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

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Classic Theory (1/9): Risk-Neutral Measure (1/2)

- A price diffuses in real world probability space as:
- There exists j=1, …, d hedge instruments:

$$
\begin{aligned}
\mathrm{d}\, V(t) &= \sum_i \Sigma_i^V(t)\,\mathrm{d}\, B_i(t) + \mu^V(t)\,\mathrm{d}\, t \\
\mathrm{d}\, A_j(t) &= \sum_i \Sigma_i^{A_j}(t)\,\mathrm{d}\, B_i(t) + \mu^{A_j}(t)\,\mathrm{d}\, t \\
\Sigma_i^V(t) &= \sum_j h_j(t)\Sigma_i^{A_j}(t) \\
h_j(t) &= \sum_k Q_{j,k}(t)\Sigma_k^V(t)
\end{aligned}
$$

- The hedged products diffuses as:

$$
\mathrm{d}\, V(t) - \sum_j h_j(t)\,\mathrm{d}\, A_j(t) = \left(\mu^V(t) - \sum_j h_j(t)\mu^{A_j}(t)\right)\mathrm{d}\, t
$$

- There should be no arbitrage:

$$
\mathrm{d}\, V(t) - \sum_j h_j(t)\,\mathrm{d}\, A_j(t) = r(t)\left(V(t) - \sum_j h_j(t)A_j(t)\right)\mathrm{d}\, t
$$

- Hence:

$$
\mu^V(t) = r(t)V(t)\,\mathrm{d}\, t + \sum_j h_j(t)\left(\mu^{A_j}(t) - r(t)A_j(t)\right)\mathrm{d}\, t
$$

Classic Theory (2/9): Risk-Neutral Measure (2/2)

- Can be rewritten:

$$\begin{aligned} \mathrm{d}\, V(t) &= \sum_i \Sigma_i^V(t)\,\mathrm{d}\, B_i^*(t) + r(t)V(t)\,\mathrm{d}\, t \\ \mathrm{d}\, B_i^*(t) &= \mathrm{d}\, B_i(t) + \sum_j Q_{j,i}(t)\left(\mu^{A_j}(t) - r(t)A_j(t)\right)\mathrm{d}\, t \end{aligned}$$

- B* doesn't depend on V!
- Change of probability measure where B* is a Brownian motion: risk-neutral probability

- $V(t)e^{-\int^t r(s)\,\mathrm{d}\, s}$ is a martingale, hence $V(t) = \mathbb{E}\left[\sum_\phi \phi e^{-\int_t^{T_\phi} r(s)\,\mathrm{d}\, s}\right]$

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…

Classic Theory (4/9): Cross-Currency Markets (1/2)

- 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 $e^{\int^t r_f(s)\,\mathrm{d}\,s}$ are assets
    - Then $X_{f/d}(t)e^{\int^t (r_f(s)-r_d(s))\,\mathrm{d}\,s}$ are martingales
    - Hence FX drift in risk-neutral probability

$$\mathrm{d}\,X_{f/d}(t) = -(r_f(t) - r_d(t))\,\mathrm{d}\,t + [\dots]\,\mathrm{d}\,\vec{B}(t)$$

Classic Theory (5/9): Cross-Currency Markets (2/2)

- 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?**

Classic Theory (7/9): Counterparty Default Risk

- 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 hypohtesis
  - 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?

Standard CSA Theory (2/12): Heuristics

- 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 transfert 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

Standard CSA Theory (3/12): Changes in Pricing Theorem (1/2)

- **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: $\mathrm{d}\, A_d(t) = \vec{\Sigma}_{A_d}(t) \cdot \mathrm{d}\, \vec{B}_d(t) + r_d(t) A_d(t)\, \mathrm{d}\, t$
  - The spot exchange rate for a foreign currency 'f' diffuses like: $\frac{\mathrm{d}\, X_{f/d}(t)}{X_{f/d}(t)} = \vec{\sigma}_{X_{f/d}}(t) \cdot \mathrm{d}\, \vec{B}_d(t) - y_{f/d}(t)\, \mathrm{d}\, t$
  - The foreign value of an product with SCSA in a foreign currency 'f' diffuses like:

$$\begin{aligned}\mathrm{d}\, X_{f/d}(t) A_f(t) &= X_{f/d}(t) \left(\vec{\Sigma}_{A_f}(t) + A_f(t) \vec{\sigma}_{X_{f/d}}(t)\right) \cdot \mathrm{d}\, \vec{B}_d(t) \\ &+ \left(r_f(t) - y_{f/d}(t)\right) X_{f/d}(t) A_f(t)\, \mathrm{d}\, t\end{aligned}$$

  Notations: Explicit the lambda
  - Overnight Rate in currency 'c':
  - Tom-Next spread defined at time 't': $y_{f/d}(t)$
    - Pay at time t+dt $(1 - y_{f/d}(t)\, \mathrm{d}\, t)\, X_{f/d}(t)$
    - Receive at time t+dt $X_{f/d}(t + \mathrm{d}\, t)$

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: $A_d(t)e^{-\int^t r_d(s)\,\mathrm{d}s}$

  - Foreign SCSA: $X_{f/d}(t)A_f(t)e^{-\int^t r_f(s)\,\mathrm{d}s+\int^t y_{f/d}(s)\,\mathrm{d}s}$

Standard CSA Theory (5/12): HJM Framework extended to SCSA

- 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

$$\begin{aligned}
\mathrm{d}\,r_c(t,T) &= \vec{\Sigma}_{r_c}(t,T)\cdot\mathrm{d}\,\vec{B}(t) + \mu^d_{r_c}(t,T)\,\mathrm{d}\,t \\
\mathrm{d}\,r_{f/d}(t,T) &= \vec{\Sigma}_{r_{f/d}}(t,T)\cdot\mathrm{d}\,\vec{B}(t) + \mu^d_{r_{f/d}}(t,T)\,\mathrm{d}\,t \\
\frac{\mathrm{d}\,X_{f/d}(t)}{X_{f/d}(t)} &= \vec{\sigma}_{X_{f/d}}(t)\cdot\mathrm{d}\,\vec{B}(t) + \nu^d_{X_{f/d}}(t)\,\mathrm{d}\,t \\
\mathrm{d}\,L_{c,X}(t,T_F) &= \vec{\Sigma}_{L_{c,X}}(t,T_F)\cdot\mathrm{d}\,\vec{B}(t) + \mu^d_{L_{c,X}}(t,T_F)\,\mathrm{d}\,t
\end{aligned}$$

$$\begin{aligned}
\mu^d_{r_d}(t,T) &= \vec{\Sigma}_{r_d}(t,T)\cdot\int_t^T \vec{\Sigma}_{r_d}(t,u)\,\mathrm{d}\,u \\
\mu^d_{r_f}(t,T) &= \vec{\Sigma}_{r_f}(t,T)\cdot\left(\int_t^T \vec{\Sigma}_{r_f}(t,u)\,\mathrm{d}\,u - \vec{\sigma}_{X_{f/d}}(t)\right) \\
\mu^d_{r_{f/d}}(t,T) &= \vec{\Sigma}_{r_{f/d}}(t,T)\cdot\left(\int_t^T \vec{\Sigma}_{r_{f/d}}(t,u)\,\mathrm{d}\,u - \vec{\sigma}_{X_{f/d}}(t)\right) \\
\nu^d_{X_{f/d}}(t) &= -y_{f/d}(t) = -(r_{f/d}(t) - r_d(t)) \\
\mu^d_{L_d(.,T_F)}(t) &= \vec{\Sigma}_{L_d(.,T_F)}(t)\cdot\int_t^T \vec{\Sigma}_{r_d}(t,u)\,\mathrm{d}\,u \\
\mu^d_{L_f(.,T_F)}(t) &= \vec{\Sigma}_{L_f(.,T_F)}(t)\cdot\left(\int_t^T \vec{\Sigma}_{r_f}(t,u)\,\mathrm{d}\,u - \vec{\sigma}_{X_{f/d}}(t)\right)
\end{aligned}$$

Standard CSA Theory (7/12): Convexity (1/5)

- **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

Free and Constrained quantities		Discount			Forward Overnight			Forward LIBOR		
		USD	GBP	EUR	USD	GBP	EUR	USD	GBP	EUR
SCSA	USD	Free	Free	Free	Free	Constr.	Constr.	Free	Constr.	Constr.
	GBP	Constr.	Free	Constr.	Constr.	Free	Constr.	Constr.	Free	Constr.
	EUR	Constr.	Constr.	Free	Constr.	Constr.	Free	Constr.	Constr.	Free

Standard CSA Theory (8/12): Convexity (2/5)

- **Expectation:** $$X_{f/d}(t)P_{f/d}(t,T_P)L_{f/d}(t,T_F) = \mathbb{E}\left[X_{f/d}(T_P)L_{f/d}(t,T_F)e^{-\int_0^{T_P} r_d(s)\,\mathrm{d}\,s}\right]$$
- **Related known expectations:**

$$\begin{aligned}
X_{f/d}(t)P_f(t,T_P)L_f(t,T_F) &= \mathbb{E}\left[X_{f/d}(T_P)L_{f/d}(t,T_F)e^{-\int_0^{T_P}\left(r_f(s)-y_{f/d}(s)\right)\mathrm{d}\,s}\right] \\
X_{f/d}(t)P_f(t,T_P) &= \mathbb{E}\left[X_{f/d}(T_P)e^{-\int_0^{T_P}\left(r_f(s)-y_{f/d}(s)\right)\mathrm{d}\,s}\right] \\
X_{f/d}(t)P_{f/d}(t,T_P) &= \mathbb{E}\left[X_{f/d}(T_P)e^{-\int_0^{T_P} r_d(s)\,\mathrm{d}\,s}\right]
\end{aligned}$$

- **Useful related martingales:**

$$\begin{aligned}
M_1(t) &= X_{f/d}(t)P_f(t,T_P)L_f(t,T_F)e^{-\int_0^t\left(r_f(s)-y_{f/d}(s)\right)\mathrm{d}\,s} \\
M_2(t) &= X_{f/d}(t)P_f(t,T_P)e^{-\int_0^t\left(r_f(s)-y_{f/d}(s)\right)\mathrm{d}\,s} \\
M_3(t) &= X_{f/d}(t)P_{f/d}(t,T_P)e^{-\int_0^{T_P} r_d(s)\,\mathrm{d}\,s}
\end{aligned}$$

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

- **Then:** $$F(t) = \frac{M_1(t)M_3(t)}{M_2(t)}$$

- **Where:**

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

- **Denoting:**

$$\frac{\mathrm{d}\,F(t)}{F(t)} = \vec{\sigma}(t)\,\mathrm{d}\,\vec{B}(t) + \mu(t)\,\mathrm{d}\,t$$

$$\mu(t) = (\vec{\sigma}_{M_1}(t) - \vec{\sigma}_{M_2}(t)) \cdot (\vec{\sigma}_{M_3}(t) - \vec{\sigma}_{M_2}(t))$$

- **We get:**

$$\begin{aligned}
\frac{\mathrm{d}\,M_i(t)}{M_i(t)} &= \vec{\sigma}_{M_i}(t) \cdot \mathrm{d}\,\vec{B}(t) + \mu_{M_i}(t)\,\mathrm{d}\,t \\
\vec{\sigma}_{M_1}(t) &= \vec{\sigma}_{M_2}(t) + \vec{\sigma}_{L_f(.,T_F)}(t) \\
\vec{\sigma}_{M_2}(t) &= \vec{\sigma}_{X_{f/d}}(t) + \vec{\sigma}_{P_f(.,T_P)}(t) \\
\vec{\sigma}_{M_3}(t) &= \vec{\sigma}_{X_{f/d}}(t) + \vec{\sigma}_{P_{f/d}(.,T_P)}(t) \\
\mu(t) &= \vec{\sigma}_{L_f(.,T_F)}(t) \cdot \left(\vec{\sigma}_{P_{f/d}(.,T_P)}(t) - \vec{\sigma}_{P_f(.,T_P)}\right)
\end{aligned}$$

- **Hence:**

$$\mu(t) = -(T_P - t)\rho_{L_f, z_{f/d}} \sigma_{L_f} \Sigma_{z_{f/d}}$$

- **Supposing sim**

$$\frac{\mathrm{d}\,F(t)e^{-\int^t \mu(u)\,\mathrm{d}\,u}}{F(t)e^{-\int^t \mu(u)\,\mathrm{d}\,u}} = e^{-\int^t \mu(u)\,\mathrm{d}\,u} \vec{\sigma}(t)\,\mathrm{d}\,\vec{B}(t)$$

- **Finally:**

$$\begin{aligned}
F(t) &= \mathbb{E}\left[F(T_P)e^{-\int^{T_P} \mu(u)\,\mathrm{d}\,u}\right] \\
\mathbb{E}\left[F(T_P)\right] &= F(t)e^{\int^{T_P} \mu(u)\,\mathrm{d}\,u}
\end{aligned}$$

Standard CSA Theory (10/12): Convexity (4/5)

$$L_{f/d}(t) = L_f(t) e^{-\frac{(T_P - t)^2}{2} \rho_{L_f, z_{f/d}} \sigma_{L_f} \Sigma_{z_{f/d}}}$$

- **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 }**

Standard CSA Theory (11/12): Convexity (5/5)

- **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

CVA And DVA Extensions (1/3)

- **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

$$
\begin{aligned}
V_d(t_0) &= V_{SCSA,d}(t_0) - CVA(t_0) + DVA(t_0) \\
CVA(t_0) &= \mathbb{E}\int_{t_0}^{\infty} \mathcal{P}(t_0,t)e^{-\int_{t_0}^{t} r_{SCSA/d}(s)\,\mathrm{d}\,s} 1_{V_d(t)>0}\lambda_{cp}(t)L_{cp}(V_{SCSA,d}(t) - C_d(t))\,\mathrm{d}\,t \\
DVA(t_0) &= \mathbb{E}\int_{t_0}^{\infty} \mathcal{P}(t_0,t)e^{-\int_{t_0}^{t} r_{SCSA/d}(s)\,\mathrm{d}\,s} 1_{V_d(t)<0}\lambda_{us}(t)L_{us}(C_d(t) - V_{SCSA,d}(t))\,\mathrm{d}\,t \\
\mathcal{P}_{\mathrm{Repl.}}(t_0,t) &= e^{-\int_{t_0}^{t}(1_{V_d(s)>0}\lambda_{cp}(s)L_{cp} + 1_{V_d(s)<0}\lambda_{us}(s)L_{us})\,\mathrm{d}\,s} \\
\mathcal{P}_{\mathrm{SCSA}}(t_0,t) &= e^{-\int_{t_0}^{t}(\lambda_{cp}(s)+\lambda_{us}(s))\,\mathrm{d}\,s}
\end{aligned}
$$

Pure FVA Viewpoint

$$
\begin{aligned}
V_d(t_0) &= V_{SCSA,d}(t_0) - CVA(t_0) + FVA(t_0) + CoVA(t_0) \\
CVA(t_0) &= \mathbb{E}\int_{t_0}^{\infty} \mathcal{P}(t_0,t) e^{-\int_{t_0}^{t} r'_d(s)\,\mathrm{d}\,s} 1_{V_d(t)>0} \lambda_{cp}(t) L_{cp}(V_{SCSA,d}(t) - C_d(t))\,\mathrm{d}\,t \\
CoVA(t_0) &= \mathbb{E}\int_{t_0}^{\infty} \mathcal{P}(t_0,t) e^{-\int_{t_0}^{t} r'_d(s)\,\mathrm{d}\,s} (r_{SCSA/d}(t) - r_{C/d}(t)) C_d(t)\,\mathrm{d}\,t \\
FVA(t_0) &= \mathbb{E}\int_{t_0}^{\infty} \mathcal{P}(t_0,t) e^{-\int_{t_0}^{t} r'_d(s)\,\mathrm{d}\,s} (r_{SCSA/d}(t) - r_{F/d}(t))(V_{SCSA,d}(t) - C_d(t))\,\mathrm{d}\,t \\
r'_d(t) &= r_{C/d}(t)\frac{C_d(t)}{V_{SCSA,d}(t)} + r_{F/d}(t)\frac{V_{SCSA,d}(t) - C_d(t)}{V_{SCSA,d}(t)} \\
\mathcal{P}_{\mathrm{Repl.}}(t_0,t) &= e^{-\int_{t_0}^{t} 1_{V_d(s)>0}\lambda_{cp}(s) L_{cp}\,\mathrm{d}\,s} \\
\mathcal{P}_{\mathrm{SCSA}}(t_0,t) &= e^{-\int_{t_0}^{t} \lambda_{cp}(s)\,\mathrm{d}\,s}
\end{aligned}
$$

CDS-Bond Basis Viewpoint

$$
\begin{aligned}
V_d(t_0) &= V_{SCSA,d}(t_0) - CVA(t_0) + DVA(t_0) + CoVA(t_0) + BasisFVA(t_0) \\
CVA(t_0) &= \mathbb{E}\int_{t_0}^{\infty} \mathcal{P}(t_0,t) e^{-\int_{t_0}^{t} r'_d(s)\,\mathrm{d}\,s} 1_{V_d(t)>0}\lambda_{cp}(t) L_{cp}(V_{SCSA,d}(t) - C_d(t))\,\mathrm{d}\,t \\
DVA(t_0) &= \mathbb{E}\int_{t_0}^{\infty} \mathcal{P}(t_0,t) e^{-\int_{t_0}^{t} r'_d(s)\,\mathrm{d}\,s} 1_{V_d(t)<0}\lambda_{us}(t) L_{us}(C_d(t) - V_{SCSA,d}(t))\,\mathrm{d}\,t \\
CoVA(t_0) &= \mathbb{E}\int_{t_0}^{\infty} \mathcal{P}(t_0,t) e^{-\int_{t_0}^{t} r'_d(s)\,\mathrm{d}\,s} (r_{SCSA/d}(t) - r_{C/d}(t)) C_d(t)\,\mathrm{d}\,t \\
BasisFVA(t_0) &= \mathbb{E}\int_{t_0}^{\infty} \mathcal{P}(t_0,t) e^{-\int_{t_0}^{t} r'_d(s)\,\mathrm{d}\,s} (r_{SCSA/d}(t) - (r_{F/d}(t) - \lambda_{us}(t) L_{us}))(V_{SCSA,d}(t) - C_d(t))\,\mathrm{d}\,t \\
r'_d(t) &= r_{C/d}(t)\frac{C_d(t)}{V_{SCSA,d}(t)} + (r_{F/d}(t) - \lambda_{us}(t) L_{us})\frac{V_{SCSA,d}(t) - C_d(t)}{V_{SCSA,d}(t)} \\
\mathcal{P}_{\mathrm{Repl.}}(t_0,t) &= e^{-\int_{t_0}^{t}(1_{V_d(s)>0}\lambda_{cp}(s) L_{cp} + 1_{V_d(s)<0}\lambda_{us}(s) L_{us})\,\mathrm{d}\,s} \\
\mathcal{P}_{\mathrm{SCSA}}(t_0,t) &= e^{-\int_{t_0}^{t}(\lambda_{cp}(s) + \lambda_{us}(s))\,\mathrm{d}\,s}
\end{aligned}
$$

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