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Re-Thinking Valuation: The Credit Crisis, Illiquid Markets and Model Risk

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In 2007–9 the financial industry experienced a "once-in-a-lifetime" crisis, which nearly brought down the entire system. A report by the IMF in April 2010 estimated bank write-downs and loan provisions between 2007 and 2010 at US$2.3 trillion, with about two-thirds of these losses (or about US$1.5 trillion) realised by the end of 2009 (International Monetary Fund 2010).[1] Originating first in the US subprime market, before spreading around the globe, the credit crisis highlighted many limitations of the industry's general valuation practices and our understanding and management of risk. Market participants clearly misunderstood and underestimated the risks in many securities, especially with respect to systematic risk, default correlation, contagion effects and liquidity.

What is the value of a security, and how do we know? The crisis further made evident the intrinsic limitation and subjectivity of our valuation models and pricing assumptions. When liquidity is thin, dealer quotes are unreliable and model parameters cannot be estimated based only on observed market prices. A quote by the famous dramatist and poet Oscar Wilde (1854–1900) comes to mind:

> Nowadays people know the price of everything and the value of nothing.

If Wilde had been alive today, his quote might have probably read:

> Before the crisis, people knew the price of everything and the value of nothing. Now they know neither of them.

When dealing with complex structures and markets with limited liquidity, it is important to understand the meaning and use of a price. Also, we must acknowledge the sometimes "heroic" assumptions in our models and the limitation of the information which we can reasonably extract from the market. In practice, we must effectively incorporate fundamental market and credit information, historical data and expert judgment into the valuation process. In addition, it is vital to develop explicit model risk and stress-testing approaches which can help us understand better the behaviour of instruments and portfolios, together with their risks and the "Knightean" uncertainties we could be facing.

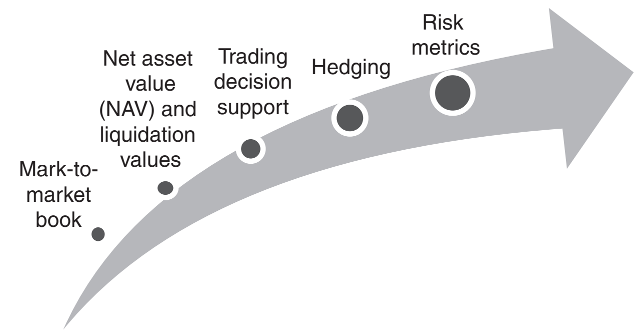
In this chapter, we discuss several lessons and best practices that we are relearning as the global banking system copes with the legacy of the crisis. Given the inevitable limitations of our models, we stress the importance of a model risk and scenario analysis framework. While the main points are general, we focus on examples of the credit crisis and, in particular, industry experience in the area of structured finance. Pricing models for structured credit securities have often been overly simplistic, with many institutions placing too much reliance on dealer quotes, on simple models based on credit ratings and on top-down views of collateral portfolios. As liquidity dried up, market participants were left in the dark, not able to reliably determine the value the portfolios or to analyse their risk.

WHAT IS THE PRICE OF A SECURITY?

In a formal sense, a price is the agreed exchange value at which buyers and sellers agree to trade a security (if it is in an open market, we generally refer to it as a market price). When we are "pricing" a portfolio, ideally we are attempting to estimate this portfolio price, should it be bought or sold. The process of price discovery is more transparent when there is liquidity in the market.

But what is a security's price when the market is illiquid and there is little or no trading? Then the meaning of a "price" depends largely on its application. We may distinguish, for example, between a "fair price", a "liquidation price", a "theoretical price" (in a "normal market") and a "fundamental price". In this case, we must largely rely on models to guide us. Pricing models (and their calibration) may vary depending on their application: marking a book to market, estimating a liquidation value, defining trading opportunities, hedging or managing risk (see Figure 33.1). For example, marking-to-market

Figure 33.1 Pricing applications



a book requires models that satisfy the applicable accounting principles, etc. In contrast, a pricing model for identifying trading opportunities purposely looks for "mispricings" in the market and bet on their later correction. Understanding that a price has different meanings in different contexts is crucial to decision making and particularly to measure and manage model risk.

Model risk can be loosely defined as the risk involved in using models to value and measure the risk of financial securities and portfolios. Depending on the application (see Figure 33.1), there are several possible definitions of model risk.[2] For example, in its most common use, derivatives traders refer to the risk that different models, calibrated with the same data (eg, prices for the underlying and hedging instruments), produce different prices for a given non-traded, bespoke product. This exposes the trader to the risk of using a mis-specified model. Similarly, we can have the risk that the same model produces different results with different calibration data curves (eg, different quotes or curves).

From the perspective of marking-to-market a trading desk or an entire institution's portfolio, model risk refers to the use of models for pricing products which are not reliably observed in the market, or when there is no liquidity at all. Essentially, the value at which an instrument would trade in the market cannot be readily determined via screen or broker quotes, looking at market transactions, etc. A model is required in order to associate a value to these instruments for marking purposes (on a daily, weekly or monthly basis, depending on the institution). When liquidity is thin, dealer quotes are unreliable and model parameters cannot be estimated by basing them only on observed market prices. The 2007–9 crisis made evident these limitations and further highlighted the subjectivity of valuation models and their assumptions.

For this case, Rebonato (2003) provides the following definition:

> Model risk is the risk of occurrence of a significant difference between the mark-to-model value of a complex and/or illiquid instrument, and the price at which the same instrument is revealed to have traded in the market.

The need for marking a portfolio, together with institutional and regulatory constraints, has important practical implications for pricing. Model risk arises not because the model value for an instrument is different from its "true" value (if one existed at all), but because of a discrepancy between the model value and the value that must be recorded for accounting purposes. In this case, there is no model risk if reliable market prices are observable (even if these prices seem unreasonable).

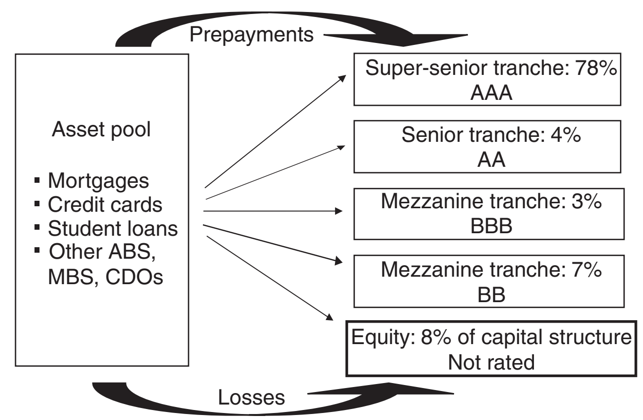
LESSONS LEARNT AND EMERGING BEST PRACTICES BEYOND THE CRISIS

The credit crisis highlighted limitations of the industry's general understanding of pricing and risk management practices. Regulators and industry associations have highlighted the need for transparency and the inadequacy, in general, of some standard valuation and risk modelling approaches used by industry participants. For example, in the case of structured credit portfolios, practitioners relied too heavily on dealer quotes and external credit ratings. Several reports have been written which explore the underlying causes of the crisis, and discuss lessons for structurers, investors and regulators.[3] In this section, we review five important lessons and best practice recommendations.

Independent valuation and internal modelling capabilities

For investment institutions, it is essential to have valuations which are independent of the dealer and traders. Independent valuation must not be done in a theoretical vacuum; it must be intimately linked to market practices and a clear understanding of liquidity. According to the Senior Supervisors Group (2008) report:

Figure 33.2 ABS structure



> Firms that performed better in late 2007 had developed in-house expertise to conduct independent assessments of the credit quality of assets underlying the complex securities to help value their exposures appropriately. In contrast, firms that faced more significant challenges tended to rely too passively on pricing services to determine values for their exposures.

The development of internal modelling capabilities is vital for firms to form their own judgment about the quality of prices. Managing risk through crisis periods requires established, rigorous internal processes with critical judgment and discipline in the valuation of illiquid and complex securities. Valuations should be tested, discussed and challenged as much and as often as possible.

Take as an example the case of structured finance securities. These are complex structures with specific features, which make their valuation challenging, when compared to simple bonds. Figure 33.2 gives an example of an asset-backed security (ABS). A key feature of ABSs is that investors bear the credit risk of the collateral. In addition, these securities may also bear prepayment risk stemming from the underlying loans. Multiple tranches of securities are issued from the collateral, offering investors various maturity and credit risk characteristics. Tranches are categorised as senior, mezzanine and subordinated/equity, according to their degree of credit risk. If there are defaults or the collateral otherwise underperforms, scheduled payments to senior tranches take precedence over those of mezzanine tranches, which in turn take precedence over subordinated/equity tranches. Senior and mezzanine tranches are typically rated (in the figure, the former receive ratings of AA to AAA at inception and the latter receive BB to BBB). The ratings are meant to reflect both the credit quality of the underlying collateral and how much protection a given tranche is afforded by tranches that are subordinate to it.

Accurate modelling, valuation and risk measurement of these products is challenging, given the complexity of the structures and the underlying risks. Investors have in practice generally relied on periodic valuations and reports provided by dealers or other third parties, as well as on simple models based on external ratings. These black-box approaches resulted in a lack of transparency in prices and limited risk capabilities (risk measures, stress testing, concentration reports, etc). During the housing and credit boom decade preceding the crisis in 2007, structured finance instruments generally performed quite well. There was a widespread perception that their risks were small and contained. This view proved to be wrong – and costly.

Even when an institution continues to rely largely on externally provided prices, it is important that it also develops internal analysis capabilities and that risk management is actively engaged in the valuation process.

Transparency, transparency, transparency!

Valuations and risk management methodologies must be transparent in order to be useful to stakeholders. A transparent valuation process allows users to understand the key drivers of the price and the underlying risks. The methodology and the assumptions must be well documented and accessible. Models assumptions should be highlighted and reviewed continuously. All potential sources of risk must be incorporated and discussed.

The events of the credit crisis have highlighted the need for transparency on the detailed structure of securities, as well as for the valuation and risk methodologies.

Take again the case of structured finance portfolios. Difficulties in valuing these securities and measuring their risk result from the following.

- The underlying collateral: collateral portfolios are composed of hundreds or thousands of loans, whose characteristics must be disclosed and modelled in detail.

- The complex structures: the cashflow structures, composed of involved cashflow waterfalls and triggers, are complex and generally opaque for standard investors. They are difficult to model and also computationally involved.
- The complex risk profiles: portfolios contain market risk (interest rates and spreads), credit risk and prepayment risk (as well as liquidity risk). These risks are intertwined, and it is difficult to capture their interaction effectively. Correlations are very important and difficult to assess, and are not standardised. Systematic concentrations have proven to be key drivers of losses as well as possible contagion (within obligors in a market, as well as across markets).
- A lack of reliable pricing data: pricing, as well as fundamental credit data, comes from multiple data sources and is often incomplete or unreliable. The lack of liquidity[4] in the market increases this problem.

It is vital to understand in detail both the collateral and the securities' structures. A high-level, top-down modelling of the collateral can lead to misleading results and does not allow us to understand key underlying risks and concentrations, nor to discriminate between securities. Similarly, the details of cashflow waterfalls and triggers, which alter the structure, can play a significant role.[5]

Valuation based on dealer quotes versus good models based on fundamentals

The credit crisis underscored the need for effective, transparent and robust valuation methods for complex and illiquid securities, and specifically for structured finance securities and credit derivatives. Consistency of valuation is also required across asset classes. The models and assumptions must be transparent. We must also make sure that we have good models, which capture all the risks and are implemented with good, reliable data.

As mentioned earlier, investors have traditionally relied on dealer quotes as a basis for marking-to-market as well as risk management. In particular, it has been common practice to use single indicative quotes, typically from dealers that originated the structures. These quotes may not reflect true prices, at which transactions could occur, especially during periods of distress and illiquidity. They also provide limited value for risk management. Dealer quotes have tended to show bias (generally upwards), as well as a tendency to remain stagnant, even as more liquid instruments show significant changes (eg, CDSs and synthetic indexes).

As the markets come under stress and credit instruments become illiquid, the reliance on dealer quotes must be thoroughly investigated. Many firms have now realised their need for an infrastructure to model these positions internally and to develop analytics to check valuations and compare them with market quotes.

In the case of structured finance securities, the commonly applied valuation models depended significantly on agency ratings, and this led to severe valuation issues throughout the crisis. Even many sophisticated players only implemented enhancements to their models as the crisis began, by using more detailed instrument information beyond ratings.

The 2007–9 events also reminded us of the importance of correlations and systematic risk. Mortgages proved to be highly correlated and exposed to common systematic factors. Specifically, the two key factors which drove their risk are

- the general level of house prices (in the US in particular),
- the lending standards, which had severely deteriorated by 2005.

MBSs were not the only securities affected by correlation and systematic risk; many other classes followed similar patterns during market crashes and crises.

During the 2007–9 crisis, models generally failed to capture systematic effects and structural market fundamentals. These models were typically calibrated on data that did not reflect the basic credit quality differences of the new loans or possible home price declines. Thus, their parameters (default rates, recoveries, prepayments and correlations) were generally inadequate. Even sophisticated econometric models from investment banks, ratings agencies and research firms failed to account for other effects, such as risk layering (eg, loans with high loan-to-value ratios and low standards of documentation).

Pricing methods for structured finance instruments can essentially be divided into two classes: bond-pricing (single-scenario) methods and stochastic (option-based, or simulation) methods. In addition, practitioners commonly use a third approach, the

Table 33.1 A summary of structured finance valuation methods

Method	Strengths	Weaknesses
Bond	• Computationally simple • Can incorporate performance of individual loans in an ABS • Efficient to understand performance and risk behaviour under various scenarios	• Does not capture correlations, optionality, non-linearities • Arbitrary base scenarios • Accurate cashflows depend on strength of underlying model for collateral
Simulation	• Option-theoretic approach: captures correlations and non-linearities • Provides more advanced risk metrics • Integration with synthetics and other instruments	• Computationally intensive • Might be computationally intractable with full bottom-up collateral simulation
Collateral value models (NAV)	• Uses market prices (if available) and less model data • Can be used to identify relative trading opportunities for super senior tranches, where other valuation methods provide limited transparency	• Relies on available market values for underlying collateral • Only approximates waterfall • Lacks explanatory power on cashflow performance projection of underlying collateral and waterfall

collateral-market-value (or net-asset-value (NAV)) method to monitor these investments. Table 33.1 summarises the advantages and disadvantages of the various valuation models.

The predominant pricing framework for structured finance instruments, widely used by dealers and investors, is based on simple bond models and matrix pricing, where the yields of these securities are expressed in a similar way to those of typical corporate bonds. These models have two key characteristics:

- they employ a single-scenario valuation, ie, they generally assume a deterministic stream of cashflows from the collateral and the structure;
- they generally rely on credit ratings as determinants of yields (spreads) and risk measurement.

Under the NAV approach, the underlying collateral is first marked-to-market (MtM).[6] The analyst can then compute various "coverage ratios" reflecting how this collateral's MtM covers the different bonds in the structure (if it were to be liquidated). Then, for example, the price of an equity tranche of a collateralized debt obligation (CDO) reflects the market value of the CDO's reference assets (net of the CDO debt and other liabilities) divided by the notional amount of equity issued. For debt tranches, dealers use formulas involving the ratio of equity over debt, which roughly expresses the amount of overcollateralisation in the structure. This method is generally used more as a monitoring and stress-testing tool, and less as a method to provide a mark-to-market values for the structured securities.

The practical application of more robust stochastic, option-pricing models to value structured credit is less than a decade old (at the time of writing). Given the complexity of the collateral and their waterfall structures, these models are computationally intensive. They generally require Monte Carlo methods, where each cashflow computation under a scenario (a particular set of market factors, default and prepayment rates) is expensive. These techniques are conceptually simple, and can be seen as a sophisticated multi-scenario extension of the single-scenario methodology, where the value is given by averaging the NPVs over all the scenarios. The parameters of the processes used to generate the scenarios are calibrated to

- market prices, where available, ie, a standard set of market quotes for representative, more liquid instruments, and
- fundamental credit information as well as subjective expert judgment.

A short, high-level description of these methods, with an example, is given in the Appendix.

Model risk framework

Given the limitations of our models, the uncertainty in the underlying data and prices and the illiquidity in the market, it is important to develop a systematic approach for capturing and communicating model risk.

From a model risk perspective, a pricing model has the following three components.

- The mathematical/financial framework: this includes the model assumptions, the model scope and applicability and the calibration methodology and calibration set (the benchmark instruments used to calibrate the parameters).
- The software implementation.
- The desired outputs: prices, sensitivities (deltas, gammas, spread, yield, capital, etc).

A comprehensive model risk assessment provides us with a deep understanding of the assumptions and their applicability as well as the sensitivities of the outputs to each component, examined at a trade-and-aggregated-book level. Model risk must also be defined and assessed in the context of its application: whether the model is used for marking a book, for hedging and trading or for risk measurement and management.

The components of a sound model risk management practice include the following.

Model application documentation: a complete inventory of models, metrics of model use, assumptions, calibration, parameters, etc, as well as clear identification of model limitations and risks.

Model development process: sound development, implementation and documentation, as well as continuous improvement and upgrading of models.

Testing: comprehensive model testing (stand alone and integration).

Independent review testing and approval: this includes validation of model applicability, model inputs and outputs and market review (changes, developments, new quotes, etc).

Valuations should be challenged continuously, and this requires the processes and knowledgeable resources to do this, as well as the analytical tools and data. We should try to use as many different market sources as possible in the analysis. Some examples are given below.

- Multiple indicative prices and quotes should be provided by price services or custodians.
- Whenever possible, some firms may try selling (or buying) a small fraction of the holding to compare model prices.
- Comparison should be made to indexes where prices are observable (in the case of structured credit, eg, against indexes such as the CDX, iTraxx, LCDX or ABX).
- In addition to prices, we can also assess the model based on the resulting sensitivities (for example, the Greeks) and comparing them to indexes or other standard instruments, where available.

Finally, stress testing is a fundamental component of any model risk framework. In the case of structured finance portfolios, we should be able to understand the valuations under different scenarios for default, recovery and prepayment vectors, discount spreads, credit downgrades (and defaults) for the collateral and correlation assumptions, in the case of more advanced models.

Risk management fundamentals

Over a decade of great performance since the late 1990s, market participants, by and large, seemed to have abandoned risk management fundamentals when dealing with structured credit investments by

- not modelling in detail or understanding their instruments' underlying collateral and structures,
- forgetting credit fundamentals and grossly misjudging credit quality and correlation,
- relying on external dealer quotes and ratings to make decisions and manage risk.

Risk systems generally failed to capture the fundamental credit quality of the underlying portfolios. They did not provide an understanding of the risks of super-senior positions (which were assumed to have zero value-at-risk or stress limits) and generally failed to treat appropriately the basis risk between cash bonds and derivatives instruments such as CDSs. In order to understand and manage the risk of these portfolios, it is necessary for an institution to develop the standard risk management tools, which effectively capture the essence of these instruments. These tools include:

- stress testing;
- concentration risk, both within a product (which impacts valuation and risk) and across products (which is important for portfolio credit risk),
- systematic risk (which has proven to be a key driver);
- comprehensive risk metrics, which should include sensitivities, scenario based measures, statistical measures (eg, VaR);
- risk contributions and performance attribution metrics.

It is important that these systems are based on a sound data foundation. Furthermore, they should allow us to understand better the interaction between the different types of risk: market, credit and liquidity risk.

FINAL REMARKS

A now famous quote by Warren Buffett[7] states that:

> Price is what you pay…. Value is what you get.

But what is a price when there is no liquidity, or a market to sell to?

In this chapter, we have discussed the meaning and uses of prices, and shown the importance of a model risk framework given the limitations of our models. We have presented several lessons and best practices that can be learnt from the credit crisis. While the main points are general, we have focused some of the examples on the area of complex structured finance instruments. The role played by the mispricing of structured finance securities in the lead-up to the 2007–9 financial meltdown leaves little doubt that the development of better methods for pricing, hedging and risk management of these instruments is an important priority. Historically, market participants have tended to rely exclusively on overly simplistic pricing methods, and credit ratings. Advanced Monte Carlo approaches have only been considered within the last decade, and remain computationally demanding. Given the limited liquidity and depth of the market, their calibration remains challenging. In addition to the limited market information, in practice we require effective use of fundamental credit data, and expert judgment to be translated into useful scenarios which can be used to get a comprehensive picture of the portfolio value and risks. The lessons learned are general, and point to the need for multiple models for pricing, and for decision making, as well as model risk tools, which necessarily make use of uncertain parameters, expert opinion and scenarios.

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APPENDIX: VALUATION MODELS FOR STRUCTURED FINANCE PORTFOLIOS

In this appendix we briefly describe the stochastic pricing methods for structured finance instruments. The practical application of more robust stochastic option-pricing models to value structured credit is less than a decade old at the time of writing. Most of this advanced modelling work was originally focused on the valuation of synthetic CDOs with underlying corporate CDSs. These instruments are analytically more tractable since they have simple, standardised waterfalls that can be readily modelled. Also, the models can be more objectively calibrated to observable indexes and tranches, which are commonly traded.[8]

In contrast to synthetic CDOs, the application of stochastic models for ABS and cash CDOs is fairly new. Given the complexity of the collateral and their waterfall structures, these models are computationally intensive. They generally require Monte Carlo methods, where each cashflow computation under a scenario (a particular set of market factors, default and prepayment rates) is expensive. Also, standardised calibration is more difficult, due to the illiquidity in the market. Several methodologies have been developed to tackle these problems in practice. In particular, implied factor models are powerful tools that can achieve consistent valuations across different portfolios and specifically model bespoke portfolios. In this approach, a set of factors is used to drive the joint credit (and prepayment) events within the underlying portfolio. Using weighted Monte Carlo techniques, the calibration of the model searches for an optimal joint distribution of the factors, such that the market prices of a set of reference securities (such as the tranches of various indexes) are matched, possibly within allowable error limits.[9]

Implied factor models using weighted Monte Carlo techniques are conceptually simple, and straightforward to implement. They can

Table 33.2 Monte Carlo pricing of the ABX Index

	Market price	Model prices	Error (%)
ABX-XHAAA72 Index	91.81	97.66	5.99
ABX-XHAA72 Index	71.06	69.91	−1.65
ABX-XHA72 Index	44.31	44.69	0.86
ABX-XHBBB72 Index	26.00	25.84	−0.63
ABX-XHBBBM72 Index	23.00	23.02	0.08

be seen as a sophisticated extension of the single-scenario methodology. Essentially, a sample of scenarios (typically very large, in the thousands) is generated, each of them containing detailed assumption vectors to generate cashflows (default, prepayment and recovery rates) as well as realisation of interest rates and other financial factors. Scenarios are generated from a well-defined stochastic joint process for all the factors, which accounts for their volatilities, correlations, etc. Under each scenario, cashflows are generated for every security and a conditional net present value (NPV) is obtained by discounting them by applying the risk-free rate. The final value is given by averaging the conditional NPVs over all the scenarios. The parameters of the processes used to generate the scenarios are calibrated from market prices, where available (eg, based on the ABS/CDO indexes such as the iTraxx, CDX, LCDX, ABX, CMBX) or to a standard set of market quotes for representative, more liquid instruments.

Figure 33.3 presents an example of the valuation of the ABX Index using the systematic weighted Monte Carlo methodology of Rosen and co-authors (Rosen and Saunders 2009; Nedeljkovic *et al* 2010a,b). Figure 33.3(a) depicts the average default rates, prepayment rates and loss-given-default for the underlying loans in each of the ABSs. These are clearly correlated through the use of a factor model. Thus, good economic scenarios tend to have low average default rates and LGDs, and high prepayment rates (and vice versa). Figure 33.3(b) shows the probability distribution for the scenarios. This can be calibrated from observed prices (risk-neutral probabilities) or perhaps from historical data (empirical probabilities). For valuation purposes, we seek to calibrate the model to observable prices.

Figure 33.3 Monte Carlo pricing of the ABX Index

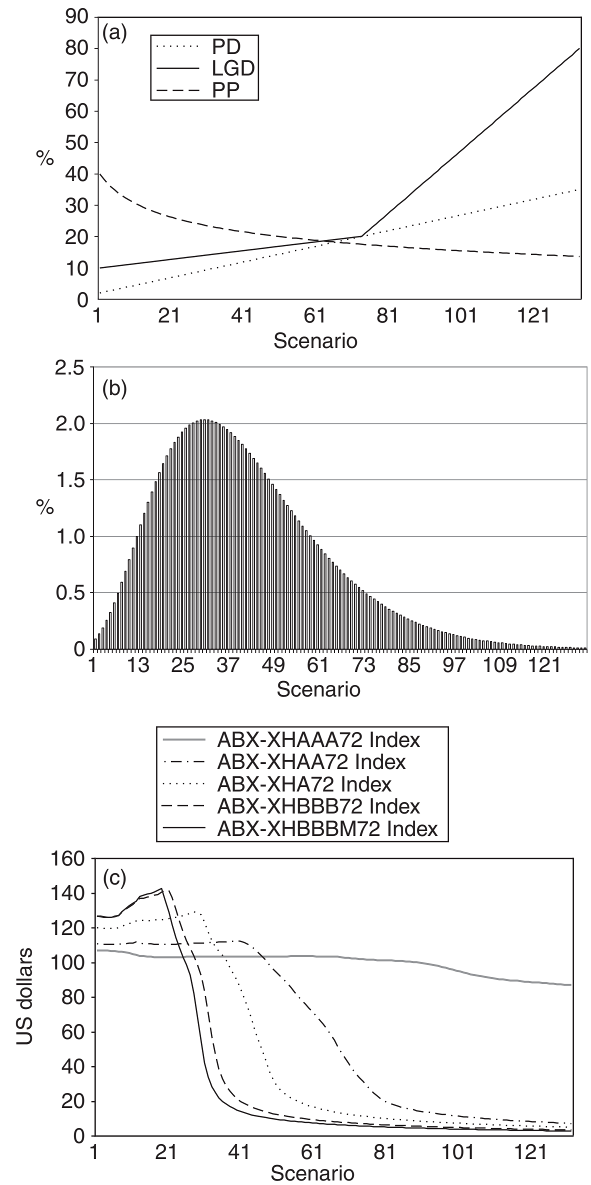

Figure 33.3(c) plots the expected discounted cashflows for each of the ABX indexes over each scenario. Finally, Table 33.2 shows the quoted market prices for the indexes as well as the model prices. As

can be seen, in this example we match very well all but the most senior tranche with the model (which has a 6% error).

This example clearly shows the key difference between a bond model and a stochastic model. The stochastic model captures explicitly the (non-linear) cashflow structure of the security over many scenarios and prices consistently all tranches based on the same collateral. We now list some important features of this Monte Carlo approach.

- It is a structured, multi-scenario approach, which effectively uses advances in credit models, Monte Carlo methods and CDO analytics developed since 2000.
- It explicitly models the key risks: credit (default, LGD, spread), prepayment and market risk, as well as their interactions.
- It is a portfolio-risk-based approach where correlations and concentration risks are captured.
- It can be implemented as an "arbitrage-free" approach, and can also be complemented with liquidity premiums, subjective views, etc).
- It provides consistent valuation of all the deals based on the same collateral pool (by using consistent parameters), as well as of various asset classes (synthetics, cash; ABS, CLO, CDO, CDO^2) through the consistent use of scenarios.
- It naturally provides sensitivities to various risks, as well as hedge ratios (this may be computationally intensive).

1 These estimates are of course subject to considerable uncertainty and range of error, including data limitations, measurement errors from consolidation, inter-country variations, changes in accounting standards and uncertainty on assumptions about exogenous variables.

2 See, for example, Rebonato (2003).

3 See, for example, Technical Committee of the International Organization of Securities Commissions (2008), Senior Supervisors Group (2008) and International Institute of Finance (2008).

4 The word "liquidity" is used in different contexts in the financial literature. In this chapter, when we refer to the liquidity of an instrument or market, we mean trading liquidity, ie, the ability to transact in a timely fashion with low transaction costs, and without undue effect on market prices.

5 Examples of the effect of triggers were evident in the asset-backed commercial paper (ABCP) market and links to auction rates.

6 This type of model is more generally applied to CDOs with underlying ABSs, which have observable market values.

7 See page 4 of http://www.berkshirehathaway.com/letters/2008ltr.pdf.

8 The prevailing synthetic CDO models are based on the Gaussian copula model (Li 2000), with the use of base correlations (McGinty and Ahluwalia 2004) and other extensions. In spite of its well-documented deficiencies, this framework is widely used, given its analytical tractability and its simple appeal for quoting prices in terms of correlations. In particular, the pricing of bespoke portfolios is problematic, with the use of *ad hoc* mapping models to relate the prices of traded indexes to those of tranches of different bespoke portfolios (St Pierre *et al* 2004).

9 The first such model was the "implied copula model" of Hull and White (2006), which is actually a top-down approach. Several others have followed including the "implied factor model" (Rosen and Saunders 2010; Nedeljkovic *et al* 2010a,b), the "implied Archimedean copula" (Vacca 2008) as well as models based on minimum entropy (Dempster *et al* 2007; Meyer-Dautrich and Wagner 2007; Halperin 2009) and others (Hull and White 2008; Walker 2006).

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