Interest Rate Theory in the Presence of Multiple Yield Curves – An FX-like Approach

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Outline

1 Introduction and Motivation

2 The General FX-like Setting

3 Outlook
We consider the following zero-coupon bonds with maturity $T$:

<table>
<thead>
<tr>
<th>Type</th>
<th>non-defaultable</th>
<th>defaultable</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>t-Price</strong></td>
<td>$P(t, T)$</td>
<td>$\tilde{P}(t, T)$</td>
</tr>
<tr>
<td><strong>Payoff</strong></td>
<td>$P(T, T) = 1$</td>
<td>$0 &lt; \tilde{P}(T, T) \leq 1$ (random)</td>
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</tbody>
</table>
We introduce a third term structure $Q(t, T) := \tilde{P}(t, T) \tilde{P}(t, t)$.

Observation: $Q(T, T) = 1$, $\tilde{P}(t, T) = \tilde{P}(t, t)$. $Q(t, T) =: StQ(t, T)$.

Paradigm (Jarrow & Turnbull 1991) $\tilde{P}(t, T)$ may be interpreted as conversion of foreign default-free counterparts. $StQ(t, T)$ is referred to as recovery rate or spot FX rate at time $t$. 
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Multiple Default Model and Fractional Recovery

\[ r_t = (r_t)_{t \geq 0} \]

is the short rate process w.r.t. EMM \( Q \),

\[ N_t = (N_t)_{t \geq 0} \]

is a Cox-process with intensity \( \lambda_t = (\lambda_t)_{t \geq 0} \) and jumps at the random times \( \{\tau_i\}_{i \in N} \),

\[ s_t = (s_t)_{t \geq 0} \]

is a \((0, 1)\)-valued loss quota process with first moments \( s_t = \mathbb{E}_Q[s_t] \),

\[ dS_t = -S_t - s_t dN_t, \quad S_0 = 1 \]

is the recovery rate process.

Theorem (Duffie-Singleton, Schönbucher)

Under suitable technical assumptions, we have for all \( 0 \leq t \leq T < \infty \)

\[ \tilde{P}(t, T) = \left( \prod_{\tau_i \leq t} (1 - s_{\tau_i}) \right) \]

\[ \mathbb{E}_Q\left[ e^{-\int_T^t r_u + s_u \lambda_u du} | \mathcal{F}_t \right] = Q(t, T). \]
Multiple Default Model and Fractional Recovery

\[ r = (r_t)_{t \geq 0} \]
short rate process w.r.t. EMM \( \mathbb{Q} \),

\[ N = (N_t)_{t \geq 0} \]
Cox-process with intensity \( \lambda = (\lambda_t)_{t \geq 0} \) and jumps at the random times \( \{\tau_i\}_{i \in \mathbb{N}} \),

\[ s = (s_t)_{t \geq 0} \]
(0, 1)-valued loss quota process with first moments \( \bar{s}_t := E_{\mathbb{Q}}[s_t] \),

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\[ = S_t \quad = Q(t, T) \]
Aspects of the FX-like Approach

FX-models are well-understood and widely used. Multi-currency models for FX rates in a target zone are of particular interest in our case.

The introduction of the foreign market is subject to knowing the recovery rate. The recovery rate is only observable sporadically, if at all.

The FX-like approach allows for interpretations that comply with the common economic intuition, e.g., the differentiation between liquidity squeezes and true default events.

The recovery rate admits a natural economic interpretation by characterising to what extent the related party is able to meet its imminent financial obligations. However, what is a meaningful recovery rate in time instances in which no payments are due?
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The General FX-like Setting

Let \((\Omega, \mathcal{F}, \mathcal{F}, \mathbb{P})\) with \(\mathcal{F} = (\mathcal{F}_t)_{t \geq 0}\) be a filtered probability space satisfying the usual conditions. We consider three \(\mathcal{F}\)-adapted series of zero-coupon bond prices, where the properties on the right-hand side shall hold a.s. for all maturities \(T \geq 0\).

\[
\left\{ \mathbb{P}(t, T) \right\}_{0 \leq t \leq T < \infty}
\]
Domestic non-defaultable zero-coupon bonds with payoff \(\mathbb{P}(T, T) = 1\).

\[
\left\{ \tilde{\mathbb{P}}(t, T) \right\}_{0 \leq t \leq T < \infty}
\]
Domestic defaultable zero-coupon bonds with a random payoff \(0 < \tilde{\mathbb{P}}(T, T) \leq 1\).

\[
\left\{ \mathbb{Q}(t, T) \right\}_{0 \leq t \leq T < \infty}
\]
Synthetic foreign non-defaultable zero-coupon bonds satisfying the relation \(\mathbb{Q}(t, T) = \tilde{\mathbb{P}}(t, T) \tilde{\mathbb{P}}(t, t)\).
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\[
\{ P(t, T) \}_{0 \leq t \leq T < \infty} \quad \text{Domestic non-defaultable zero-coupon bonds with payoff } P(T, T) = 1.
\]

\[
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\{ Q(t, T) \}_{0 \leq t \leq T < \infty} \quad \text{Synthetic foreign non-defaultable zero-coupon bonds satisfying the relation}
\]

\[
Q(t, T) = \frac{\tilde{P}(t, T)}{\tilde{P}(t, t)}.
\]
The General FX-like Setting

Moreover, we consider the following two \( F \)-adapted processes:

\[ B_t = (B_t)_{t \geq 0} \]

Domestic risk-free bank account with initial value of 1 monetary unit.

\[ S_t = (S_t)_{t \geq 0} \]

Recovery/FX rate process satisfying \( S_t \equiv \tilde{P}(t, t) \).

Having the Fundamental Theorem of Asset Pricing for frictionless markets in mind, we assume that there exists an equivalent local martingale measure (ELMM) \( Q \approx P \) such that the discounted processes

\[ \left( P(t, T) B_t \right)_{0 \leq t \leq T}, \]

\[ \left( S_t Q(t, T) B_t \right)_{0 \leq t \leq T} = \left( \tilde{P}(t, T) B_t \right)_{0 \leq t \leq T} \]

are local \( Q \)-martingales for all \( T \geq 0 \).

Corresponding HJM-framework: Amin and Jarrow Economy, [AJ1991]
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\left( \frac{P(t, T)}{B_t} \right)_{0 \leq t \leq T}, \quad \left( \frac{S_t Q(t, T)}{B_t} \right)_{0 \leq t \leq T} = \left( \frac{\tilde{P}(t, T)}{B_t} \right)_{0 \leq t \leq T}
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*Corresponding HJM-framework: Amin and Jarrow Economy, [AJ1991]*
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The Forward Recovery/FX Rate

In multi-currency settings, the ratio 

\[ F(t, T) := \tilde{P}(t, T) \frac{P(t, T)}{Q(t, T)} \]

is usually referred to as forward FX rate. As seen from time \( t \), the agreement to exchange one foreign monetary unit for locked-in domestic monetary units at time \( T \) is at arm’s length and worth zero. Obviously it holds 

\[ \tilde{P}(t, T) = F(t, T) \frac{P(t, T)}{Q(t, T)} \]

\( F(t, T) \) shall refer to as forward recovery rate.

If \( Q \) is an EMM and \( Q_T \) denotes the induced \( T \)-forward measure associated with the numéraire \( P(t, T) \), then 

\[ (F(t, T))_{0 \leq t \leq T} \]

defines a \( Q_T \)-martingale.
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If \( Q \) is an EMM and \( \mathbb{Q}^T \) denotes the induced \( T \)-forward measure associated with the numéraire \( (P(t, T))_{0 \leq t \leq T} \), then \( (F(t, T))_{0 \leq t \leq T} \) defines a \( \mathbb{Q}^T \)-martingale.
Arbitrage-Free Interpolation
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$t \rightarrow P(t, T)$

$T_i \rightarrow \tilde{P}(t, T_i)$

$S_t \rightarrow 1$
We assume that a intermittent but arbitrage-free interest rate framework is given w.r.t. EMM $\mathbb{Q}$:

$$B = (B_t)_{t \geq 0}$$

bank account numéraire,

$$[t, \infty) \longrightarrow \mathbb{R}, \; T \longmapsto P(t, T)$$

comprehensive term structure for non-defaultable bonds for any $t \geq 0$,

$$0 = T_0 < T_1 < \ldots < T_N = T^*$$

discrete tenor structure,

$$(\tilde{P}(t, T_i))_{0 \leq t \leq T_i}$$

inferrable defaultable bond prices for $i = 1, 2, \ldots, N$. 
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inferrable defaultable bond prices for $i = 1, 2, \ldots, N$.

Objective: Complementing this setting to an enhanced credit risk framework by interpolating the discrete defaultable term structure in the maturity dimension.
Let $k(T) := \max\{i = 1, 2, \ldots, N | T_i - 1 < T\}$ be the index of the next upcoming gridpoint and $\vartheta: T \rightarrow [0, 1]$ be any (deterministic) RCLL function with $
abla T_i + \delta \rightarrow 0^+$ $
abla T_i + 1 - \delta \rightarrow 0$ for all $i = 0, 1, \ldots, N - 1$.

We make for all $T \in [0, T^\ast]$ the ansatz

$$S_T := \vartheta(T) \frac{1}{P(T, T_k(T) - 1, T)} S_{T_k(T) - 1} + (1 - \vartheta(T)) \frac{1}{P(T, T_k(T))} F(T, T_k(T)).$$
Arbitrage-Free Interpolation

Let

\[ k(T) := \max \{ i = 1, 2, \ldots, N \mid T_{i-1} < T \} \]

be the index of the next upcoming gridpoint and \( \vartheta : \mathbb{T} \to [0, 1] \) be any (deterministic) RCLL function with

\[
\lim_{\delta \to 0^+} \vartheta(T_i + \delta) = 1, \quad \lim_{\delta \to 0^+} \vartheta(T_{i+1} - \delta) = 0
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for all \( i = 0, 1, \ldots, N - 1 \).

We make for all \( T \in [0, T^*] \) the ansatz

\[
S_T := \vartheta(T) \frac{1}{P(T_{k(T)-1}, T)} S_{T_{k(T)-1}} + (1 - \vartheta(T)) P(T, T_{k(T)}) F(T, T_{k(T)}).
\]
Arbitrage-Free Interpolation

\[
F(t, T) := \vartheta(T') \frac{P(t, T)}{P(t, T')} F(t, T_{k(T')-1}) + (1 - \vartheta(T')) \frac{P(t, T_{k(T')})}{P(t, T')} F(t, T_{k(T')}).
\]

\[
F(t, T_{k(T')-1}) := \vartheta(T') \frac{P(t, T_{k(T')-1})}{P(t, T)} F(t, T_{k(T')-1}) + (1 - \vartheta(T')) \frac{P(t, T_{k(T')})}{P(t, T')} F(t, T_{k(T')}).
\]
More precisely,

\[ F(t, T) := \begin{cases} 
\vartheta(T) \frac{P(t, T_{k(T)-1})}{P(t, T)} F(t, T_{k(T)-1}) + (1 - \vartheta(T)) \frac{P(t, T_{k(T)})}{P(t, T)} F(t, T_{k(T)}) & \text{, if } t \leq T_{k(T)-1}, \\
\vartheta(T) \frac{1}{P(T_{k(T)-1}, T)} S_{T_{k(T)-1}} + (1 - \vartheta(T)) \frac{P(t, T_{k(T)})}{P(t, T)} F(t, T_{k(T)}) & \text{, if } t > T_{k(T)-1}. 
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\vartheta(T) \frac{1}{P(T_{k(T)}-1, T)} S_{T_{k(T)}-1} + (1 - \vartheta(T)) \frac{P(t, T_{k(T)})}{P(t, T)} F(t, T_{k(T)}) & \text{, if } t > T_{k(T)}-1.
\end{cases}
\]

**Proposition**

Let the intermittent interest rate framework be given. If one follows the proposed interpolation scheme, then \((F(t, T))_{0 \leq t \leq T}\) forms a \(\mathcal{Q}^T\)-martingale for each \(T \in [0, T^*]\).
More precisely,

\[ F(t, T) := \begin{cases} 
\vartheta(T) \frac{P(t, T_{k(T) - 1})}{P(t, T)} F(t, T_{k(T) - 1}) + (1 - \vartheta(T)) \frac{P(t, T_{k(T)})}{P(t, T)} F(t, T_{k(T)}) & \text{if } t \leq T_{k(T) - 1}, \\
\vartheta(T) \frac{1}{P(T_{k(T) - 1}, T)} S_{T_{k(T) - 1}} + (1 - \vartheta(T)) \frac{P(t, T_{k(T)})}{P(t, T)} F(t, T_{k(T)}) & \text{if } t > T_{k(T) - 1}.
\end{cases} \]

**Proposition**

Let the intermittent interest rate framework be given. If one follows the proposed interpolation scheme, then \((F(t, T))_{0 \leq t \leq T}\) forms a \(\mathbb{Q}^T\)-martingale for each \(T \in [0, T^*]\).

- Remarkably, the scheme implies arbitrage-free dynamics for the forward recovery rate and works irrespective of the underlying distributions.
- It provides a very nice option of what a meaningful (forward) recovery rate may be in time instances in which no payments are due.
Outline

1. Introduction and Motivation
2. The General FX-like Setting
3. Outlook
[CFG2014] provides a general HJM-framework for multiple yield curve modelling. Each Libor rate to a certain tenor has its own foreign market.
Outlook (work in progress)
Modelling of the interbank market and credit derivatives based on one foreign market
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Aspects of liquidity, [FT2013]
Modelling of the interbank market and credit derivatives based on one foreign market

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Outlook (work in progress)

- Modelling of the interbank market and credit derivatives based on one foreign market

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  - Asset liquidity / liquidity in the interbank market: Concept of eligible numéraires, [KST2013]
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Intertwinement of liquidity risk with credit risk
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[CFG2014] Cuchiero, C., Fontanta, C. and Gnoatto, A.

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