Abstract

SA-CCR has major issues including: lack of self-consistency for linear trades; lack of appropriate risk sensitivity (zero positions can have material add-ons; moneyness is ignored); dependence on economically-equivalent confirmations. We show that SA-CCR is, by re-construction, based on a 3-factor Gaussian Market Model model with particular calibration to volatility and inter-bucket correlation structure. Hence we proposed RSA-CCR (Berrahoui, Islah, and Kenyon 2019) based on cashflow decomposition and this 3-factor Gaussian Market Model model. RSA-CCR solves the issues with SA-CCR for linear trades and is calibrated to SA-CCR apart from avoiding SA-CCR’s issues.

This Technical appendix provides background material, proofs and technical details behind RSA-CCR not present in the source paper (Berrahoui, Islah, and Kenyon 2019). There is some duplication to make this appendix more readable.
1 Introduction

The request for comments (OCC 2018) offers an opportunity to address major issues with the Basel standardised approach for measuring counterparty credit risk exposures (SA-CCR) (BCBS 2014b; BCBS 2018a) and may inform other jurisdictions (BCBS 2018b). Major issues include: lack of self-consistency for linear trades; lack of appropriate risk sensitivity (zero positions can have material add-ons; moneyness is ignored); dependence on economically-equivalent confirmations. Medium issues include: ambiguity of risk assignment (i.e. requirement of a single primary risk factor); and lack of clear extensibility. The issues with SA-CCR, and the point suggestions by other authors (BCBS 2013), highlight appropriate principles on which to reconstruct SA-CCR, namely appropriate risk-sensitivity (same exposure for same economics, positive exposure for non-zero risk), transparency, consistency, and extensibility.

In (Berrahoui, Islah, and Kenyon 2019) we propose minimal changes to address issues with SA-CCR by taking a cashflow-decomposition and model-based approach where we calibrate the model to the current SA-CCR to ensure numerical consistency as far as possible (we do not reproduce self-inconsistent aspects of the current SA-CCR). Starting from cashflows automatically provides self-consistency. Using an explicit model as a base ensures transparency and extensibility to situations and details not explicitly documented. A start in the model-based direction is present in (BCBS 2014a) which we generalized.
Looking at cashflows rather than trades is an increase in implementation complexity but this is small, i.e. equivalent to adding a loop into previous calculations, and this decomposition approach is already applied in (BCBS 2014b; OCC 2018) for options. Using decomposition also for linear products produces an appropriately risk sensitive (same exposure for same economics, positive exposure for non-zero risk) and booking-insensitive (i.e. without dependence on economically-equivalent confirmations) standard.

This appendix provides background material, proofs and technical details behind RSA-CCR, (Berrahoui, Islah, and Kenyon 2019).

A Background and results

A.1 Structure of SA-CCR EAD

In (BCBS 2014b; BCBS 2014a), the Basel Committee recalls that in formulating the SA-CCR, their main objectives “were to devise an approach that is suitable to be applied to a wide variety of derivatives transactions (margined and unmargined, as well as bilateral and cleared) is capable of being implemented simply and easily, addresses known deficiencies of the CEM and the SM,...and improves the risk sensitivity of the capital framework without creating undue complexity”.

The SA-CCR specifies in article 128 of (BCBS 2014b), the Exposure-at-default for a netting set. It is defined as a coefficient $\alpha = 1.4$ multiplied by an Effective Expected Positive Exposure which is the sum of the replacement cost ($RC$) and a potential future exposure ($PFE$):

$$EAD = \alpha EEPE = \alpha (RC + PFE)$$ (A.1)

The SA-CCR defines in articles 136 (respectively article 134) of (BCBS 2014b), the replacement cost $RC$ for an unmargined netting set as $RC = \max(V-C,0)$ (respectively for margined netting sets as $RC = \max(V-C,TH+MTA-NICA,0)$) where $V$ is the total mark-to-market of the netting set, $C$ is the net collateral (with adequate haircuts for the corresponding margin period of risk), $TH$ (threshold amount), $MTA$ (minimum transfer amount) and $NICA$ (total initial margin received net of unsegregated initial margin posted).

The $PFE$ is then defined as :

$$PFE_{SA-CCR} = W \left( \frac{V-C}{AddOn_{agg}} \right) AddOn_{agg}$$ (A.2)

Where

$$W(y) = \min \left\{ 1, f + (1-f) \exp \left( \frac{y}{2(1-f)} \right) \right\}, \text{ with } 0 < f < 1 \quad (A.3)$$

and $AddOn_{agg} = \sum AddOn_i$ is the aggregate add-on i.e. the sum of Add-ons by asset class. The approach to compute the aggregate add-ons is a bottom-up approach performed in the following steps :

1. Allocation of a trade to its risk drivers ;
2. Calculation of a trade level add-on

\[ \text{AddOn}_i^{\text{trade}} = \delta_i S F_i^{(a)} a_i^{(a)} MF_i \]  

(A.4)

which is made of four components according to article 154 in (BCBS 2014b):

(a) An adjusted notional amount \( d_i^{(a)} \). The rules prescribe that it should be “based on actual notional or price .. calculated at the trade level. For interest rate and credit derivatives, this adjusted notional amount also incorporates a supervisory measure of duration”;

(b) A maturity factor \( MF_i \);

(c) A directional delta \( \delta_i \) which equals \( \pm 1 \) for linear derivatives and equals the delta of non-linear products;

(d) supervisory factor \( SF_i^{(a)} \) is a measure of volatility by asset class

3. Netting of trade level add-ons by risk drivers and aggregation by hedging set;

4. Aggregation of hedging sets add-ons by asset class then as an aggregate netting set add-on.

Article 153 claims that “The add-on for each asset class is calculated using asset-class-specific formulas that represent a stylised Effective EPE calculation under the assumption that all trades in the asset class have zero current mark-to-market value (ie they are at-the-money)”. We are going to show that the At-the-money assumption is not needed for the SA-CCR formula for Effective EPE to be correct. This will in turn fully justify our cash-flow based approach.

A.2 Theoretical foundation of PFE expression in SA-CCR

As in the technical paper, (BCBS 2014a), we make the following assumptions:

**Assumption A.1.**

- The trade level MtMs follow a driftless arithmetic Brownian process
- The trades have no-cashflows under one year
- The bank neither holds nor has posted collateral for the netting set.

Unlike the BCBS paper (BCBS 2014a), we do not assume that trades are at-the-money. The assumption about collateral is made only for exposition purposes and is not needed. Under these assumptions, we are going to prove that the formula (A.2) for the PFE provides a conservative estimate of the Expected positive exposure.

For this purpose, let us introduce some notations:

- \( V_i(t) \) is the Mark-to-Market of trade \( i \) at time \( t \) dynamics :

\[ dV_i(t) = \sigma_i dW_i(t) \]

(A.5)

With \( dW_i dW_j = \rho_{i,j} dt \).

- Let \( V(t) \) be the netting set MtM of trades and \( \sigma_{\text{total}} = \sqrt{\sum \rho_{i,j} \sigma_i \sigma_j} \), the we have :
\[ dV(t) = r_t V(t) dt + \sigma_{\text{total}} dW(t) \]  
\[(A.6)\]

We assume that we have asset classes \( a = 1, \ldots, A \), within each asset class \( a \) hedging sets \( H_{a,1}, \ldots, H_{a,b_a} \) and for each each hedging set \( H_{a,b} \) risk factors \( F_{a,b,1}, \ldots, F_{a,b,f_{a,b}} \) supposed to be independent (or derived from original risk factors such as risk factors for interest rates via a Cholesky decomposition and transformed into independent risk factors). The factors \( F_{a,b,f} \) are driven by independent standard Brownian motions \( W_{a,f,b}(t) \). Moreover, for each trade \( i \), we decompose the trade dynamics by its risk drivers as prescribed by Article 153 and we get \( \beta_{i,a,b,f} \) such that:

\[ W_i(t) = \sum_{a,b,f} \beta_{i,a,b,f} W_{a,b,f}(t) \]  
\[(A.7)\]

With these notations, we define the trade level add-on at horizon \( T \) (or maturity factor) as:

\[ \text{AddOn}_i = \frac{2}{3} \sigma_i \sqrt{\frac{T}{2\pi}} \]  
\[(A.8)\]

The add-on for hedging sets \( H_{a,b} \) belonging to asset class \( a \) is then given by:

\[ \text{AddOn}_{a,b} = \sqrt{\sum_f \left( \sum_i \text{AddOn}_i \beta_{i,a,b,f} \right)^2} \]  
\[(A.9)\]

The corresponding volatility is:

\[ \sigma_{a,b} = \sqrt{\sum_f \left( \sum_i \sigma_i \beta_{i,a,b,f} \right)^2} \]

The aggregate volatility is then simply \( \sigma_{\text{agg}} = \sum_a \sum_h \sigma_{a,h} \) and the aggregate add-on is therefore:

\[ \text{AddOn}_{\text{agg}} = \frac{2}{3} \sigma_{\text{agg}} \sqrt{\frac{T}{2\pi}} \]  
\[(A.10)\]

It is straightforward to verify that:

\[ \sigma_{\text{total}} = \sqrt{\sum_{a,b} \sum_f \sum_{i,j} \sigma_i \sigma_j \beta_{i,a,b,f} \beta_{j,a,b,f}} \leq \sigma_{\text{agg}} = \sum_a \sum_h \sqrt{\sum_f \left( \sum_i \sigma_i \beta_{i,a,b,f} \right)^2} \]  
\[(A.11)\]

We define the theoretical expected positive exposure at a horizon \( T \):

\[ EPE(T) = \frac{1}{T} \int_0^T \mathbb{E} \left[ \left( \sum_i V_i(t) \right)^+ \right] dt \]  
\[(A.12)\]

Similarly to the formula on page 13 of the BCBS technical paper (BCBS 2014a) , we define a model based estimate of the EPE :

\[ EPE_{\text{model}}(T) = V(0)^+ + 1_{V(0) \leq 0} \left\{ V(0) \Phi \left( \frac{3V(0)}{2\sigma_{\text{total}} \sqrt{T}} \right) + \frac{2}{3} \sigma_{\text{total}} \sqrt{T} \varphi \left( \frac{3V(0)}{2\sigma_{\text{total}} \sqrt{T}} \right) \right\} \]
\[+ 1_{V(0) > 0} \sigma_{\text{total}} \frac{2}{3} \sqrt{\frac{T}{2\pi}} \]  
\[(A.13)\]
Where \( \varphi(x) = \frac{e^{-x^2/2}}{\sqrt{2\pi}} \) is the standard normal probability distribution and 
\( \Phi(x) = \int_{-\infty}^{x} \varphi(u) du \) the cumulative standard normal distribution.

**Theorem A.2** (PFE is conservative non-ATM). With the notations above and with the assumptions (A.1), the model based estimate given by equation (A.13) is a conservative estimate of the theoretical EPE given by (A.12) for an un-margined and uncollateralised netting set:

\[
EPE(T) \leq EPE_{\text{model}}(T) \tag{A.14}
\]

Let \( W(y) = \min\{1, f + (1 - f) \exp\left(\frac{-y^2}{2(1-f)}\right)\} \) be the SA-CCR multiplier defined above. Then, the SA-CCR official EEPE is a conservative estimate of the EPE given by (A.12) i.e. :

\[
EPE(T) \leq EPE_{\text{model}}(T) \leq EPE_{\text{SA-CCR}}(T) \tag{A.15}
\]

Where \( EPE_{\text{SA-CCR}}(T) = V(0)^+ + AddOn_{\text{agg}} W\left(\frac{V(0)}{\sqrt{2\pi AddOn_{\text{agg}}}}\right) \) and \( AddOn_{\text{agg}} \) given by (A.10).

**Proof.** See appendix (C.1)

**Remark A.3.** This result has been obtained in full generality without assuming that the derivatives are at-the-money or that the netting set is fully collateralised. We have proved rigorously that the SA-CCR EEPE provides a conservative estimate of the EPE as long as the MtM of the trades follow an arithmetic Brownian motion process and that the cash-flows within the horizon of the calculations are ignored. It is crucial that the assumption of the trades being at-the-money, has been dropped. This is because in the next section, we will want to generalise trade level add-ons of interest rate products to trades that are not necessarily at-the-money and at the same time we want to remain consistent with the general SA-CCR framework. This is why we needed to prove that the EEPE estimates are conservative for non ATM trades/uncollateralised netting set.

We proved and stated Theorem A.2 for an unmargined and uncollateralised netting set. If we modify the definition of the EPE in equation (A.12) in the following ways:

- for unmargined netting set with initial collateral \( C \)

\[
EPE(T) = \frac{1}{T} \int_{0}^{T} \mathbb{E} \left[ \left( \sum_i V_i(t) - C \right)^+ \right] dt
\]

- for margined netting set with initial collateral \( C \) and \( K = (TH + MTA - NICA)^+ \):

\[
EPE(T) = \frac{1}{T} \int_{0}^{T} \mathbb{E} \left[ \left( K + \left( \sum_i V_i(t) - C - K \right)^+ \right) \right] dt
\]

Then, we could with these definitions, repeat exactly the same steps of the proof of Theorem (A.2) and generalise the result to these collateralisation situations.

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A.3 Identity of SA-CCR and 1-factor Hull-White for single maturity bucket

Here we show that there is an identity between SA-CCR and a one-factor Hull-White model for interest rate swaps in a single maturity bucket.

A one factor Hull-White model (Hull and White 1990) has short rate, \( r(t) \), dynamics:

\[
dr_t = a(\phi_t - r_t)dt + \sigma dW_t
\] (A.16)

This means that the dynamics of a zero coupon bond \( P(t,T) \) price are:

\[
dP(t,T) = r_t P(t,T) dt - \frac{\sigma}{a} (1 - e^{-a(T-t)}) P(t,T) dW_t
\] (A.17)

Consider a payer, i.e. pay-fixed rate \( R \), notional \( N \), swap price \( V \) at \( t \)

\[
V(t) = V_{float}(t) - V_{fixed}(t)
\] (A.18)

\[
= N \sum_{i=s+1}^{e} P(t,T_i) \delta_i L(t, T_{i-1}, T_i) - N \sum_{i=s+1}^{e} P(t,T_i) \delta_i R
\] (A.19)

Now we have the identity between SA-CCR and a one-factor Hull-White model in Theorem A.4 below.

**Theorem A.4 (SA-CCR Hull-White identity).** With zero bond dynamics given by Equation A.17, if \( V \) is the value process of a forward starting payer swap, then the instantaneous volatility of \( V \) for \( t \leq T_s \) can be decomposed into three contributions :

\[
\sigma_V(t) = \sigma_{ATM}(t) + \sigma_{Float}(t) + \sigma_{Fixed}(t)
\]

Where :

\[
\sigma_{ATM}(t) = N \sum_{i=s+1}^{e} P(t,T_{i-1}) \frac{\sigma}{a} (e^{-a(T_{i-1}-t)} - e^{-a(T_{i}-t)})
\]

\[
\sigma_{Float}(t) = -N \sum_{i=s+1}^{e} P(t,T_i) \frac{\sigma}{a} (1 - e^{-a(T_{i}-t)}) \delta_i L(t, T_{i-1}, T_i)
\]

\[
\sigma_{Fixed}(t) = N \sum_{i=s+1}^{e} P(t,T_i) \frac{\sigma}{a} (1 - e^{-a(T_{i}-1-t)}) \delta_i R
\]

If at time \( t \), the swap is ATM, taking the standard weight-freezing assumption (see proof) we have:

\[
\sigma_V(t) = N \sum_{i=s+1}^{e} P(t,T_i) \frac{\sigma}{a} (e^{-a(T_{i-1}-t)} - e^{-a(T_{i}-t)}) = \sigma_{ATM}(t)
\]

Moreover if the yield curve is flat and equal to zero, then the instantaneous volatility of an ATM swap in one maturity bucket is given exactly by the SA-CCR regulatory formula i.e.:

\[
\sigma_{ATM}(t) = N \frac{\sigma}{a} (e^{-a(T_s-t)} - e^{-a(T_e-t)})
\] (A.20)

Proof: see Section C.2.
B  Volatilities for typical cashflows

See Section D.1 and Section D.2 for worked examples for Floating and Constant Maturity Swap (CMS) cashflows.

B.1 Fixed cashflow

For a fixed cash-flow \( N \) with payment date \( T \), its present value \( V(t) = NP(t,T) \), so by Ito-lemma: \( dV(t) = (\ldots) dt + \sigma a (1 - e^{-aT})(P(t,T)) \), clearly the add-on parameters that allow to retrieve the volatility of \( V \) at \( t = 0 \), are

- Maturity bucket : \( M(T) \)
- Notional: \( NP(0,T) \)
- Duration: \( \frac{1}{a}(1 - e^{-aT}) \)
- If receive delta –1

B.2 Floating cashflow

For a floating rate cash-flow based on a money market index with fixing at \( T_f \), tenor \( \tau \) (tenor less than 1 year) and payment at \( T \geq \tau \), with notional \( N \). This includes timing mismatches such as a Libor rate paid in advance. The forward value of the index is \( \delta \tau L_f(t,T_f,T_f+\tau) = P_f(t,T_f)/P_f(t,T_f+\tau) - 1 \) (where \( \delta \tau \) is the day count fraction of underlying money market index). Ignoring the convexity adjustment and viewed from time \( t \), the present value of the cashflow is: \( V(t) = NP(t,T)(P_f(t,T_f)/P_f(t,T_f+\tau) - 1) \). An application of the Ito-Lemma shows that the add-on will have three components, one coming from the index volatility, another from the cashflow present value and finally, a third component from the basis risk volatility:

B.3 Floating (index) cashflow

For both index volatility and basis spread volatility (adding this will depend on which scenario of Libor fallback is implemented) there will be contributions to two buckets, one for the fixing date and another for the fixing date shifted by the underlying tenor:

1. fixing date:
   - Maturity bucket \( M(T_f) \)
   - Notional: \( NP(0,T)(1 + \delta \tau L_f(0,T_f,T_f+\tau)) \)
   - Duration: \( \frac{1}{a}(1 - e^{-aT_f}) \)
   - Delta : –1

2. payment date of the underlying money market index :
   - Maturity bucket \( M(T_f+\tau) \)
   - Notional: \( NP(0,T)(1 + \tau L_f(0,T_f,T_f+\tau)) \)
   - Duration: \( \frac{1}{a}(1 - e^{-a(T_f+\tau)}) \)
A possible simplification to remain consistent with the rules as they have been formulated, is to set $P(0, T) = 1$. A further simplification would be to aggregate the two maturity buckets and allocate the contribution of the index to the largest maturity.

Contribution from the present value of the cash-flow:

- Maturity bucket $M(T)$
- Notional: $NP(0, T)\tau L_f(0, T_f, T_f + \tau)$
- Duration: $\frac{1}{\sigma}(1 - e^{-aT})$
- Delta : $-1$

Similarly a simplification for this contribution is to set $P(0, T) = 1$.

B.4 CMS cashflow

Constant Maturity Swap Index: we consider a swap rate $S_r(T_s, T_e)$ with fixing time $T_s$ for the maturity $T_e$ with underlying money market index of tenor $\tau$ i.e with floating rate payments at dates $T_{s+1}, ..., T_e$ also with period $\tau$. Let’s assume a cashflow received at time time $T \geq T_s$ that is $\delta(T_s, T_e)NS_r(T_s, T_e)$ (where $\delta(T_s, T_e)$ is the swap tenor). Viewed from time $t \leq T_s$ consider the forward swap rate $S_r(t, T_s, T_e) = \sum_{i=s+1}^{e} w_i(t)L(t, T_i-1, T_i)$ where $w_i(t) = \frac{P(t, T_i)\delta_i(\tau)}{\sum_{i=s+1}^{e} P(t, T_i)\delta_i(\tau)}$.

Ignoring convexity adjustments and viewed from $t$, the present value of the cashflow is:

$$V(t) \approx \delta(T_s, T_e)NP(t, T)S_r(t, T_s, T_e)$$

Since the swap rate can be viewed as a basket of floating flows, again by application of the Ito lemma and using the coefficient freezing approximation, we have the following three different kind of contributions:

1. For each one of the forward rates underlying the CMS index, there will be as for floating rate cashflows, a rates add-on contribution from the rates curve volatility and a basis risk:

   (a) At each fixing date $T_i$ with $T_s \leq T_i \leq T_{e-1}$:
   - Maturity bucket $M(T_i)$
   - Notional: $\delta(T_s, T_e)NP(0, T)w_i(0)(1 + \delta_i(\tau)L(0, T_i, T_{i+1}))$
   - Duration: $\frac{1}{\sigma}(1 - e^{-aT_i})$
   - Delta : $-1$

   (b) At each payment date of the underlying Libor rate:
   - Maturity bucket $M(T_{i+1})$
   - Notional: $\delta(T_s, T_e)NP(0, T)w_i(0).L(0, T_i, T_{i+1})$
   - Duration: $\frac{1}{\sigma}(1 - e^{-aT_{i+1}})$
   - Delta : $1$

To simplify this expression we consider that the curve is flat, so all weights are equal and all forwards equal the swap rate. Then the add-on contributions to all three buckets have the same notional amount $N(1 + \tau S_r(0, T_s, T_e))P(0, T)$, delta of 1 and following durations:
- Bucket $M_1$: $\frac{1}{a}(e^{-a \min(1,T_s)} - e^{-a \min(1,T_e)})$
- Bucket $M_2$: $\frac{1}{a}(e^{-a \min(\max(1,T_s),5)} - e^{-a \min(\max(1,T_e),5)})$
- Bucket $M_3$: $\frac{1}{a}(e^{-a \max(5,T_s)} - e^{-a \max(5,T_e)})$

If the underlying swap does not overlap with a bucket, then there is no contribution to the add-on of that bucket. This preserves the decomposability principle and is also fairly consistent with the limit case where the CMS index is actually a Libor based floating flow as given above.

2. The cashflow contribution is simply:

- Maturity bucket $M(T)$
- Notional: $NP(0,T)S_T(0,T_s,T_e)$ or PV of the cashflow
- Duration: $\frac{1}{a}(1 - e^{-aT})$
- Delta: $-1$

A simplification is again to set $P(0,T) = 1$

**B.5 Year-on-Year inflation cashflow**

Consider a Year-on-Year Inflation linked payoff (base on an inflation curve $P_I(t,T)$ which plays exactly the same role as the projection curve for Libor indices). Assumed the cashflow at a date $T$, is based on a notional $N$ and the performance of the inflation index $I$ between the future dates $T_s$ and $T_e$: $N\left(\frac{P_I(T_e)}{P_I(T_s)} - 1\right)$. This situation is completely analogous to that of floating rate flows with money market indices but the main difference is that there is no basis risk contribution because the inflation curve has its own hedging set. Given that the expected cashflow is given by $N\left(\frac{P_I(T_e)}{P_I(T_s)} - 1\right)$ and its present value is approximatively (by ignoring convexity) $V(t) = P(t,T)N\left(\frac{P_I(T_e)}{P_I(T_s)} - 1\right)$, we have the following contributions to add-ons:

1. Inflation add-on:
   (a) Initial observation date:
   - Maturity bucket $M(T_s)$
   - Notional: $N(1 + V(0))$
   - Duration: $\frac{1}{a}(1 - e^{-aT_s})$
   - Delta: $-1$
   (b) Final observation date:
   - Maturity bucket $M(T_e)$
   - Notional: $N(1 + V(0))$
   - Duration: $\frac{1}{a}(1 - e^{-aT_e})$
   - Delta: $1$

2. Interest rate add-on:
   - Maturity bucket $M(T)$
Notional: \( NV(0) \)

Duration: \( \frac{1}{a} (1 - e^{-aT}) \)

Delta: \(-1\)

We can make the usual simplifications. Moreover if the initial observation date \( T_s \) is in the past, then it should be replaced with the next observation date of the inflation index (usually monthly observation). Moreover this also cover the case of zero coupon inflation or the so-called real coupons.

### B.6 Compounded floating rate index

We consider a compounded floating rate index with notional \( N \)

- Trade date \( t_0 < 0 \)
- Final payment at maturity \( T \geq K\tau + t_0 > 0 \) (so this include potential timing mismatches)
- Payoff at maturity is the initial notional compounded at floating rate index of tenor \( \tau \) observed at dates \( \{ t_k = t_0 + k\tau; 0 \leq k \leq K - 1 \} \):

\[
N \prod_{k=0}^{K-1} (1 + \tau L(t_0 + k\tau, t_0 + (k + 1)\tau))
\]

Define a rolling spot account as for \( t \leq t_0 \):

\[ I(t) = 1 \]

For \( n \geq 1 \):

\[ I(t_0 + (n-1)\tau) = \prod_{k=0}^{n-1} (1 + \tau L(t_0 + k\tau, t_0 + (k + 1)\tau)) \]

And for \( t_0 + n\tau < t < t_0 + (n + 1)\tau \):

\[ I(t) = I(t_0 + n\tau)P(t, t_0 + (n + 1)\tau) \]

Ignoring possible convexity adjustments and viewed from time \( t \) the present value of the cashflow is (with \( \tau_f(t) \) is the next reset after \( t \) and \( \tau_f(t) - \tau \) the previous reset)

\[ V(t) \approx NI(\tau_f(t) - \tau)P(t, T)P_f(t, t_0 + K\tau) / P_f(t, t_0 + K\tau) \]

From an application of Ito’s lemma and as in the case of simple floating cashflow, we see that there are contributions from the index projection, from the basis risk and from the cashflow itself (for the interest rate component, the latter will net off with the contribution from the end of the last compounding period if there is no or little timing mismatch for the payment date):
1. Index volatility and basis risk contributions:

(a) Next reset:
- Maturity bucket $M(\tau_f)$, (where $\tau_f$ represents the time to the next reset)
- Notional: $V(0)$ (the actual present value of the cashflow and not the approximation above which is used just for volatility decomposition)
- Duration: $\frac{1}{a}(1 - e^{-a\tau_f})$
- Delta : $-1$

(b) End of last compounding period :
- Maturity bucket $M(t_0 + K\tau)$
- Notional: $V(0)$
- Duration: $\frac{1}{a}(1 - e^{-a(t_0+K\tau)})$
- Delta : $1$

2. Contribution from discount factor volatility of the cash-flow (this will net off if there is a no mismatch between the end of last compounding period and the cashflow date):
- Maturity bucket $M(T)$
- Notional: $V(0)$
- Duration: $\frac{1}{a}(1 - e^{-aT})$
- Delta : $-1$

A variation could be that the compounding period starts in the future. In that case, the formulae provided are still valid and the next reset date becomes the start of the first compounding period. Another variation of this compounded floating rate index with notional $N$ could be to have a spread on top of the compounding index. And the formulae are still valid provided the present value of the cash-flow is used.

A simplification applicable to all these variations, would be to ignore discount factors and use the projected cashflow instead of their present value $V(0)$.

C Proofs of results

C.1 Proof of Theorem A.2, PFE is conservative non-ATM

Proof. The variation of the mark-to-market of all trades in the netting set is the following i for all times $t > 0$:

$$\Delta V(t) = V(t) - V(0) = \sigma_{total}W_i$$

So :

$$EPE(T) = \frac{1}{T} \int_0^T \mathbb{E} \left[ (V(0) + Y\sqrt{t}\sigma_{total})^+ \right] dt$$
Where $Y$ is a standard normal random variable. Using $(a + b)^+ \leq a^+ + b^+$, we get:

$$EPE(T) \leq 1_{V(0) \leq 0} \frac{1}{T} \int_0^T E \left[ \left( V(0) + Y \sqrt{\tilde{t}} \sigma_{\text{total}} \right)^+ \right] dt$$

$$+ 1_{V(0) > 0} \left( V^+(0) + \frac{1}{T} \int_0^T E \left[ (Y \sqrt{\tilde{t}} \sigma_{\text{total}})^+ \right] dt \right)$$

We deduce from this that:

$$EPE(T) \leq V(0)^+ + \frac{1_{V(0) \leq 0}}{T} \int_0^T E \left[ (V(0) + \sigma_{\text{total}} \sqrt{\tilde{t}} Y)^+ \right] dt \quad (C.1)$$

$$+ 1_{V(0) > 0} \frac{2}{3} \sigma_{\text{total}} \sqrt{\frac{T}{2\pi}}$$

By Fubini Theorem, we obtain:

$$1_{V(0) \leq 0} \int_0^T E \left[ (V(0) + \sigma_{\text{total}} \sqrt{\tilde{t}} Y)^+ \right] dt = 1_{V(0) \leq 0} E \left[ \int_0^T 1_{V(0) \leq \sigma_{\text{total}} \sqrt{\tilde{t}}} (V(0) + \sigma_{\text{total}} \sqrt{\tilde{t}} Y) dt \right]$$

$$\leq 1_{V(0) \leq 0} E \left[ \int_0^T (V(0) + \sigma_{\text{total}} \sqrt{\tilde{t}} Y)^+ dt \right]$$

Because $1_{V(0) \leq \sigma_{\text{total}} \sqrt{\tilde{t}}} Y \leq 1_{V(0) \leq \sigma_{\text{total}} \sqrt{\tilde{t}}} Y$ when $V(0) \leq 0$, we deduce:

$$1_{V(0) \leq 0} \int_0^T E \left[ (V(0) + \sigma_{\text{total}} \sqrt{\tilde{t}} Y)^+ \right] dt \leq 1_{V(0) \leq 0} E \left[ \int_0^T (V(0) + \sigma_{\text{total}} \sqrt{\tilde{t}} Y)^+ dt \right]$$

$$\leq T \left( V(0) + \frac{2}{3} \sigma_{\text{total}} \sqrt{\tilde{T}} Y \right)^+$$

(C.2)

Since

$$E \left[ (V(0) + \frac{2}{3} \sigma_{\text{total}} \sqrt{\tilde{T}} Y)^+ \right] = V(0) \Phi \left( \frac{3V(0)}{2 \sigma_{\text{total}} \sqrt{T}} \right) + \frac{2}{3} \sigma_{\text{total}} \sqrt{\tilde{T}} \varphi \left( \frac{3V(0)}{2 \sigma_{\text{total}} \sqrt{T}} \right)$$

Substituting (C.2) in (C.1), we obtain the inequality (A.14).

Now define for $y \leq 0$, $g(y) = y \Phi \left( \frac{\sqrt{y}}{\sqrt{2}} \right) + e^{-\frac{y^2}{2}} - (1 - f)e^{\varphi \left( \frac{3V(0)}{2 \sigma_{\text{total}} \sqrt{T}} \right)}$. The derivative of $g$ is given by $g'(y) = \Phi \left( \frac{\sqrt{y}}{\sqrt{2}} \right) - \frac{1}{2} e^{\varphi \left( \frac{3V(0)}{2 \sigma_{\text{total}} \sqrt{T}} \right)}$ and its second derivative is $g''(y) = \frac{e^{-\frac{y^2}{2}}}{4\pi} - \frac{1}{4(1 - f)} e^{\varphi \left( \frac{3V(0)}{2 \sigma_{\text{total}} \sqrt{T}} \right)}$. It is to check that $g''$ is negative on $(-\infty, \gamma)$ where $\gamma$ is the negative root of $\frac{e^{-\frac{y^2}{2}}}{4\pi} + \frac{1}{4(1 - f)} e^{\varphi \left( \frac{3V(0)}{2 \sigma_{\text{total}} \sqrt{T}} \right)} - \varphi \left( \frac{3V(0)}{2 \sigma_{\text{total}} \sqrt{T}} \right)$ if it exists and otherwise 0. Since $\lim_{x \to -\infty} g'(x) = 0$, it means that $g'$ is negative on $(-\infty, \kappa)$ for some $\kappa < 0$ and is positive on $(\kappa, 0]$. Since $\lim_{x \to -\infty} g(x) = g(0) = 0$, then $g(y) \leq 0$ for all $y \leq 0$. 

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With this inequality in hand, we conclude that with \( \text{AddOn}_{\text{total}} = \frac{2}{\pi} \sigma_{\text{total}} \sqrt{\frac{t}{2\pi}} \):

\[
EPE_{\text{model}}(T) \leq V(0)^+ + \text{AddOn}_{\text{total}} W \left( \frac{V(0)}{\sqrt{2\pi} \text{AddOn}_{\text{total}}} \right) \quad (C.3)
\]

To obtain (A.15) from (C.3), we just remark that \( \sigma_{\text{total}} \leq \sigma_{\text{agg}} \) and \( W \) is an increasing function of the add-on.

### C.2 Proof of Theorem A.4, SA-CCR Hull-White identity

We consider a payer, i.e. pay-fixed rate \( R \). Let \( (t, T) \) be the maturity of a total coupon swap then we have:

\[
V(t) = N \cdot A(t, T_s, T_e) \cdot (S(t, T_s, T_e) - R) \quad (A.19)
\]

Proof. Since \( \delta_i L(t, T_{i-1}, T_i) = \frac{P(t, T_{i-1})}{P(t, T_i)} = 1 \) and the zero coupon bond process (A.17), we have by Ito- Lemma for \( s + 1 \leq i \leq e \):

\[
\delta_i dL(t, T_{i-1}, T_i) = (..)dt - \frac{\sigma}{a} (e^{-a(T_i-T)} - e^{-a(T_{i-1}-T)}) \frac{P(t, T_{i-1})}{P(t, T_i)} dW_t
\]

So, one hand:

\[
dV_{\text{float}}(t) = r_t V_{\text{float}}(t) dt - \frac{\sigma}{a} N \sum_{i=s+1}^{e} (e^{-a(T_i-T)} - e^{-a(T_{i-1}-T)}) P(t, T_{i-1})dW_t
\]

\[
- \frac{\sigma}{a} N \sum_{i=s+1}^{e} (1 - e^{-a(T_i-T)}) P(t, T_i) \delta_i L(t, T_{i-1}, T_i) dW_t
\]

On the other hand, for the fixed leg:

\[
dV_{\text{fixed}}(t) = r_t V_{\text{fixed}}(t) dt + N \sum_{i=s+1}^{e} P(t, T_i) \frac{\sigma}{a} (1 - e^{-a(T_i-T)}) \delta_i RdW_t
\]

Combining both and with a little algebra, we get what we wanted:

\[
dV(t) = r_t V(t) dt - \frac{\sigma}{a} N \sum_{i=s+1}^{e} (e^{-a(T_i-T)} - e^{-a(T_{i-1}-T)}) P(t, T_{i-1})dW_t
\]

\[
- N \sum_{i=s+1}^{e} P(t, T_i) \frac{\sigma}{a} (1 - e^{-a(T_i-T)}) \delta_i L(t, T_{i-1}, T_i) dW_t
\]

\[
+ N \sum_{i=s+1}^{e} P(t, T_i) \frac{\sigma}{a} (1 - e^{-a(T_i-T)}) \delta_i RdW_t
\]
Consider now, another point of view where we write $V$ as in (C.4), then the dynamics of $V(t)$ are given by:

$$dV(t) = (\ldots)dt + N(S(t, T_e, T_n) - R)dA(t, T_s, T_e) + NA(t, T_s, T_e)\,dS(t, T_s, T_e)$$

We rewrite the swap rate as

$$S(t, T_e, T_n) = \sum_{i=s+1}^{e} w_i(t) L(t, T_{i-1}, T_i)$$

where weights $w_i(t) = \frac{P(t, T_i)}{\sum_{i=s+1}^{e} P(t, T_i)} \delta_i$. We assume that this weight is deterministic (i.e. classical weight freezing approximation):

$$dV(t) = (\ldots)dt + N(S(t, T_e, T_n) - R)dA(t, T_s, T_e) + NA(t, T_s, T_e)\,dS(t, T_s, T_e)$$

From this we see first that if the swap is at-the-money then:

$$\sigma_V(t) \approx N \sum_{i=s+1}^{e} P(t, T_{i-1}) \frac{\sigma}{a} (e^{-a(T_i - T_{i-1})} - e^{-a(T_i - t)}) = \sigma_{ATM}(t)$$

We also notice that under the weight freezing approximation:

$$\sigma_{Float}(t) + \sigma_{Fixed}(t) \approx N(S(t, T_e, T_n) - R) \sum_{i=s+1}^{e} \frac{1}{a} (1 - e^{-a(T_i - t)}) \delta_i P(t, T_i)$$

(D.5)

**D Worked examples**

We provide worked examples for a Floating cashflow and a CMS cashflow.

**D.1 Floating cashflow**

Here we provide an example of how to derive the entries in Section B for a floating coupon for deterministic and stochastic index-vs-discounting basis.

The floating rate cash-flow is based on a money market index with fixing at $T_f$, tenor $\tau$ (less than 1 year) and payment at $T \geq \tau$, with notional $N$.

We ignore convexity so this setup includes timing mismatches such as a Libor rate paid in advance.

The forward value of the index is

$$\delta_s L(t, T_f, T_f + \tau) = P_f(t, T_f)/P_f(t, T_f + \tau) - 1$$

We define the index-vs-discounting basis $P_b$ via

$$P_f(t, s) = P_b(t, s) P(t, s)$$
Ignoring convexity the coupon value is
\[ V(t) = NP(t,T)(P_f(t,T_f)/P_f(t,T_f + \tau) - 1) \]

Applying Ito’s Lemma to \( V(t) \) we see that the instantaneous volatility of \( V(t) \)
has three components, one from the floating rate index volatility, another from the
cashflow’s present value and a third from the basis risk volatility:
\[
dV_t = (\ldots)dt + N[\delta_fL(t,T_f,T_f + \tau)dP(t,T)
+ P(t,T)P_b(t,T_f)/P_f(t,T_f + \tau)dP(t,T_f) + P(t,T)P_f(t,T_f)/P_b(t,T_f + \tau)d(1/P_b(t,T_f + \tau))
+ P(t,T)P(t,T_f)/P_f(t,T_f + \tau)dP_b(t,T_f) + P(t,T)P_f(t,T_f)/P(t,T_f + \tau)d(1/P(t,T_f + \tau))]
\]

No \( dP, dP_b \) terms are present above as these result in drift \((dt)\) contributions
not volatility \((dW)\) contributions.

### D.1.1 Floating coupon: deterministic basis

Assume first that the basis curve is deterministic, then we have for \( P(t,T), P(t,T_f) \) and \( P(t,T_f + \tau) \) the following dynamics from the 3-factor Gaussian
Market Model:
\[
dP(t,T) = (\ldots)dt - \frac{\sigma}{a}(1 - e^{-a(T-t)})P(t,T)dz_t^{M(T)} \quad (D.1)
\]
\[
dP(t,T_f) = (\ldots)dt - \frac{\sigma}{a}(1 - e^{-a(T-t)})P(t,T)dz_t^{M(T_f)} \quad (D.2)
\]
\[
d(\frac{1}{P(t,T_f + \tau)}) = (\ldots)dt + \frac{\sigma}{a}(1 - e^{-a(T_f + \tau - t)})\frac{1}{P(t,T_f + \tau)}dz_t^{M(T_f + \tau)} \quad (D.3)
\]

Hence
\[
dV_t = r_tV_tdt - \frac{\sigma}{a}(1 - e^{-a(T-t)})P(t,T)\delta_fL(t,T_f,T_f + \tau)dz_t^{M(T)}
- \frac{\sigma}{a}(1 - e^{-a(T_f - t)})P(t,T)N(1 + \delta_fL(t,T_f,T_f + \tau))dz_t^{M(T_f)} \quad (D.4)
+ \frac{\sigma}{a}(1 - e^{-a(T_f + \tau - t)})P(t,T)N(1 + \delta_fL(t,T_f,T_f + \tau))dz_t^{M(T_f + \tau)}
\]

From Equation D.4 we see that the floating rate cash-flow add-ons bucket contributions are:

1. contribution from the present value of the cash-flow:
   - Maturity bucket \( M(T) \)
   - Notional: \( NP(0,T)\delta_fL(0,T_f,T_f + \tau) \)
   - Duration: \( \frac{1}{a}(1 - e^{-aT}) \)
   - Delta: \(-1\)

2. index volatility: fixing date contribution
   - Maturity bucket \( M(T_f) \)
   - Effective Notional: \( NP(0,T)(1 + \delta_fL(0,T_f,T_f + \tau)) \)
   - Duration: \( \frac{1}{a}(1 - e^{-aT_f}) \)
   - Delta: \(-1\)
3. index volatility: payment date contribution

- Maturity bucket $M(T_f + \tau)$
- Effective Notional: $NP(0,T)(1 + \tau L(0,T_f,T_f + \tau))$
- Supervisory Duration: $\frac{1}{\delta}(1 - e^{-a(T_f + \tau)})$
- Delta : 1

D.1.2 Floating coupon: stochastic basis

If we assume a stochastic basis spread curve (some implementation scenarios for Libor decommissioning fallback may make this irrelevant) as

$$dP_b(t,T_f) = (...)dt - \frac{\sigma_b}{\alpha}(1 - e^{-a(T_f-t)})P_b(t,T_f)dZ^{M(T_f)}_t$$

$$d\left(\frac{1}{P_b(t,T_f + \tau)}\right) = (...)dt + \frac{\sigma_b}{\alpha}(1 - e^{-a(T_f+\tau-t)})\frac{1}{P_b(t,T_f + \tau)}dZ^{M(T_f+\tau)}_t$$

The volatility of $V(t)$ adds basis contributions

$$dV_t = (...)dt + (...)dZ^M_t + (...)dZ^t_t + (...)dZ^{M(T_f+\tau)}_t$$

$$- \frac{\sigma_b}{\alpha}(1 - e^{-a(T_f-t)})P(t,T)N(1 + \delta L(t,T_f,T_f + \tau))dZ^{M(T_f)}_t$$

$$+ \frac{\sigma_b}{\alpha}(1 - e^{-a(T_f+\tau-t)})P(t,T)N(1 + \delta L(t,T_f,T_f + \tau))dZ^{M(T_f+\tau)}_t$$

This gives additional contributions to two buckets, one for the fixing date and another for the fixing date shifted by the underlying tenor:

4. fixing date:

- Maturity bucket $M(T_f)$
- Effective Notional: $NP(0,T)(1 + \delta L(0,T_f,T_f + \tau))$
- Duration: $\frac{1}{\delta}(1 - e^{-aT_f})$
- Delta : -1

5. payment date of the underlying money market index :

- Maturity bucket $M(T_f + \tau)$
- Effective Notional: $NP(0,T)(1 + \tau L(0,T_f,T_f + \tau))$
- Supervisory Duration: $\frac{1}{\delta}(1 - e^{-a(T_f + \tau)})$
- Delta : 1

D.2 CMS cashflow

We consider a swap rate $S_{\tau}(T_s,T_e)$ with fixing time $T_s$ for the maturity $T_e$ with underlying money market index of tenor $\tau$ i.e with floating rate payments at dates $T_{s+1},..,T_e$ also with period $\tau$. Let’s assume a cashflow received at time time $T \geq T_s$ that is $\delta(T_s,T_e)NS_{\tau}(T_s,T_e)$ (where $\delta(T_s,T_e)$ is the swap tenor). Viewed from time $t \leq T_s$ consider the forward swap rate $S_{\tau}(t,T_s,T_e) =$
\[ \sum_{s=1}^{e} w_i(t) L(t, T_{i-1}, T_i) \] where \( w_i(t) = \frac{P(t, T_i) \delta_i(t)}{\sum_{s=1}^{e} P(t, T_s) \delta_i(t)} \). Ignoring convexity adjustments and viewed from \( t \), the present value of the cashflow is:

\[ V(t) \approx \delta(T_s, T_e) NP(t, T) S_r(t, T_s, T_e) = \delta(T_s, T_e) NP(t, T) \sum_{i=s+1}^{e} w_i(t) L(t, T_{i-1}, T_i) \]

We then apply Ito-lemma and assume that \( w_i(t) \) is deterministic (this is related to the fact that the present value of an at-the-money swap is sensitive only to the changes in value of the par swap rate and not the Annuity, as such this approximation also ignores convexity). We assume moreover that \( w_i(t) \approx \frac{\delta_i(t)}{\sum_{s=1}^{e} \delta_i(t)} \) i.e we ignore the dependency of the par swap rate on the discount curve and consider the par swap rate as a deterministic basket of forward rates. We obtain:

\[ dV(t) = (...) dt + \delta(T_s, T_e) NS_r(t, T_s, T_e) dP(t, T) \]

\[ \delta(T_s, T_e) NP(t, T) \sum_{i=s+1}^{e} w_i(t) dL(t, T_{i-1}, T_i) \quad (D.5) \]

Since, we have :

\[ dP(t, T) = (...) dt - \frac{\sigma}{a} (1 - e^{-a(T-t)}) P(t, T) dZ_t^M(T) \quad (D.6) \]

And for all, \( s + 1 \leq i \leq e \):

\[ \delta_i(t) dL(t, T_{i-1}, T_i) = \frac{\sigma}{a} (1 - e^{-a(T_{i-1}-t)}) P(t, T) N(1 + \delta_i(t) L(t, T_{i-1}, T_i)) dZ_t^M(T_i) \]

\[ - \frac{\sigma}{a} (1 - e^{-a(T_{i-1}-t)}) P(t, T) N(1 + \delta_i(t) L(t, T_{i-1}, T_i)) dZ_t^M(T_{i-1}) \]

\[ (D.7) \]

We make the additional assumption (or approximation) that the projection curve is flat and therefore for all, \( s + 1 \leq i \leq e \) the forward rates \( L(t, T_{i-1}, T_i) \) are equal, so \( L(t, T_{i-1}, T_i) \approx S_r(t, T_s, T_e) \). We simplify now the dynamics of the PV of a CMS flow by substituting (D.6) and (D.7) into (D.5) :

\[ dV(t) = r(t)V(t) dt - \delta(T_s, T_e) NS_r(t, T_s, T_e) \frac{\sigma}{a} (1 - e^{-a(T-t)}) P(t, T) dZ_t^M(T) \]

\[ + P(t, T) N(1 + \tau S_r(t, T_s, T_e)) \sum_{i=s+1}^{e} \frac{\sigma}{a} (1 - e^{-a(T_{i-1}-t)}) dZ_t^M(T_i) \]

\[ - P(t, T) N(1 + \tau S_r(t, T_s, T_e)) \sum_{i=s+1}^{e} \frac{\sigma}{a} (1 - e^{-a(T_{i-1}-t)}) dZ_t^M(T_{i-1}) \]

This expression can be simplified further by netting out the contributions by maturity buckets that the underlying swap rate overlaps with and obtain :
\[ dV(t) = r_t V(t) dt - \delta(T_s, T_e) N S_r(t, T_s, T_e) \frac{\sigma}{\alpha} (1 - e^{-a(T-t)}) P(t, T) dZ_t^M(T) \]
\[ + P(t, T) N(1 + \delta_i(\tau) S_r(t, T_s, T_e)) \sum_{T_{i-1} < 1, T_i \geq 1} \frac{\sigma}{\alpha} [(e^{-a(T_{i-1} - t)} - 1) dZ_t^{M_1} + (1 - e^{-a(T_{i-1})}) dZ_t^{M_2}] \]
\[ + P(t, T) N(1 + \delta_i(\tau) S_r(t, T_s, T_e)) \sum_{T_{i-1} < 5, T_i \geq 5} \frac{\sigma}{\alpha} [(e^{-a(T_{i-1} - t)} - 1) dZ_t^{M_2} + (1 - e^{-a(T_{i-1})}) dZ_t^{M_3}] \]
\[ + P(t, T) N(1 + \delta_i(\tau) S_r(t, T_s, T_e)) \sum_{T_{i-1} \geq 5} \frac{\sigma}{\alpha} (e^{-a(T_{i-1} - t)} - e^{-a(T_{i-1})}) dZ_t^{M_3} \]

We finally just allocate the contributions at turning points (i.e. underlying Libor rates across maturity buckets) to the end points of the maturity bucket and obtain the following expression for the add-on: the add-on contributions to all three buckets have the same notional amount \(N(1 + \tau S_r(0, T_s, T_e)) P(0, T)\), delta of 1 and following durations:

- Bucket \(M_1\): \(\frac{1}{4} (e^{-a \min(1, T_s)} - e^{-a \min(1, T_e)})\)
- Bucket \(M_2\): \(\frac{1}{4} (e^{-a \min(\max(1, T_s), 5)} - e^{-a \min(\max(1, T_e), 5)})\)
- Bucket \(M_3\): \(\frac{1}{4} (e^{-a \max(5, T_s)} - e^{-a \max(5, T_e)})\)

If the underlying swap does not overlap with a bucket, then there is no contribution to the add-on of that bucket. This preserves the decomposability principle and is also fairly consistent with the limit case where the CMS index is actually a Libor based floating flow as given above.

The cashflow contribution has simply the following characteristics:

- Maturity bucket \(M(T}\)
- Notional: \(N \delta(T_s, T_e) P(0, T) S_r(0, T_s, T_e)\) or PV of the cashflow
- Duration: \(\frac{1}{a} (1 - e^{-a T})\)
- Delta: -1

A simplification is again to set \(P(0, T) = 1\)

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