(t)P(t,T_P)L(t,T_F) = \mathbb{E} \left[ X_{f/d}(T_P)L(t,T_F)e^{-\int_0^{T_P} (r_f(s)-y_{f/d}(s))\,ds} \right] \]

\[ X_{f/d}(t)P(t,T_P) = \mathbb{E} \left[ X_{f/d}(T_P)e^{-\int_0^{T_P} (r_f(s)-y_{f/d}(s))\,ds} \right] \]

\[ X_{f/d}(t)P_{f/d}(t,T_P) = \mathbb{E} \left[ X_{f/d}(T_P)e^{-\int_0^{T_P} r_d(s)\,ds} \right] \]

\[ M_1(t) = X_{f/d}(t)P_{f/d}(t,T_P)L_{f/d}(t,T_F)e^{-\int_0^{T_P} (r_f(s)-y_{f/d}(s))\,ds} \]

• **Useful related martingales:**

\[ M_2(t) = X_{f/d}(t)P_{f/d}(t,T_P)e^{-\int_0^{T_P} (r_f(s)-y_{f/d}(s))\,ds} \]

\[ M_3(t) = X_{f/d}(t)P_{f/d}(t,T_P)e^{-\int_0^{T_P} r_d(s)\,ds} \]

\[ X_{f/d}(t)P_{f/d}(t,T_P)L_{f/d}(t,T_F) = \mathbb{E} \left[ F(T_P) \right] \]

• **Then:**

\[ F(t) = \frac{M_1(t)M_3(t)}{M_2(t)} \]

• **Where:**
Standard CSA Theory (9/12): Convexity (3/5)

- Denoting:

\[
\frac{d F(t)}{F(t)} = \sigma(t) d \tilde{B}(t) + \mu(t) dt
\]

\[
\mu(t) = (\sigma_{M1}(t) - \sigma_{M2}(t)) \cdot (\sigma_{M3}(t) - \sigma_{M2}(t))
\]

\[
\frac{d M_i(t)}{M_i(t)} = \sigma_{M_i}(t) \cdot d \tilde{B}(t) + \mu_{M_i}(t) dt
\]

\[
\sigma_{M1}(t) = \sigma_{M2}(t) + \sigma_{L_i,...,T_F}(t)
\]

\[
\sigma_{M2}(t) = \sigma_{X_{j|a}}(t) + \sigma_{P_i,...,T_P}(t)
\]

\[
\sigma_{M3}(t) = \sigma_{X_{j|a}}(t) + \sigma_{P_{i|a},...,T_P}(t)
\]

\[
\mu(t) = \sigma_{L_i,...,T_F}(t) \cdot \left( \sigma_{P_{i|a},...,T_P}(t) - \sigma_{P_i,...,T_P} \right)
\]

- Hence:

\[
\mu(t) = -(T_P - t) \rho_{L_i,z_{j|a}} \sigma_{L_i} \Sigma_{z_{j|a}}
\]

- Supposing sim\[
\frac{d F(t)e^{-\int^t \mu(u) du}}{F(t)e^{-\int^t \mu(u) du}} = e^{-\int^t \mu(u) du} \sigma(t) d \tilde{B}(t)
\]

- Finally:

\[
F(t) = E \left[ F(T_P)e^{-\int^{T_P} \mu(u) du} \right]
\]

\[
E[F(T_P)] = F(t)e^{\int^{T_P} \mu(u) du}
\]
Standard CSA Theory (10/12): Convexity (4/5)

\[
L_{f/d}(t) = L_f(t) e^{-\frac{(T_P-t)^2}{2} \rho L_f \Sigma_f \sigma L_f \Sigma_f / \Sigma_f}
\]

- LIBOR: 5%
- LIBOR log vol: 15%
- Basis normal vol: 0.1%
- Correlation: { -25%; 0%; 25%}
- Expiry: 10y

- Corrected LIBOR: { 0.94 bp; 0 bp; -0.94 bp }
**Simple rules when ignoring convexity effects:**
- Forward overnight, LIBOR and exchange rates are independent of the SCSA currency
- Prices got from:
  - Compute payoffs with mono-currency forward rates
  - Convert in SCSA currency with forward exchange rates
  - Discount with overnight rate of SCSA currency

**Convexity effects induce more market flexibility**
- Without convexity, cross-currency OIS and cross-currency LIBOR basis swap spreads would be redundant market data
- With convexity, those two basis spreads are not redundant
Standard CSA Theory (12/12): BRL Market

- BRL overnight rate: CDI

- Liquid instruments:
  - Onshore:
    - DI Futures: give onshore CDI projection curve
    - US Dollar Futures and DDI Futures: give USD discount curve funded at CDI
  - Offshore:
    - NDF: give BRL discount curve funded at FedFund
    - IRS: give offshore CDI projection curve

- Compared to EUR or GBP case, we add:
  - An offshore CDI projection curve, as if convexity on top of onshore CDI projection curve was mark to market
  - A USD discount curve funded at CDI, as if convexity on top of the discount rate deduced from BRL discount curve funded at FedFund was mark to market

- Remarks:
  - No need for virtual USB or BRD currency
  - No need for virtual USD/CDI/1D index
Part 3: Credit and Funding Extensions
Introduction

- Legacy CSA with collateral were defined to reduce credit risk without adding complexity to pricing
- Today, the impact of collateral specificities is material
- Two routes:
  1. Develop complex pricing mechanics to price legacy CSA features
  2. Simplify legacy CSA features to get the initial objective: reduce credit risk without adding pricing complexity
Suppose a cash collateral but not necessarily full (one-way CSA, thresholds, etc...)

Pricing formula as deviation from SCSA case

In this set-up, products with full cash collateral are the rule, other products “anomalies”! The issue is not when a product has a collateral and needs to raise/hold cash for it, the issue is when a product has not a full cash collateral!
Risk-free Rate Viewpoint

\[
V_d(t_0) = V_{SCSA,d}(t_0) - CV_A(t_0) + DV_A(t_0)
\]

\[
CV_A(t_0) = \mathbb{E} \int_{t_0}^{\infty} \mathcal{P}(t_0, t) e^{-\int_{t_0}^{t} r_{SCSA/d(s)} ds} 1_{V_d(t)>0} \lambda_{cp}(t) L_{cp} (V_{SCSA,d}(t) - C_d(t)) \, dt
\]

\[
DV_A(t_0) = \mathbb{E} \int_{t_0}^{\infty} \mathcal{P}(t_0, t) e^{-\int_{t_0}^{t} r_{SCSA/d(s)} ds} 1_{V_d(t)<0} \lambda_{us}(t) L_{us} (C_d(t) - V_{SCSA,d}(t)) \, dt
\]

\[
\mathcal{P}_{Repl.}(t_0, t) = e^{-\int_{t_0}^{t} (1_{V_d(s)>0} \lambda_{cp}(s) L_{cp} + 1_{V_d(s)<0} \lambda_{us}(s) L_{us}) \, ds}
\]

\[
\mathcal{P}_{SCSA}(t_0, t) = e^{-\int_{t_0}^{t} (\lambda_{cp}(s)+\lambda_{us}(s)) \, ds}
\]
Pure FVA Viewpoint

\[ V_d(t_0) = V_{SCSA,d}(t_0) - CV A(t_0) + F V A(t_0) + Co V A(t_0) \]

\[ CV A(t_0) = E \int_{t_0}^{\infty} \mathcal{P}(t_0, t) e^{-\int_{t_0}^{t} r'_d(s) ds} \mathbbm{1}_{V_d(t) > 0} \lambda_{cp}(t) L_{cp}(V_{SCSA,d}(t) - C_d(t)) \, dt \]

\[ Co V A(t_0) = E \int_{t_0}^{\infty} \mathcal{P}(t_0, t) e^{-\int_{t_0}^{t} r'_d(s) ds} (r_{SCSA/d}(t) - r_{C/d}(t)) C_d(t) \, dt \]

\[ F V A(t_0) = E \int_{t_0}^{\infty} \mathcal{P}(t_0, t) e^{-\int_{t_0}^{t} r'_d(s) ds} (r_{SCSA/d}(t) - r_{F/d}(t))(V_{SCSA,d}(t) - C_d(t)) \, dt \]

\[ r'_d(t) = r_{C/d}(t) \frac{C_d(t)}{V_{SCSA,d}(t)} + r_{F/d}(t) \frac{V_{SCSA,d}(t) - C_d(t)}{V_{SCSA,d}(t)} \]

\[ \mathcal{P}_{Repl.}(t_0, t) = e^{-\int_{t_0}^{t} \mathbbm{1}_{V_d(s) > 0} \lambda_{cp}(s) L_{cp} \, ds} \]

\[ \mathcal{P}_{SCSA}(t_0, t) = e^{-\int_{t_0}^{t} \lambda_{cp}(s) \, ds} \]
CDS-Bond Basis Viewpoint

\[ V_d(t_0) = V_{SCSA,d}(t_0) - CV_A(t_0) + DV_A(t_0) + CoV_A(t_0) + BasisFVA(t_0) \]

\[ CV_A(t_0) = \mathbb{E} \int_{t_0}^{\infty} \mathcal{P}(t_0, t) e^{-\int_{t_0}^{t} r_d(s) \, ds} 1_{V_d(t)>0} \lambda_{cp}(t) L_{cp}(V_{SCSA,d}(t) - C_d(t)) \, dt \]

\[ DV_A(t_0) = \mathbb{E} \int_{t_0}^{\infty} \mathcal{P}(t_0, t) e^{-\int_{t_0}^{t} r_d(s) \, ds} 1_{V_d(t)<0} \lambda_{us}(t) L_{us}(C_d(t) - V_{SCSA,d}(t)) \, dt \]

\[ CoV_A(t_0) = \mathbb{E} \int_{t_0}^{\infty} \mathcal{P}(t_0, t) e^{-\int_{t_0}^{t} r_d(s) \, ds} (r_{SCSA/d}(t) - r_{C/d}(t)) C_d(t) \, dt \]

\[ BasisFVA(t_0) = \mathbb{E} \int_{t_0}^{\infty} \mathcal{P}(t_0, t) e^{-\int_{t_0}^{t} r_d(s) \, ds} (r_{SCSA/d}(t) - (r_{F/d}(t) - \lambda_{us}(t) L_{us}))(V_{SCSA,d}(t) - C_d(t)) \, dt \]

\[ r_d'(t) = r_{C/d}(t) \frac{C_d(t)}{V_{SCSA,d}(t)} + (r_{F/d}(t) - \lambda_{us}(t) L_{us}) \frac{V_{SCSA,d}(t) - C_d(t)}{V_{SCSA,d}(t)} \]

\[ \mathcal{P}_{Repl.}(t_0, t) = e^{-\int_{t_0}^{t} (1_{V_d(s)>0} \lambda_{cp}(s)L_{cp} + 1_{V_d(s)<0} \lambda_{us}(s)L_{us}) \, ds} \]

\[ \mathcal{P}_{SCSA}(t_0, t) = e^{-\int_{t_0}^{t} (\lambda_{cp}(s) + \lambda_{us}(s)) \, ds} \]
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