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Discounting Revisited. Valuations under Funding Costs, Counterparty Risk and Collateralization.

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Valuations under Funding Costs, Counterparty Risk and Collateralization.

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Abstract

Looking at the valuation of a swap when funding costs and counterparty risk are neglected (i.e., when there is a unique risk free discounting curve), it is natural to ask “What is the discounting curve of a swap in the presence of funding costs, counterparty risk and/or collateralization”.

In this note we try to give an answer to this question. The answer depends on who you are and in general it is “There is no such thing as a unique discounting curve (for swaps).” Our approach is somewhat “axiomatic”, i.e., we try to make only very few basic assumptions. We shed some light on use of *own credit risk* in mark-to-market valuations, giving that the mark-to-market value of a portfolio increases when the owner’s credibility decreases.

We presents two different valuations. The first is a mark-to-market valuation which determines the liquidation value of a product. It does, by construction, exclude any funding cost. The second is a portfolio valuation which determines the replication value of a product including funding costs.

We will also consider counterparty risk. If funding costs are presents, i.e., if we value a portfolio by a replication strategy then counterparty risk and funding are tied together:

- In addition to the default risk with respect to our exposure we have to consider the loss of a potential funding benefit, i.e., the impact of default on funding.
- Buying protection against default has to be funded itself and we account for that.

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Contents

| | | |
|----------|--|-----------|
| 1 | Introduction | 4 |
| 1.1 | Two Different Valuations | 4 |
| 1.2 | Related Works | 4 |
| 2 | Discounting Cash Flows: The Third Party (Mark-to-Market) Liquidation View | 6 |
| 2.1 | Discount Factors for Outgoing and Incoming Cash Flows | 6 |
| 2.1.1 | Valuation of a Fixed Coupon Bond | 6 |
| 2.2 | Counterparty Risk | 7 |
| 2.2.1 | Example | 7 |
| 2.3 | Netting | 7 |
| 2.4 | Valuation of Stochastic Cash Flows | 8 |
| 2.4.1 | Example: A simple approach to construct a multi-curve model | 8 |
| 2.5 | Credit Linking | 9 |
| 2.5.1 | Examples | 9 |
| 2.6 | Collateralization | 10 |
| 2.6.1 | Interpretation | 11 |
| 2.6.2 | Example | 11 |
| 2.6.3 | Full Bilateral Collateralization | 12 |
| 3 | Discounting Cash Flows: The Hedging View | 13 |
| 3.1 | Moving Cash Flow through Time | 13 |
| 3.1.1 | Moving Positive Cash to the Future | 14 |
| 3.1.2 | Moving Negative Cash to the Future | 14 |
| 3.1.3 | Hedging Negative Future Cash Flow | 14 |
| 3.1.4 | Hedging Positive Future Cash Flow | 14 |
| 3.2 | Construction of Forward Bonds | 14 |
| 3.2.1 | Forward Bond 1: Hedging Future Incoming Cash with Outgoing Cash | 15 |
| 3.2.2 | Forward Bond 2: Hedging Future Outgoing Cash with Incoming Cash | 15 |
| 3.2.3 | Forward Bond 1': Hedging Future Credit Linked Incoming Cash with Credit Linked Outgoing Cash | 15 |
| 3.2.4 | Price of Counterparty Risk Protection | 16 |
| 3.2.5 | Example: Expressing the Forward Bond in Terms of Rates | 16 |
| 3.2.6 | Interpretation: Funding Cost as Hedging Costs in Cash Flow Management | 17 |
| 3.3 | Valuation with Hedging Costs in Cash flow Management (Funding) | 17 |
| 3.3.1 | Interest for Borrowing and Lending | 18 |
| 3.3.2 | From Static to Dynamic Hedging | 18 |
| 3.3.3 | Valuation of a Single Product including Cash Flow Costs | 19 |
| 3.3.4 | Valuation within a Portfolio Context - Valuing Funding Benefits | 19 |
| 3.4 | Valuation with Counterparty Risk and Funding Cost | 20 |
| 3.4.1 | Static Hedge of Counterparty Risk in the Absence of Netting | 20 |

| | | |
|----------|---|-----------|
| 3.4.2 | Dynamic Hedge of Counterparty Risk in the Presence of Netting | 21 |
| 3.4.3 | Interpretation | 23 |
| 3.4.4 | The Collateralized Swap with Funding Costs | 23 |
| 4 | The Relation of the Different Valuations | 23 |
| 4.1 | One Product - Two Values | 24 |
| 4.2 | Valuation of a Bond | 25 |
| 4.2.1 | Valuation of a Bond at Mark-To-Market | 25 |
| 4.2.2 | Valuation of a Bond at Funding | 25 |
| 4.3 | Convergence of the two Concepts | 25 |
| 5 | Credit Valuation Adjustments | 26 |
| 6 | Modeling and Implementation | 27 |
| 7 | Conclusion | 28 |
| | References | 29 |

1 Introduction

Looking at the valuation of a swap when funding costs and counterparty risk are neglected (i.e., when there is a unique risk free discounting curve), it is natural to ask “What is the discounting curve of a swap in the presence of funding costs, counterparty risk and/or collateralization”.

The answer depends on who you are and how we value. Factoring in funding costs the answer to that question is “There is no such thing as a unique discounting curve (for swaps).”

1.1 Two Different Valuations

In Section 2 we will first take a simplified view in valuing claims and cash flows: We view the market price of a zero coupon bond as the value of a claim and value all claims according to such zero coupon bond prices. However, this is only one point of view. We could call it the third party (mark-to-market) liquidation view which is to ask what is the value of a portfolio of claims if we liquidate it today. This approach does not value funding cost.

In Section 3 we will then construct a different valuation which includes the funding costs of net cash requirements. These funding costs occur over the life time of the product. They are of course not present if the portfolio is liquidated. This alternative valuation will also give an answer to an otherwise puzzling problem: In the mark-to-market valuation it appears that the value of the portfolio increases if its credit rating decreases (because liabilities are written down). However, if we include the funding cost, then the effect is reversed since funding costs are increased, and since we are not liquidating the portfolio we have to factor them in.

The difference of the two valuations is their point of view. Liquidating a portfolio we value it from “outside” as a third party. Accounting for operational cost we value it from the “inside”. The two parties come to different values because of a very simple fact: We cannot short sell our own bond (sell protection on our self). However, a third party can do.

1.2 Related Works

The backward algorithm to value under different curves for borrowing and lending was already given in the textbook [4]. Some of our examples below (e.g., the multi-curve model using deterministic default intensities in Section 2.4.1) were also taken from this book.

The usual setup of other papers discussing “multiple” curves is to consider a two or three curve valuation framework: one (forward) curve for the indices (forward rates and swap rates), one (discounting) curve for collateralized deals and one (discounting) curve for funded deals, see, e.g., [1, 9]. However, as we will illustrate, funding cost and netting agreements may imply that there is no such thing as a product independent discounting curve.

Piterbarg [8] discusses the effects of the correlation term induced by a mismatch of the index and the discounting curve, i.e., convexity adjustments. Those convexity adjustment are reflected by our (numerical) valuation algorithm once corresponding

assumptions (e.g., correlations of rates and spreads) are introduced into the underlying model.¹ The formulas derived in [8] are of great importance since they can be used to provide efficient approximations for a multi-curve model's calibration products.

For the modeling of rates (e.g., through basis swap spreads) see, e.g., [5].

In [7] Morini and Prampolini considered a zero coupon bond together with its funding and counterparty risk. They showed that, for a zero coupon, the mark-to-market valuation including own credit can be re-interpreted as a funding benefit. However, their argument relies on the fact that there is a premium paid which can be factored in as a funding benefit, i.e., they consider the liquidation or inception of the deal (i.e., they consider a mark-to-market valuation). Doing so, the premium paid for a future liability can always function as funding, hence funding cost beyond the bond-cds basis do not occur. Our approach is more general in the sense that we consider the true net cash position. The net cash position will give rise to a complex discounting algorithm, where a funding benefit may or may not occur (in a stochastic way). Morini and Prampolini clarify the relation of the so called bond-cds-basis, i.e. the difference between bond spread and cds spread. In theory a defaultable bond for which one buys protection should equal a non defaultable bond as long as the protection itself cannot default. However, market prices often do not reflect that situation, which is attributed to liquidity aspects of the products. See also the short comment after equation (2).

For the valuation of CVAs using the modeling of default times / stopping times to value the contract under default see [2] and Section 8 in [6]. In the latter a homogeneity assumption is made resulting in $P^A(T; t) = P^B(T; t)$. In contrast to the CVA approach modeling default times we considered market prices of zero coupon bonds only and the valuation would require a model of the zero coupon bond process (one way is to model default times, another is to model spreads and survival probabilities). With the possible exception of the Section 6 on "Modeling" we did not explicitly model the impact of liquidity or default risk.

¹ Our presentation is essentially "model free".

2 Discounting Cash Flows: The Third Party (Mark-to-Market) Liquidation View

Let us first take the point of view of being a third party and value claims between to other entities A and B. We lay the foundation of discounting, which is given by considering a single financial product: *the zero coupon bond*. Discounting, i.e., discount factors are given by the price at which a zero coupon bond can be sold or bought. Let us formalize this set up:

2.1 Discount Factors for Outgoing and Incoming Cash Flows

Assume entity A can issue a bond with maturity T and notional 1. By this we mean that A offers the financial product which offers the payment of 1 in time T . Let us denote the time t market price of this product by $P^A(T; t)$. This is the value at which the market is willing to buy or sell this bond.

Likewise let $P^B(T; t)$ denote the price at which the market is willing to buy or sell bonds issued by some other entity B.

Assume that A receives a cash flow $C(T) > 0$ from entity B. This corresponds to A holding a zero coupon bond from entity B having notional $C(T)$ and maturity T . Hence, the time T value of this isolated cash flow is $C(T)P^B(T; T)$ (seen from A's perspective). Given that $C(T)$ is not stochastic, the time $t < T$ value of this isolated cash flow then is $C(T)P^B(T; t)$. We will call this cash flow "incoming", however we want to stress that we view ourself as a third party independent of A and B trading in bonds. Thus we have: $P^B(T; t)$ is the discount factor of all *incoming cash flows* from entity B.

Consider some other contract featuring a cash flow $C(T) > 0$ from A to B at time T . The time T value of this cash flow is $-C(T)P^A(T; T)$, where we view the value from A's perspective, hence the minus sign. We will call this cash flow outgoing, however we want to stress again that view ourself as a third party independent of A and B trading in bonds. Given that $C(T)$ is not stochastic, the time $t < T$ value of this isolated cash flow then is $C(T)P^A(T; t)$. Thus we have: $P^A(T; t)$ is the discount factor of all *outgoing cash flows* of entity A.

Since we view ourself as a third party, we have that in this framework the discount factor of a cash flow is determined by the value of the zero coupon bonds of the originating entity.

If we view a cash flow $|C(T)|$ between A and B from the perspective of the entity A such that $C(T) > 0$ means that the cash flow is incoming (positive value for A) and $C(T) < 0$ means that the cash flow is outgoing, then its time T value can be written as

$$\min(C(T), 0) P^A(T; T) + \max(C(T), 0) P^B(T; T).$$

2.1.1 Valuation of a Fixed Coupon Bond

The knowledge of the discount factors allows the valuation of a fixed coupon bond, because here all future cash flows have the same origin.

2.2 Counterparty Risk

The price $P^A(T; t)$ contains the time-value of a cash flow from **A** (e.g., through a risk free interest rate) and the counterparty risk of **A**.

Usually we expect

$$0 \leq P^A(T; T) \leq 1,$$

and due to **A**'s credit risk we may have $P^A(T; T, \omega) < 1$ for some path ω . As a consequence, we will often use the symbol $P^A(T; T)$ which would not be present if counterparty risk (and funding) would have been neglected.

In Section 2.6 we will see a case where $P^{Ac}(T; T, \omega) > 1$ will be meaningful for some "virtual" entity A_C , namely for over-collateralized cash flows from **A**.

2.2.1 Example

If we do not consider "recoveries" then $P^A(T; T, \omega) \in \{0, 1\}$. For example, if entity **A** defaults in time $\tau(\omega)$, then we have that $P^A(T; t, \omega) = 0$ for $t > \tau(\omega)$.

2.3 Netting

Let us now consider that entity **A** and **B** have two contracts with each other: one resulting in a cash flow from **A** to **B**. The other resulting in a cash flow from **B** to **A**. Let us assume further that both cash flow will occur at the same future time T . Let $C^A(T) > 0$ denote the cash flow originating from **A** to **B**. Let $C^B(T) > 0$ denote the cash flow originating from **B** to **A**. Individually the time T value of the two contracts is

$$-C^A(T) P^A(T; T) \quad \text{and} \quad +C^B(T) P^B(T; T),$$

where the signs stem from considering the value from **A**'s perspective. From **B**'s perspective we would have the opposite signs. If $C^A(T)$ and $C^B(T)$ are deterministic, then the time t value of these cash flows is

$$-C^A(T) P^A(T; t) \quad \text{and} \quad +C^B(T) P^B(T; t),$$

respectively.

However, if we have a netting agreement, i.e., the two counter parties **A** and **B** agree that only the net cash flow is exchanged, then we effectively have a single contract with a single cash flow of

$$C(T) := -C^A(T) + C^B(T).$$

The origin of this cash flow is now determined by its sign. If $C(T) < 0$ then $|C(T)|$ flows from **A** to **B**. If $C(T) > 0$ then $|C(T)|$ flows from **B** to **A**. The time T value of the netted cash flow $C(T)$, seen from **A**'s perspective, is

$$\min(C(T), 0) P^A(T; T) + \max(C(T), 0) P^B(T; T).$$

Note that if

$$P^A(T; t) = P^B(T; t) =: P(T; t)$$

then there is no difference between the value of a netted cash flow and the sum the individual values, but in general this property does not hold.

2.4 Valuation of Stochastic Cash Flows

If cash flows $C(T)$ are stochastic, then we have to value their time t value using a valuation model, e.g., risk neutral valuation using some numeraire N and a corresponding martingale measure \mathbb{Q}^N . The analytic valuation (which actually stems from a static hedge) as $C(T)P^A(T; t)$ no longer holds. Let N denote a numeraire and \mathbb{Q}^N a corresponding martingale measure, such that,

$$\frac{P^A(T; t)}{N(t)} = \mathbb{E}^{\mathbb{Q}^N} \left(\frac{P^A(T; T)}{N(T)} \middle| \mathcal{F}_t \right).$$

Then a possibly stochastic cash flow $C(T)$, outgoing from **A** is evaluated in the usual way, where the value is given as

$$\mathbb{E}^{\mathbb{Q}^N} \left(\frac{C(T) P^A(T; T)}{N(T)} \middle| \mathcal{F}_t \right)$$

Note that the factor $P^A(T; T)$ determines the effect of the origin of the cash flow, here **A**. In theories where counterparty risk (and funding) is neglected, the cash flow $C(T)$ is valued as

$$\mathbb{E}^{\mathbb{Q}^N} \left(\frac{C(T)}{N(T)} \middle| \mathcal{F}_t \right).$$

2.4.1 Example: A simple approach to construct a multi-curve model

A simple approach to include counterparty risk, i.e., different discounting curves, into a standard single curve interest rate model is by assuming a deterministic default intensity. To formalize this, let \mathcal{F}_t denote the filtration including counterparty risk and assume that

$$\mathcal{F}_t = \mathcal{G}_t \times \mathcal{H}_t,$$

where \mathcal{G}_t is the filtration associated with our given the counterparty risk-free model. In other words, we assume that default free payoffs are valued as

$$P(T; t) = N(t) \mathbb{E}^{\mathbb{Q}^N} \left(\frac{1}{N(T)} \middle| \mathcal{F}_T \right) = N(t) \mathbb{E}^{\mathbb{Q}^N} \left(\frac{1}{N(T)} \middle| \mathcal{G}_T \right)$$

and we implicitly define the counterparty risk as

$$\begin{aligned} P^A(T; t) &= N(t) \mathbb{E}^{\mathbb{Q}^N} \left(\frac{P^A(T; T)}{N(T)} \middle| \mathcal{F}_T \right) \\ &= N(t) \mathbb{E}^{\mathbb{Q}^N} \left(\frac{1}{N(T)} \middle| \mathcal{G}_T \right) P^A(t; t) \exp \left(- \int_t^T \lambda^A(\tau) d\tau \right) \\ &= P(T; t) P^A(t; t) \exp \left(- \int_t^T \lambda^A(\tau) d\tau \right). \end{aligned}$$

So in other words, every time T cashflow has to carry a *marker* $P^A(T; T)$ which identifies its counterparty (source), here **A**. The time t valuation of this cashflow, i.e., the numeraire relative conditional expectation of the cashflow, is given by the conditional

expectation of the corresponding counterparty risk-free cashflow (i.e., with respect to the filtration \mathcal{G} of the single curve model) times the survival probability times a new marker $P^A(t; t)$. Obviously, the process $P^A(T)$ is a \mathbb{Q}^N -martingale (with respect to the full filtration \mathcal{F}). Note that the default event, i.e., the filtration \mathcal{H} , is not modelled at all. The assumption that the default intensity λ is deterministic is sufficient to value the default indicator function. See also Chapter 28 in [4].

Note that such a model does not explicitly distinguish liquidity effects and default risk effects. They are all subsummed in the market implied default intensity λ .

2.5 Credit Linking

Let us consider a bond $P^C(T; t)$ issued by entity **C**. Let us consider a contract where **A** pays $P^C(T; T)$ in $t = T$, i.e., **A** pays 1 only if **C** survived, otherwise it will pay **C**'s recovery. However, this cash flow still is a cash flow originating (granted) by **A**. The time T value of this cash flow is $P^C(T; T)P^A(T; T)$.

This contract can be seen as a credit linked deal.

2.5.1 Examples

If $P^C(T; T, \omega) = 1$ for all $\omega \in \Omega$, then P^C has no credit risk. In this case we have

$$N(t)\mathbb{E}^{\mathbb{Q}^N} \left(\frac{P^C(T; T)P^A(T; T)}{N(T)} \mid \mathcal{F}_t \right) = P^A(T; t).$$

Also, if $P^C(T; T, \omega) = P^A(T; T, \omega) \in \{0, 1\}$ for all $\omega \in \Omega$, then **C** defaults if and only if **A** defaults and there are no recoveries. In that case we also have

$$N(t)\mathbb{E}^{\mathbb{Q}^N} \left(\frac{P^C(T; T)P^A(T; T)}{N(T)} \mid \mathcal{F}_t \right) = P^A(T; t).$$

If the two random variables $P^A(T; T)$ and $P^C(T; T)$ are independent we have

$$N(t)\mathbb{E}^{\mathbb{Q}^N} \left(\frac{P^C(T; T)P^A(T; T)}{N(T)} \mid \mathcal{F}_t \right) = P^C(T; t) P^A(T; t) \frac{1}{P(T; t)},$$

where $P(T; t) := N(t)\mathbb{E}^{\mathbb{Q}^N} \left(\frac{1}{N(T)} \mid \mathcal{F}_t \right)$.

To prove the latter we switch to terminal measure (i.e., choose $N = P(T)$ such that $N(T) = 1$) and get

$$\begin{aligned} & N(t)\mathbb{E}^{\mathbb{Q}^N} \left(\frac{P^C(T; T)P^A(T; T)}{N(T)} \mid \mathcal{F}_t \right) \\ &= N(t) \mathbb{E}^{\mathbb{Q}^N} \left(P^C(T; T) \mid \mathcal{F}_t \right) \mathbb{E}^{\mathbb{Q}^N} \left(P^A(T; T) \mid \mathcal{F}_t \right) \\ &= P^C(T; t) P^A(T; t) \frac{1}{N(t)} = P^C(T; t) P^A(T; t) \frac{1}{P(T; t)} \end{aligned}$$

2.6 Collateralization

Collateralization is not some “special case” which has to be considered in the above valuation framework. Collateralization is an additional contract with an additional netting agreement (and a credit link). As we will illustrate, we can re-interpret a collateralized contract as a contract with a different discount curve, however, this *is* only a re-interpretation.

For simplicity let us consider the collateralization of a single future cash flow.

Let us assume that counterparty **A** pays M in time $T = 1$. Thus, seen from the perspective of **A**, there is a cash flow

$$-MP^A(T;T) \quad \text{in } t = T.$$

Hence, the time t value of the non-collateralized cash flow is $-MP^A(T;t)$. Next, assume that counterparty **A** holds a contract where an entity **C** will pay K in time T . Thus, seen from the the perspective of **A** there is a cash flow

$$KP^C(T;T) \quad \text{in } t = T.$$

Hence, the time t value of this cash flow is $KP^C(T;t)$.

If we value both contracts separately, then the first contract evaluates to $-N$, the second contract evaluates to K . If we use the second contract to “collateralize” the first contract we bundle the two contracts in the sense that the second contract is passed to the counterparty **B** as a pawn. This can be seen as letting the second contract default if the first contract defaults. The time T value thus is

$$\left(KP^C(T;T) - M\right) P^A(T;T),$$

where we assumed that the net cash flow is non-positive, which is the case if $K < M$ and $P^C(T;T) \leq 1$, so we do not consider over-collateralization. The random variable $P^C(T;T)$ accounts for the fact that the collateral may itself default over the time, see “credit linked” above.

We have

$$\begin{aligned} & \left(KP^C(T;T) - M\right) P^A(T;T) \\ &= KP^C(T;T) - MP^A(T;T) + K \left(P^C(T;T)P^A(T;T) - P^C(T;T)\right) \end{aligned}$$

Thus, the difference of the value of the collateralized package and the sum of the individual deals ($M - K$) is

$$K \left(P^C(T;T)P^A(T;T) - P^C(T;T)\right).$$

It is possible to view this change of the value of the portfolio as a change of the value of the outgoing cash flow. Let us determine the implied zero coupon bond process P^{Ac} such that

$$\begin{aligned} -M P^{Ac}(T;T) &\stackrel{!}{=} -M P^A(T;T) \\ &+ K \left(P^C(T;T)P^A(T;T) - P^C(T;T)\right). \end{aligned}$$

It is

$$P^{Ac}(T; T) := P^A(T; T) - \frac{K}{M} \left(P^C(T; T)P^A(T; T) - P^C(T; T) \right). \quad (1)$$

We refer to P^{Ac} as the discount factor for collateralized deals. It should be noted that a corresponding zero coupon bond does not exist (though it may be synthesized) and that this discount factor is simply a computational tool. In addition, note that the discount factor depends on the value (K) and quality ($P^C(T; T)$) of the collateral.

2.6.1 Interpretation

From the above, we can check some limit cases:

- For $P^C(T; T)P^A(T; T) = P^C(T; T)$ we find that $P^{Ac}(T; T) = P^A(T; T)$. Note that this equations holds, for example, if $P^A(T; T) < 1 \Rightarrow P^C(T; T)$. This can be interpreted as: if the quality of the collateral is “less or equal” to the quality of the original counterpart, then collateralization has no effect.
- For $P^C(T; T)P^A(T; T) = P^A(T; T)$ and $0 \leq K \leq M$ we find that $P^{Ac}(T; T) = \alpha P^C(T; T) + (1 - \alpha)P^A(T; T)$, where $\alpha = \frac{K}{M}$, i.e., if the collateral does not compromise the quality of the bond as a credit linked bond, then collateralization constitutes a mixing of the two discount factors at the ratio of the collateralized amount.
- For $P^C(T; T)P^A(T; T) = P^A(T; T)$ and $K = M$ we find that $P^{Ac}(T; T) = P^C(T; T)$, i.e., if the collateral does not compromise the quality of the bond as a credit linked bond and the collateral matches the future cash flow, then the collateralized discount factor agrees with the discount factor of the collateral.

Given that $P^C(T; T)P^A(T; T) = P^A(T; T)$ we find that collateralization has a positive value for the entity receiving the collateral. The reason can be interpreted in a funding sense: The interest payed on the collateral is less than the interest payed on an issued bond. Hence, the entity receiving collateral can save funding costs.

2.6.2 Example

Let us consider entities **A** and **C** where

$$N(t) E^{\mathbb{Q}^N} \left(\frac{P^A(T; T)}{N(T)} | \mathcal{F}_t \right) = \exp(-r(T-t)) \exp(-\lambda^A(T-t))$$

$$N(t) E^{\mathbb{Q}^N} \left(\frac{P^C(T; T)}{N(T)} | \mathcal{F}_t \right) = \exp(-r(T-t)) \exp(-\lambda^C(T-t))$$

and

$$\begin{aligned} N(t) E^{\mathbb{Q}^N} \left(\frac{P^C(T; T) P^A(T; T)}{N(T)} | \mathcal{F}_t \right) \\ = \exp(-r(T-t)) \exp(-\lambda^C(T-t)) \exp(-\lambda^A(T-t)). \end{aligned}$$

The first two equations could be viewed as a definition of some base interest rate level r and the counterparty dependent default intensities λ . So to some extent these equations are definitions and do not constitute an assumption. However, given that the base level r is given, the third equation constitutes an assumption, namely that the defaults of **A** and **C** are independent.

From this we get for the impact of collateralization that

$$P^{Ac}(T; t) = \exp(-r(T-t)) \exp(-\lambda^A(T-t)) \cdot \left(1 + \frac{K}{M} \exp(-\lambda^C(T-t)) \left(\exp(\lambda^A(T-t)) - 1 \right) \right).$$

Note that for $K > M$ this discount factor could have $P^{Ac}(T; T) > 1$. This would correspond to the case where the original deal is over-collateralized. We excluded this case in the derivation and in fact the formula above does not hold in general for an over-collateralized deal, since we would need to consider the discount factor of the counterpart receiving the collateral (the over-collateralized part is at risk now). Nevertheless, a similar formula can be derived.

2.6.3 Full Bilateral Collateralization

Full bilateral collateralization with collateral having the same discount factor, i.e., $P^{Ac}(T) = P^{Bd}(T)$, will result in a single discounting curve (namely that of the collateral) regardless of the origin of the cash flow.

3 Discounting Cash Flows: The Hedging View

We now take a different approach in valuing cash flows and we change our point of view. We now assume that *we are* entity **A** and as a consequence postulate that

Axiom 1: (Going Concern)

Entity A wants to stay in business (i.e., liquidation is not an option) and cash flows have to be “hedged” (i.e., neutralized, replicated). In order to stay in business, future outgoing cash flows have to be ensured.

The axiom means that we do not value cash flows by relating them to market bond prices (the liquidation view). Instead we value future cash flows by trading in assets such that future cash flows are hedged (neutralized). The costs or proceeds of this trading define the value of future cash flows. An entity must do this because all uncovered negative net cash flow will mean default. Future net (!) cash flow is undesirable. A future cash flow has to be managed.

This is to some extent reasonable since cash itself is a bad thing. It does not earn interest. It needs to be invested. We will take a replication / hedging approach to value future cash. In addition we take a conservative point of view: a liability in the future (which cannot be neutralized by trading in some other asset (netting)) has to be secured in order to ensure that we stay in business. Not paying is not an option. This relates to the “going concern” as a fundamental principle in accounting.

At this point one may argue that a future outgoing cash flow is not a problem. Once the cash has to flow we just sell an asset. However, then we would be exposed to risk in that asset. This is not the business model of a bank. A bank hedges its risk and so future cash flow has to be hedged as well. Valuation is done by valuing hedging cost.

Changing the point of view, i.e., assuming that *we are* entity **A** has another consequence, which we also label as an “Axiom”:

Axiom 2:

We cannot short sell our own bond.

The rationale of this is clear: While a third party **E** actually can short sell a bond issued by **A** by selling protection on **A**, **A** itself cannot offer such an instrument. It would offer an insurance on its own default, but if the default occurs, the insurance does not cover the event. Hence the product is worthless.

3.1 Moving Cash Flow through Time

Axiom 1 requires that we consider transactions such that all future cash flow is converted into today's cash flow, where then a netting of cash occurs. Axiom 2 then restricts the means how we can move cash flows around.

Let us explore the means of “moving” cash through time. To illustrate the concept we first consider deterministic cash flows only. These allow for static hedges through the construction of appropriate forward bonds in Section 3.2. Dynamic hedges will be considered in Section 3.3.

Let us assume that there is a risk free entity issuing risk free bonds $P^\circ(T; t)$ by which we may deposit cash.²

3.1.1 Moving Positive Cash to the Future

If entity A (i.e., *we*) has cash N in time t it can invest it and buy bonds $P^\circ(T; t)$. The cash flow received in T then is $N \frac{1}{P^\circ(T; t)}$.

This is the way by which positive cash can be moved from t to a later time $T > t$ (risk less, i.e., suitable for hedging). Note that investing in to a bond $P^B(T; t)$ of some other entity B is not admissible since then the future cash flow would be credit linked to B.

3.1.2 Moving Negative Cash to the Future

If entity A (i.e., *we*) has cash $-N$ in time t it has to issue a bond in order to cover this cash. In fact, there is no such thing as negative cash. Either we have to sell assets or issue a bond. Assume for now that selling assets is not an option. Issuing a bond generating cash flow $+N$ (proceeds) the cash flow in T then is $-N \frac{1}{P^A(T; t)}$ (payment).

This is the way by which negative cash can be moved from t to a later time $T > t$.

3.1.3 Hedging Negative Future Cash Flow

If entity A (i.e., *we*) is confronted with a cash flow $-N$ in time T it needs to hedge (guarantee) this cash flow by depositing $-N \frac{1}{P^\circ(T; t)}$ today (in bonds $P^\circ(T; t)$).

This is the way by which negative cash can be moved from T to an earlier time $t < T$.

A remark is in order now: An alternative to net a future outgoing cash flow is by buying back a corresponding $-P^A(T; t)$ bond. However, let us assume that buying back bonds is currently not an option, e.g., for example because there are no such bonds. Note that due to Axiom 2 it is not admissible to short sell our own bond.³

3.1.4 Hedging Positive Future Cash Flow

If entity A (i.e., *we*) is confronted with a cash flow $+N$ in time T it needs to hedge (net) this cash flow by issuing a bond with proceeds $N \frac{1}{P^A(T; t)}$ today (in bonds $P^\circ(T; t)$).

This is the way by which positive cash can be moved from T to an earlier time $t < T$.

3.2 Construction of Forward Bonds

The basic instrument to manage cash flows will be the forward bond transaction, which we consider next. To comply with Axiom 2 we simply assume that we can only enter in one of the following transactions, never sell it. Hence we have to consider two different forward bonds.

² Counterparty risk will be considered at a later stage.

³ We will later relax this assumption and allow for (partial) funding benefits by buying back bonds.

3.2.1 Forward Bond 1: Hedging Future Incoming Cash with Outgoing Cash

Assume we have an incoming cash flow M from some counterparty risk free entity to entity **A** in time T_2 and an outgoing cash flow $-N$ from entity **A** (i.e., *we*) to some other entity in time T_1 . Then we perform the following transactions

- We neutralize (secure) the outgoing cash flow by an incoming cash flow N by investing $-NP^\circ(T_1; 0)$ in time 0.
- We net the incoming cash flow by issuing a bond in $t = 0$ paying back $-M$, where we securitize the issued bond by the investment in $NP^\circ(T_1; 0)$, resulting in $MP^A(T_2; 0) \frac{P^\circ(T_1; 0)}{P^A(T_1; 0)}$. Note that the issued bond is securitized only over the period $[0, T_1]$.

This transaction has zero costs if $N = M \frac{P^A(T_2; 0)}{P^A(T_1; 0)}$. Let

$$P^A(T_1, T_2) := \frac{P^A(T_2)}{P^A(T_1)}.$$

3.2.2 Forward Bond 2: Hedging Future Outgoing Cash with Incoming Cash

Assume we have an outgoing cash flow $-M$ in T_2 and an incoming cash flow N from some counterparty risk free entity to entity **A** (i.e., *us*) in T_1 . Then we perform the following transactions

- We neutralize (secure) the outgoing cash flow by an incoming cash flow N by investing $-NP^\circ(T_2; 0)$ in time $t = 0$.
- We net the incoming cash flow by issuing a bond in $t = 0$ paying back $-M$, where we securitize the issued bond by the investment in $NP^\circ(T_2; 0)$, resulting in $MP^\circ(T_1; 0)$.

This transaction has zero costs if $N = M \frac{P^\circ(T_2; 0)}{P^\circ(T_1; 0)}$. Let

$$P^\circ(T_1, T_2) := \frac{P^\circ(T_2)}{P^\circ(T_1)}.$$

3.2.3 Forward Bond 1': Hedging Future Credit Linked Incoming Cash with Credit Linked Outgoing Cash

In the presence of counterparty risk, the construction of the forward bond (discounting of an incoming cash flow) is a bit more complex. Assume we have an incoming cash flow M from entity **B** to entity **A** in time T_2 . We assume that we can buy protection on M received from **B** at $-CDS^B(T_2; t)$, where this protection fee is paid in T_2 . Assume further that we can sell protection on N received from **B** at $CDS^B(T_1; t)$, where this protection fee is paid in T_1 . Then we repeat the construction of the forward bond with the net protected amounts $M(1 - CDS^B(T_2; t))$ and $N(1 - CDS^B(T_1; t))$, replacing M and N in 3.2.1 respectively. In other words we perform the following transactions

- We buy protection on **B** resulting in a cash flow $-MCDS^B(T_2; t)$ in T_2 .

- We issue a bond to net the T_2 net cash flow $M(1 - \text{CDS}^{\text{B}}(T_2; t))$.
- We sell protection on \mathbf{B} resulting in a cash flow $N\text{CDS}^{\text{B}}(T_1; t)$ in T_1 .
- We invest $N(1 - \text{CDS}^{\text{B}}(T_1; t))P^{\circ}(T_1; 0)$ in t to generate a cash flow of $N(1 - \text{CDS}^{\text{B}}(T_1; t))$ in T_1 .
- We collateralized the issued bond using the risk free bond over $[0, T_1]$ resulting in proceeds $M(1 - \text{CDS}^{\text{B}}(T_2; t))P^{\text{A}}(T_2; 0)\frac{P^{\circ}(T_1; 0)}{P^{\text{A}}(T_1; 0)}$ in t .

This transaction has zero costs if $N = M\frac{P^{\text{A}}(T_2; 0)}{P^{\text{A}}(T_1; 0)}\frac{1 - \text{CDS}^{\text{B}}(T_2; t)}{1 - \text{CDS}^{\text{B}}(T_1; t)}$. Let

$$P^{\text{A}|\text{B}}(T_1, T_2) := \frac{P^{\text{A}}(T_2)}{P^{\text{A}}(T_1)} \frac{1 - \text{CDS}^{\text{B}}(T_2; t)}{1 - \text{CDS}^{\text{B}}(T_1; t)}.$$

However, while this construction will give us a cash flow in T_1 which is (because of selling protection) under counterparty risk, netting of such a cash flow will require more care. We will consider this in Section 3.4, there we apply this construction with $t = T_1$ such that selling protection does not apply.

3.2.4 Price of Counterparty Risk Protection

We denote the price of one unit of counterparty risk protection until T_2 as contracted in t by $\text{CDS}^{\text{B}}(T_2; t)$. If we do not consider liquidity effects a fair (mark-to-marked) valuation will give

$$P^{\text{B}}(T_2; t) + \text{CDS}^{\text{B}}(T_2; t)P^{\circ}(T_2; t) = P^{\circ}(T_2; t),$$

where we assume that the protection fee flows in T_2 (and independently of the default event). This gives

$$1 - \text{CDS}^{\text{B}}(T_2; t) = \frac{P^{\text{B}}(T_2; t)}{P^{\circ}(T_2; t)}.$$

The latter can be interpreted as as a market implied survival probability.

3.2.5 Example: Expressing the Forward Bond in Terms of Rates

If we define

$$\begin{aligned} \frac{P^{\circ}(T_2; t)}{P^{\circ}(T_1; t)} &= \exp\left(-\int_{T_1}^{T_2} r(\tau; t) d\tau\right) \\ \frac{P^{\text{A}}(T_2; t)}{P^{\text{A}}(T_1; t)} &= \exp\left(-\int_{T_1}^{T_2} r(\tau; t) + s^{\text{A}}(\tau; t) d\tau\right) \\ \frac{1 - \text{CDS}^{\text{B}}(T_2; t)}{1 - \text{CDS}^{\text{B}}(T_1; t)} &= \exp\left(-\int_{T_1}^{T_2} \lambda^{\text{B}}(\tau; t) d\tau\right) \end{aligned}$$

then we have

$$P^{A|B}(T_1, T_2) = \exp\left(-\int_{T_1}^{T_2} r(\tau; t) + s^A(\tau; t) + \lambda^B(\tau; t) d\tau\right) \quad (2)$$

and we see that discounting an outgoing cash flow backward in time by buying the corresponding forward bonds generates additional costs of $\exp\left(-\int_{T_1}^{T_2} s^A(\tau; t) d\tau\right)$ (funding) compared to discounting an incoming cash flow. In addition incoming cash flows carry the counterparty risk by the additional discounting (cost of protection) at $\exp\left(-\int_{T_1}^{T_2} \lambda^B(\tau; t) d\tau\right)$.

The expression (2) is similar to a corresponding term in [7], except that there

$$\exp\left(-\int_{T_1}^{T_2} r(\tau; t) + \gamma^A(\tau; t) + \lambda^B(\tau; t) d\tau\right)$$

had been derived, where γ^A is the bond-cds basis (i.e., $\gamma^A = s^A - \lambda^A$). The difference stems from the fact that [7] always factors in own-credit, which we do not do according to axiom 1. However, in the end we can arrive at a similar result since the effective funding required applies only on the net amount (after all netting has been performed).⁴

Not that these single time step static hedges do not consider any correlation, e.g., the correlation between A's funding and B's counterparty risk. This correlation will come in once we assume a dynamic model for the corresponding rates and consider dynamic hedges (e.g., in a time-discrete model). We will do so next, in Section 3.3.

3.2.6 Interpretation: Funding Cost as Hedging Costs in Cash Flow Management

From the above, we see that moving cash flows around generates costs and the *cash flow replication value* of future cash flows will be lower than the *portfolio liquidation value* of future cash flow. The difference of the two corresponds to the “operating costs of managing un-netted cash flows”, which are just the funding costs. Clearly, liquidating there are no operating cost (so we save them). However these costs are real. If we have cash lying around we can invest only at a risk free rate, however we fund ourself at a higher rate. The only way to reduce cash cost is to net them with other cash flows (e.g. of assets generating higher returns).

3.3 Valuation with Hedging Costs in Cash flow Management (Funding)

The cash flow replication value is now given by the optimal combination of forward bonds to hedge (replicate) the future cash flow, where nearby cash flows are “netted” as good a possible. This is given by a backward algorithm, discounting each cash flow according to the appropriate forward bond and then netting the result with the next cash flow.

⁴ Netting will play an important role how funding and counterparty risk will enter. Note that for the net exposure we have to net all cashflows related to a single counterparty, for the net funding we have to net all cashflows over all counterparties.

Let us first consider the valuation neglecting counter party risk, or, put differently, all future cash flows exposed to counter party risk have been insured by buying the corresponding protection first (and reducing net the cash flow accordingly). We will detail the inclusion of counterparty risk in Section 3.4.

3.3.1 Interest for Borrowing and Lending

Obviously, using our two assumptions (Axiom 1 and Axiom 2) we arrived at a very natural situation. The interest to be paid for borrowing money over a period $[T_1, T_2]$ is (as seen in t)

$$\frac{1}{T_2 - T_1} \left(\frac{P^A(T_1; t)}{P^A(T_2; t)} - 1 \right),$$

i.e., our funding rate. The interest earned by depositing money (risk free) over a period $[T_1, T_2]$ is

$$\frac{1}{T_2 - T_1} \left(\frac{P^\circ(T_1; t)}{P^\circ(T_2; t)} - 1 \right),$$

i.e., the risk free rate. Hence we are in a setup where interest for borrowing and lending are different. The valuation theory in setups when rates for lending and borrowing are different is well understood, see for example [3].

3.3.2 From Static to Dynamic Hedging

The forward bonds, e.g., $P^\circ(T_1, T_2; t)$ or $P^A(T_1, T_2; t)$ define a static hedge in the sense that their value is known in t . If we are discounting / hedging stochastic cash flows $C(T)$ a dynamic hedge is required and $C(T_i)P^A(T_{i-1}, T_i; T_{i-1})$ is replaced by

$$N(T_{i-1}) \mathbb{E}^{\mathbb{Q}^N} \left(\frac{C(T_i)P^A(T_i; T_i)}{N(T_i)} \right).$$

Note: It is

$$P^A(T_{i-1}, T_i; T_{i-1}) = P^A(T_i; T_{i-1}) = N(T_{i-1}) \mathbb{E}^{\mathbb{Q}^N} \left(\frac{P^A(T_i; T_i)}{N(T_i)} \right),$$

i.e., for $t = S$ the forward bond $P(S, T; t)$ is just a bond.

Example: Implementation using Euler simulation of Spreads and Intensities

If we express the bonds in terms of the risk free bond P° , e.g.,

$$\frac{P^A(T_i; t)}{P^\circ(T_i; t)} =: \exp \left(- \int_{T_{i-1}}^{T_i} s^A(\tau; t) d\tau \right)$$

and model (!) the process on the right hand side such that $s^A(\tau; t)$ is $\mathcal{F}_{T_{i-1}}$ -measurable for $t \in [T_{i-1}, T_i]$ (which is usually case if we employ a numerical scheme like the Euler

scheme for the simulation of spreads s and default intensities λ), then we find that for any cash flow $C(T_i)$

$$\begin{aligned} & N(T_{i-1}) \mathbb{E}^{\mathbb{Q}^N} \left(\frac{C(T_i) P^A(T_i; T_i)}{N(T_i)} \right) \\ &= N(T_{i-1}) \mathbb{E}^{\mathbb{Q}^N} \left(\frac{C(T_i)}{N(T_i)} \right) \exp \left(- \int_{T_{i-1}}^{T_i} s^A(\tau; t) d\tau \right) P^A(T_{i-1}; T_{i-1}) \end{aligned}$$

and likewise for P^B .

3.3.3 Valuation of a Single Product including Cash Flow Costs

Let us consider the valuation of a collateralized swap being the only product held by entity **A**. Let us assume the swap is collateralized by cash. The package consisting of the swap's (collateralized) cash flows and the collateral flows has a mark-to-market value of zero (valued according to Section 2), by definition of the collateral. However, the package represents a continuous flow of cash (margining). If valued using the collateral curve $P^C = P^\circ$ these marginal collateral cash flows have mark-to-market value zero (by definition of the collateral).

Let us assume that this swap constitutes the only product of entity **A** and that we value cash flows by a hedging approach, i.e., dynamically using the two forward bonds from Section 3.2. Taking into account that for cash we have different interest for borrowing and lending, the collateral cash flow will generate additional costs. These are given by the following recursive definition:

$$\begin{aligned} \frac{V_i^d(T_{i-1})}{N(T_{i-1})} &= \mathbb{E}^{\mathbb{Q}^N} \left(\frac{\max(X_i + V_{i+1}^d(T_i), 0)}{N(T_i)} P^A(T_i; T_i) \right. \\ &\quad \left. + \frac{\min(X_i + V_{i+1}^d(T_i), 0)}{N(T_i)} P^\circ(T_i; T_i) \Big| \mathcal{F}_{T_{i-1}} \right). \end{aligned} \quad (3)$$

Here $V_{i+1}^d(T_i)$ is the net cash position required in T_i to finance (e.g., fund) the future cash flows in $t > T_i$. X_i is the collateral margin call occurring in time $t = T_i$. Hence we have to borrow or lend the net amount

$$V_i^d(T_i) = X_i + V_{i+1}^d(T_i)$$

over the period $(T_{i-1}, T_i]$. This amount is then transferred to T_{i-1} using the appropriate forward bond (discounting) for netting with the next margining cash flow X_{i-1} .

This is the valuation under the assumption that the X_i is the *net cash flow* of entity **A**, e.g., as if the collateralized swap is our only product.

3.3.4 Valuation within a Portfolio Context - Valuing Funding Benefits

The situation of Section 3.3.3 now carries over to the valuation of a portfolio of products held by entity **A**. In this the algorithm (3) will determine the discount factor to be used in the period $[T_{i-1}, T_i]$ from the portfolio's net cash position $V_i^d(T_i)$, regardless of a product having an outgoing or incoming cash flow.

Let us discuss a product having a cash flow $C(T_i)$ in T_i being part of entity **A**'s portfolio resulting in a net (cash) position $V_i^d(T_i)$.

Incoming Cash Flow, Positive Net Position

Given that our net position $V_i^d(T_i)$ is positive in T_i , an incoming (positive) cash flow $C(T_i)$ can be factored in at earlier time only by issuing a bond. Hence it is discounted with P^A (resulting in a smaller value at $t < T_i$, compared to a discounting with P°). Note that for $t > T_i$ this cash flow can provide a funding benefit for a future negative cash flow which would be considered in the case of a negative net position, see 3.3.4).

Outgoing Cash Flow, Positive Net Position

Given that our net position $V_i^d(T_i)$ is positive in T_i , an outgoing (negative) cash flow $C(T_i)$ can be served from the positive (net) cash position. Hence it does not require funding for $t < T_i$ as long as our net cash position is positive. Factoring in the funding benefit it is discounted with P^A (resulting in a larger value at $t < T_i$, compared to a discounting with P°).

Incoming Cash Flow, Negative Net Position

Given that our net position $V_i^d(T_i)$ is negative in T_i , an incoming (positive) cash flow $C(T_i)$ reduces the funding cost for the net position. Hence it represents a funding benefit and is discounted with P° (resulting in a larger value at $t < T_i$, compared to a discounting with P^A).

Outgoing Cash Flow, Negative Net Position

Given that our net position $V_i^d(T_i)$ is negative in T_i , an outgoing (negative) cash flow $C(T_i)$ has to be funded on its own (as long as our net position remains negative). Hence it is discounted with P° (resulting in a smaller value at $t < T_i$, compared to a discounting with P^A).

3.4 Valuation with Counterparty Risk and Funding Cost

So far Section 3 did not consider counterparty risk in incoming cash flow. Of course, it can be included using the forward bond which includes the cost of protection of a corresponding cash flow.

3.4.1 Static Hedge of Counterparty Risk in the Absence of Netting

Assume that all incoming cash flows from entity B are subject to counterparty risk (default), but all outgoing cash flow to entity B have to be served. This would be the case if we consider a portfolio of (zero) bonds only and there is no netting agreement.

Since there is no netting agreement we need to buy protection on each individual cash flow obtained from B. It is not admissible to use the forward bond $P^{A|B}(T_1, T_2)$ to net a T_2 incoming cash flow for which we have protection over $[T_1, T_2]$ with a T_1 outgoing (to B) cash flow and then buy protection only on the net amount.

If we assume, for simplicity, that all cash flows $X_{i,k}^{B_j}$ received in T_i from some entity B_j are known in T_0 , i.e., \mathcal{F}_{T_0} -measurable, then we can attribute for the required

protection fee in T_0 (i.e., we have a static hedge against counterparty risk) and our valuation algorithm becomes

$$\begin{aligned} \frac{V_i^d(T_{i-1})}{N(T_{i-1})} = & \mathbb{E}^{\mathbb{Q}^N} \left(\frac{\max(X_i + V_{i+1}^d(T_i), 0)}{N(T_i)} P^A(T_i; T_i) \right. \\ & \left. + \frac{\min(X_i + V_{i+1}^d(T_i), 0)}{N(T_i)} P^\circ(T_i; T_i) \mid \mathcal{F}_{T_{i-1}} \right). \end{aligned} \quad (4)$$

where the time T_i net cash flow X_i is given as

$$X_i := X_i^\circ + \sum_j \sum_k \left(\min(X_{i,k}^{B_j}, 0) + (1 - \text{CDS}^{B_j}(T_i; T_0)) \max(X_{i,k}^{B_j}, 0) \right).$$

where B_j denote different counterparties and $X_{i,k}^{B_j}$ is the k -th cash flow (outgoing or incoming) between us and B_j at time T_i . So obviously we are attributing full protection costs for all incoming cash flows and consider serving all outgoing cash flow a must. Note again, that in any cash flow $X_{i,k}^{B_j}$ we account for the full protection cost from T_0 to T_i .

Although this is only a special case we already see that counterparty risk cannot be separated from funding since (4) makes clear that we have to attribute funding cost for the protection fees.⁵

3.4.2 Dynamic Hedge of Counterparty Risk in the Presence of Netting

However, many contracts feature netting agreements which result in a “temporal netting” for cash flows exchanged between two counterparties and only the net cash flow carries the counterparty risk. It appears as if we could then use the forward bond $P^{A|B}(T_{i-1}, T_i)$ and $P^B(T_{i-1}, T_i)$ on our future T_i net cash flow and then net this one with all T_{i-1} cash flows, i.e., apply an additional discounting to each netted set of cash flows between two counterparties. This is not exactly right. Presently we are netting T_i cash flows with T_{i-1} cash flows in a specific way which attributes for our own funding costs. The netting agreement between two counterparties may (and will) be different from our funding adjusted netting. For example, the contract may specify that upon default the close out of a product (i.e., the outstanding claim) is determined using the risk free curve for discounting.

Let us denote by $V_{\text{CLSOUT},i}^B(T_i)$ the time T_i cash being exchanged / being at risk at T_i if counterparty B defaults according to all netting agreements (the deals close out). This value is usually a part of the contract / netting agreement. Usually it will be a mark-to-market valuation of V^B at T_i . One approach to account for the mismatch is to buy protection over $[T_{i-1}, T_i]$ for the positive part of $V_{\text{CLSOUT},i}^B(T_i)$ (i.e., the exposure), then additionally buy protection for the mismatch of the contracted default value $V_{\text{CLSOUT},i}^B(T_i)$ and netted non-default value $V_i^B(T_i)$.

⁵ We assumed that the protection fee is paid at the end of the protection period, it is straight forward to include periodic protection fees.

As before let $X_{i,k}^{\mathbb{B}_j}$ denote the k -th cash flow (outgoing or incoming) exchanged between us and entity \mathbb{B}_j at time T_i . Let

$$R_i^{\mathbb{B}_j}(T_i) := \sum_k X_{i,k}^{\mathbb{B}_j} + V_{i+1}^{\mathbb{B}_j}(T_i)$$

denote the value contracted with \mathbb{B}_j , valued in T_i , including our future funding costs. Then

$$\begin{aligned} V_i^{\mathbb{B}_j}(T_i) := & R_i^{\mathbb{B}_j}(T_i) - \underbrace{p_j \max(R_i^{\mathbb{B}_j}(T_i), 0)}_{\substack{\text{protection on netted value} \\ \text{including our funding}}} \\ & + p_j \underbrace{\left(\min(V_{\text{CLSOUT},i}^{\mathbb{B}_j}(T_i), 0) - \min(R_i^{\mathbb{B}_j}(T_i), 0) \right)}_{\substack{\text{mismatch of liability} \\ \text{in case of default}}} \end{aligned}$$

is the net value including protection fees over the period $[T_{i-1}, T_i]$, where p_j is the price of buying or selling one unit of protection against \mathbb{B}_j over the period $[T_{i-1}, T_i]$, i.e.,

$$p_j := \text{CDS}^{\mathbb{B}_j}(T_i; T_{i-1}).$$

Let

$$V_i(T_i) := \sum_j V_i^{\mathbb{B}_j}(T_i).$$

The general valuation algorithm including funding and counterparty risk is then given as

$$\begin{aligned} \frac{V_i(T_{i-1})}{N(T_{i-1})} = & \mathbb{E}^{\mathbb{Q}^N} \left(\frac{\max(V_i(T_i), 0)}{N(T_i)} P^{\mathbb{A}}(T_i; T_i) \right. \\ & \left. + \frac{\min(V_i(T_i), 0)}{N(T_i)} P^{\circ}(T_i; T_i) \mid \mathcal{F}_{T_{i-1}} \right). \end{aligned} \quad (5)$$

In our valuation the time T_{i-1} value being exposed to entities \mathbb{B}_j counterparty risk is given by

$$\begin{aligned} \frac{V_i^{\mathbb{B}_j}(T_{i-1})}{N(T_{i-1})} := & \mathbb{E}^{\mathbb{Q}^N} \left(\frac{\max(V_i(T_i), 0) - \max(V_i(T_i) - V_i^{\mathbb{B}_j}(T_i), 0)}{N(T_i)} P^{\mathbb{A}}(T_i; T_i) \right. \\ & \left. + \frac{\min(V_i(T_i), 0) - \min(V_i(T_i) - V_i^{\mathbb{B}_j}(T_i), 0)}{N(T_i)} P^{\circ}(T_i; T_i) \mid \mathcal{F}_{T_{i-1}} \right). \end{aligned}$$

In other words, $V_i^{\mathbb{B}_j}(T_{i-1})$ is the true portfolio impact (including side effects of funding) if the flows $X_{l,k}^{\mathbb{B}_j}$, $l \geq i$, are removed from the portfolio.

In the case where the mismatch of contracted default value $V_{\text{CLSOUT},i}^{\mathbb{B}_j}(T_i)$ and

netted non-default value $R_i^{B_j}(T_i)$ is zero we arrive at

$$\begin{aligned}
 V_i^{B_j}(T_i) &:= \min\left(R_i^{B_j}(T_i), 0\right) + (1 - p_j) \max\left(R_i^{B_j}(T_i), 0\right) \\
 &= R_i^{B_j}(T_i) + p_j \max\left(R_i^{B_j}(T_i), 0\right) \\
 &= R_i^{B_j}(T_i) - p_j \max\left(R_i^{B_j}(T_i), 0\right) \\
 &= \sum_k X_{i,k}^{B_j} + V_{i+1}^{B_j}(T_i) - p_j \max\left(\sum_k X_{i,k}^{B_j} + V_{i+1}^{B_j}(T_i), 0\right).
 \end{aligned}$$

- in this case we get an additional discount factor on the positive part (exposure) of the netted value, attributing for the protection costs.

3.4.3 Interpretation

From algorithm (5) it is obvious that the valuation of funding (given by the discounting using either P° or P^A) and the valuation of counterparty risk (given by buying/selling protection at p) cannot be separated. Note that

- We not only account for the default risk with respect to our exposure ($V_{\text{CLSOUT},i}^B(T_i)$), but also to the loss of a potential funding benefit, i.e., the impact of default on funding.
- Buying protection against default has to be funded itself and we account for that.

The algorithms (5) values the so called wrong-way-risk, i.e., the correlation between counterparty default and counterparty exposure via the term $p_j \max(R_i^{B_j}(T_i), 0)$.

3.4.4 The Collateralized Swap with Funding Costs

Let us consider the collateralized swap again. While the mark-to-market value of a collateralized (secured) cash flow can be calculate off the curve implied by the collateral, the presents of funding cost changes the picture significantly:

- The discount curve determining the collateral may be different from the curve discount curve attributing for the funding cost. Hence, the collateral will not match the expected value of the future cashflows including funding costs.
- Collateral may require funding or may represent a funding benefit. In case of default these cashflows are lost.

The surprising result is, that the presents of funding cost may introduce counterparty risk into a collateralize (secured) deal. As a consequence, the collateralized deal has to be valued within (5) to account for these effects.

4 The Relation of the Different Valuations

Let us summarize the relation of the two different discounting in the presents of counterparty risk. The mark-to-market value of a time T_i cash flow is

| cash flow | discount factor over $[T_{i-1}, T_i]$ |
|---------------------------|---------------------------------------|
| outgoing ($C(T_i) < 0$) | $P^A(T_{i-1}, T_i)$ |
| incoming ($C(T_i) > 0$) | $P^B(T_{i-1}, T_i)$ |

In this situation a liability of **A** is written down, because in case of liquidation of **A** its counterparts accepts to receive less than the risk free discounted cash flow today.

The hedging (replication) value of a time T_i cash flow depends however on our net cash position, because the net cash position decides if funding cost apply or a funding benefit can be accounted for. The net cash position has to be determined with the backward algorithm (3) where each cash flow X_i is adjusted according to his (netted) counterparty risk. Using $P^B(T_i; T_i)P^\circ(T_{i-1}, T_i) = P^B(T_{i-1}, T_i)$ we can formally write

| cash flow | discount factor over $[T_{i-1}, T_i]$ | |
|---------------------------|---------------------------------------|----------------------------|
| | positive net cash in T | negative net cash in T_i |
| outgoing ($C(T_i) < 0$) | $P^A(T_{i-1}, T_i)$ | $P^\circ(T_{i-1}, T_i)$ |
| incoming ($C(T_i) > 0$) | $P^B(T_i; T_i)P^A(T_{i-1}, T_i)$ | $P^B(T_{i-1}, T_i)$ |

The two valuation concepts coincide when $P^A(T_{i-1}, T_i) = P^\circ(T_{i-1}, T_i)$, i.e., we do not have funding cost. They also coincide if an outgoing cash flow appears only in the situation of positive net cash in T_i (funding benefit) and an incoming cash flow appears only in the situation of negative net cash T_i (funding benefit).

Put differently: The liquidation valuation neglects funding by assuming funding benefits in all possible situations.⁶

4.1 One Product - Two Values

Given the valuation framework discussed above a product has at least two values:

- the product can be evaluated “mark-to-marked” as a single product. This value can be seen as a “fair” market price. Here the product is valued according to Section 2. This is the product’s *idiosyncratic value*.
- the product can be evaluated within its context in a portfolio of products owned by an institution, i.e., including possible netting agreements *and* operating costs (funding). This will constitute the value of the product for the institution. Here the value of the product is given by the change of the portfolio value when the product is added to the portfolio, where the portfolio is valued with the algorithm (3). This is the products *marginal portfolio value*.

However, both valuations share the property that the sum of the values of the products belonging to the portfolio does not necessarily match the portfolio’s value. This is clear for the first value, because netting is neglected all together. For the second value, removing the product from the portfolio can change the sign of netted cash flow, hence change the choice of the chosen discount factors.

⁶ This is, assuming zero bond-cds basis spread, the situation in [7].

4.2 Valuation of a Bond

To test our frameworks, let us go back to the zero coupon bond from which we started and value it.

4.2.1 Valuation of a Bond at Mark-To-Market

Using the mark-to-market approach we will indeed recover the bonds market value $-P^A(T; 0)$ (this is a liability). Likewise for $P^B(T)$ we get $+P^B(T; 0)$.

4.2.2 Valuation of a Bond at Funding

Factoring in funding costs it appears as if issuing a bond would generate an instantaneous loss, because the bond represents a negative future cash flow which has to be discounted by P° according to the above. This stems from assuming that the proceeds of the issued bond are invested risk free. Of course, it would be unreasonable to issue a risky bond and invest its proceeds risk free.

However, note that the discount factor only depends on the *net* cash position. If the net cash position in T is negative, it would be indeed unreasonable to increase liabilities at this maturity and issue another bond.

Considering the hedging cost approach we get for $P^A(T)$ the value $-P^\circ(T; 0)$ if the time T net position is negative. This will indeed represent loss compared to the mark-to-market value. This indicated that we should instead buy back the bond (or not issue it at all). If however our cash position is such that this bond represents a funding benefit (in other words, it is needed for funding), its value will be $P^A(T; 0)$.

For P^B we get

$$N(0)E^{\mathbb{Q}}\left(\frac{P^B(T; T)P^A(T; T)}{N(T)} \mid \mathcal{F}_0\right)$$

Assuming that A's funding and B's counterparty risk are independent from $P^\circ(T)$ we arrive at

$$P^B(T; 0)\frac{P^A(T; 0)}{P^\circ(T; 0)}$$

which means we should sell B's bond if its return is below our funding (we should not hold risk free bonds if it is not necessary).

4.3 Convergence of the two Concepts

Not that if A runs a perfect business, securing every future cash flow by hedging it (using the risk free counterpart $P^\circ(T; T)$), and if there are no risk in its other operations, then the market will likely value it as risk free and we will come close to $P^A(T; T) = P^\circ(T; T)$. In that case, we find that both discounting methods agree and symmetry is restored.

However, there is even a more closer link between the two valuations. Let us consider that entity A holds a large portfolio of products V_1, \dots, V_N . Let $V_1(0), \dots, V_N(0)$ denote the mark-to-market (liquidation) value of those products. Let $\Pi[V_1, \dots, V_N](0)$ denote the hedging value of the portfolio of those products. If the portfolio's cash

flows are hedged in the sense that all future net cash flows are zero, then, neglecting counterparty risk, we have (approximately)

$$V_k(0) \approx \Pi[V_1, \dots, V_N](0) - \Pi[V_1, \dots, V_{k-1}, V_{k+1}, \dots, V_N](0).$$

Thus, the mark-to-market valuation which includes “own-credit” for liabilities corresponds to the marginal cost or profit generated when removing the product from a large portfolio which includes funding costs. However, portfolio valuation is non-linear in the products and hence the sum of the mark-to-market valuation does not agree with the portfolio valuation with funding costs.

We proof this result only for product consisting of a single cash flow. A linearization argument shows that it then hold (approximately) for products consisting of many small cash flows.

If the portfolio is fully hedged the all future cash flows are netted. In other words, the entity A attributed for all non-netted cash flows by considering issued bonds or invested money. Then we have $V_j^d(T_j) = 0$ for all j . Let V_k be a product consisting of a single cash flow $C(T_i)$ in T_i , exchanged with a risk free entity. If this cash flow is incoming, i.e. $C(T_i) > 0$ then removing it the portfolio will be left with an un-netted outgoing cash flow $-C(T_i)$, which is according to our rules discounted with $P^\circ(T_i)$. Likewise, if this cash flow is outgoing, i.e. $C(T_i) < 0$ then removing it the portfolio will be left with an un-netted incoming cash flow $C(T_i)$, which is according to our rules discounted with $P^A(T_i)$.

Hence the marginal value of this product corresponds to the mark-to-market valuation.

5 Credit Valuation Adjustments

The valuation defined above includes counter party risk as well as funding cost. Hence, valuing a whole portfolio using the above valuation, there is no counter party risk adjustment.

However, the valuation above is computationally very demanding. First, all products have to be valued together, hence it is not straight forward to look at a single products behavior without valuing the whole portfolio.

Second, even very simple products like a swap have to be evaluated in a backward algorithm using conditional expectations in order to determine the net exposure and their effective funding costs. This is computationally demanding, especially if Monte-Carlo simulations is used.

As illustrated above, the valuation simplifies significantly if all counterparts share the same zero coupon bond curve $P(T; t)$ and/or the curve for lending an borrowing agree. A credit valuation adjustment is simply a splitting of the following form

$$V(t) = V|_{P^*=P^*}(t) + \underbrace{(V(t) - V|_{P^*=P^*}(t))}_{\text{CVA}}$$

where $V|_{P^*=P^*}(t)$ denotes the simplified valuation assuming a single discounting curve P^* (neglecting the origin or collateralization of cash flows).

While the use of a credit valuation adjustment may simplify the implementation of a valuation system it brings some disadvantages:

- The valuation using the simplified single curve, in general, is not correct.
- Hedge parameters (sensitivities) calculated such valuation, in general, are wrong.

In order to cope with this problem we propose the following setup:

- Construction of proxy discounting curve P^* such that the CVA is approximately zero.
- Transfer of sensitivity adjustments calculated from the CVA's sensitivities.

6 Modeling and Implementation

So far we expressed all valuation in terms of products of cash flows and zero coupon bond processes like $P^A(T; t)$. The value of a stochastic time T cash flow $C(T)$ originating from entity A was given as of time T as

$$C(T)P^A(T; T)$$

and the corresponding time $t < T$ value was expressed using risk neutral valuation

$$N(0)E^{\mathbb{Q}^N} \left(\frac{C(T)P^A(T; T)}{N(T)} \mid \mathcal{F}_0 \right).$$

Our presentation was model independent so far. Depending on the cash flow the term $C(T)P^A(T; T)$ may give rise to valuation changes stemming from the covariance of $C(T)$ and $\frac{P^A(T; T)}{N(T)}$.

For an implementation of the valuation algorithm consider a time discretization $0 =: t_0 < t_1 < \dots < t_n$. We assume that the discretization scheme of the model primitives models the counterparty risk over the interval $[t_i, t_{i+1})$ as an \mathcal{F}_{t_i} -measurable survival probability such that we have for all t_{i+1} cash flows $C(t_{i+1})$ that

$$\begin{aligned} N(t_i)E^{\mathbb{Q}^N} \left(\frac{C(t_{i+1})P^A(t_{i+1}; t_{i+1})}{N(t_i)} \mid \mathcal{F}_{t_{i+1}} \right) \\ = N(t_i)E^{\mathbb{Q}^N} \left(\frac{C(t_{i+1})}{N(t_{i+1})} \mid \mathcal{F}_{t_i} \right) \exp \left(- \int_{t_i}^{t_{i+1}} \lambda^A(s; t_i) ds \right). \end{aligned} \quad (6)$$

The expression $\exp \left(- \int_{t_i}^{t_{i+1}} \lambda^A(s; t_i) ds \right)$ represents an additional “discounting” stemming from the issuers credit risk / funding costs. It can be interpreted as and (implied) survival probability (see Chapter 28 in [4]).⁷

Hence any counterparty-risk-free valuation model can be augmented with funding costs, counterparty risk and collateralization effects by two modifications:

- The model is augmented by a simulation of the (conditional) one step (forward) survival probabilities (or funding spreads), e.g., $\exp \left(- \int_{t_i}^{t_{i+1}} \lambda^A(s; t_i) ds \right)$.
- The valuation is performed using the backward algorithm (3), where in each time step the survival probabilities and/or funding adjusted discount factors are applied according to (6).

⁷ A very simple model is to assume that $\exp \left(- \int_{t_i}^{t_{i+1}} \lambda^A(s; t_i) ds \right)$ is deterministic.

7 Conclusion

We considered the valuation of cash flows including counterparty risk and funding. We shed some light on the *own credit risk paradox* that the mark-to-market value of a portfolio increases if its owner's credibility decreases. After our discussion the situation now appears much clear: This increase in value is reasonable when considering the portfolios liquidation since lenders are willing to accept a lower return upon liquidation in exchange for the increased credit risk.

If we value the portfolio under a hedging perspective (where hedging to some extent means funding) we see that the portfolio value decreases if its owner's credibility decreases. This is also reasonable since funding cost (operating costs) have risen.

The two notion of valuation can co-exist. They do not contradict. One discounting should be used for mark-to-market valuation. The other should be used for risk management and the governance (managing) of positions.

To see the effect of a single deal on the cash flow management the bank could use a curve for borrowing and lending and every deal would have to be valued according to the algorithm (3).

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Notes

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