A Practical Guide to
Market Risk Model Validations
(Chapter I - Introduction)

Vilen Abramov
Matt Lowdermilk
Xianwen Zhou

May 18, 2017

Contents

Abstract

The financial crisis of 2008 has been extremely challenging and, at the same time, illuminating period for market risk managers. The crisis revealed a convoluted nature of the market risk and put market risk models to the crash test. The epic failure of the risk management models culminated in a historic US credit rating downgrade on political risks and rising debt burden. In this paper series, we review common modeling issues and validation techniques used in the market risk management area. We focus on the pricing, hedging and value at risk (VaR) models. Counterparty credit risk models have been excluded as they deserve a separate treatment. We discuss model risk events, market risk functional areas, common modeling issues, and model validation techniques. We have developed practical model validation procedures that should help validators to provide "effective challenge." The paper also contains a number of real examples.

1 What is Market Risk?

Risk management processes can be broken down into three major groups - market risk, credit risk, and operational risk. In addition to these three categories, one can also consider compliance risk, liquidity risk, reputation risk, strategic risk, etc. Many risks have multiple dimensions and can be assigned to multiple categories. For example, counterparty credit risk is a combination of market and credit risks. Furthermore, different risks may impact each other. Operational risk may lead to both, credit risk (stale credit score records) and market risk (rogue trader). These are typically called "boundary events" since they fall in a gray area between credit risk and operational risk or perhaps falling potentially between operational risk and market risk. Examples can include improper recording of liens that result in credit losses or perhaps something like an improperly executed counterparty agreement that results in market losses.

In this paper, we focus on the market risk management models. Following Federal Reserve Bank's (FRB) definition [1], market risk encompasses the risk of financial loss resulting from movements in market prices. Interest rate risk is one example of the market risk. It measures the exposure of a bank's current and future earnings and capital arising from adverse movements in interest rates. In addition to the interest rate risk, banks are exposed to the foreign exchange risk (changes in currency exchange rates and foreign interest rates affect foreign currency denominated instruments), credit spread risk (changes in credit spreads affect bond pricing and loan pricing), volatility risk (changes in volatility affect financial instruments with embedded optionality, such as mortgage-backed securities), commodity risk (changes in crude oil prices affect both credit spreads of oil producing companies and commodity swap valuations), etc.

2 What is Model Risk?

Following the 2008 crash, many practitioners blamed models that have been utilized to value complex products such as CDO (collateralized debt obligation). The banks' risk management models lost track of risk. The CDOs sliced into tranches (based on credit quality) were modeled by financial engineers. Some of these tranches had AAA credit ratings. Due to the risk underestimation, the banks were comfortable to invest into these assets to get higher returns. The banks also used leveraging to boost their profits. A turn in the housing market revealed the weaknesses of the risk management models. Due to the complex nature of CDOs, it was quite often difficult for banks and investors to fully appreciate the risk involved in them. As such, many investors and banks purchased them assured by rating agencies they held little risk in the highest tranches. However, they could not have known how the lower tranches would collapse and lead to much higher than expected defaults in the upper tranches.

Furthermore, the interdependencies between counterparties revealed another huge weakness in the counterparty credit risk modeling. Some banks heavily relied on CDS (credit default swap) instruments to "decrease" their credit risk. In reality, CDS only allows a bank to transfer credit risk. These transferred credit risk got accumulated at large institutions (such as AIG and Lehman Brothers). In addition to the credit risk, a number of mid-size banks offset their client derivate trades (such as interest rate swaps, commodity swaps, etc.) with these large banks. This allowed the mid-size banks to transfer market risk. Due to the high concentration, the collapse of these giants seemed inevitable and could destroy the world's financial system. The CDS market was also unchecked and this allowed market participants to enter into CDS contracts many times the size of the actual outstanding debt they sought to offset.

Since models played an important role in the risk assessment, the modelers were held accountable as well. Pablo Triana [2] recommended a radical reform in mathematical finance. Steven Shreve countered these convictions [3] by pointing out integrity issues of the people who manage financial system and make decisions. A long term critic of financial modeling techniques, Nassim Taleb, testified in front of the Senate [4]. Taleb presented an idea of the fourth quadrant (complex pay-off structures and heavy tails) [5] where conventional methods fail in tracking large deviations. This is the proverbial "black swan" event where since no one had ever seen one it was assumed it did not exist. In reality it was simply something outside of the historical data the models were built upon instead of something that couldn't happen. Paul Wilmott along with Emanuel Derman have written the Financial Modeler's Manifesto [6] to reassure reliability of the modeling practices.

A number of factors (beyond modeling weaknesses) played a role in the crisis. The Community Reinvestment Act [7] was rewritten in 1995 by President Bill Clinton. The revised Act forced banks to lend in low-income neighborhoods. Extension of the mortgages to the low income families along with lowered down payment requirements were reinforcing risky lending practices. Furthermore, regulators created a low interest rate environment that allowed banks to use leveraging for their risky investments. The compensation system allowed top rank bankers to make strategic decisions that were based on relatively short horizon risk assessment. A combination of these factors coupled with model weaknesses resulted in the financial system gridlock. Please, refer to [8] for a thorough review of 21 books on the crisis.

Following the collapse of Lehman Brothers, the main goals of the regulators were to keep systemically important institutions afloat in order to avoid collapse of the financial system, and to help banks recapitalize and unload toxic assets from their balance sheets. In order to restore a rigid risk modeling culture, the regulators issued Supervisory Guidance on Model Risk Management (SR 11-7) [9] and model risk management (MoRM) was born.

2.1 Derman's Classification and Beyond

One of the first systematic descriptions of model risk appeared in the mid 1990s [10]. In this prominent publication, Derman identified the following seven types of model risk.

- Inapplicability of model: a mathematical model may not be relevant to describe the problem at hand.

- Incorrect model: the risk of using a model that does not accurately describe the reality being modeled. This is the most common interpretation of model risk.
- Correct model/incorrect solutions: these can lead to, for example, inconsistent pricing of related claims.
- Correct model/inappropriate use: the risk related to an inaccurate numerical solution of an otherwise correct model (for example, the risk related to Monte Carlo calculations with too few simulations).
- Badly approximated solutions: this risk appears when numerical methods are used to solve a model.
- Software and hardware errors.
- Unstable data: financial data is of notoriously poor quality. Models must be robust with respect to errors in input data.

The risks listed above can be addressed. However, it is clear that there are no perfect models. The deeper question is - how accurate/reliable is the model? Given the use of the model, a modeler needs to wisely (easier said than done) choose a modeling approach understanding the impact of limitations on the model performance. It is important to note a model's weaknesses and limitations during model development. Two different models can be used to price one financial instrument. What model poses higher model risk? Rama Cont has introduced model uncertainty concept [11] in the context of derivative valuation and proposed a quantitative framework to measure model uncertainty. This quantitative framework is based on the computation of the price ranges for a set of calibrated models - wider ranges signal higher level of uncertainty. This is an attempt to measure systematic model risk caused by our inability to accurately represent reality using mathematical models. This systematic risk affects all agents in the market and can't be diversified. In many cases, modelers don't have exhaustive information to model reality precisely, they have to make assumptions and when they introduce assumptions they introduce uncertainty.

Generally speaking, market risk models use mark-to-market approach in which market information is used as an input. In essence, this is an inverse problem[1]. This poses in an important question of market data reliability.

The systemic risk is the risk of the financial system collapse. A great example of the systemic risk is the aforementioned 2008 crisis. In particular, the failure of the market risk models to

[1] To predict the result of a measurement requires (1) a model of the system under investigation, and (2) a physical theory linking the parameters of the model to the parameters being measured. This prediction of observations, given the values of the parameters defining the model constitutes the "normal problem," or, in the jargon of inverse problem theory, the forward problem. The "inverse problem" consists in using the results of actual observations to infer the values of the parameters characterizing the system under investigation.

correctly assess credit risk associated with CDO structures. When there is a common misconception in the market, the market information becomes misleading and even dangerous. Following Dudley's speech on asset bubbles [12], "during the boom, the structured finance models appeared to be sound because losses on the underlying subprime mortgage loans were low and because the correlation rates in performance across different assets in the pools were low, just as the models had assumed." But how can one tell whether the market information is right or wrong? As one said, it is not a bubble until it bursts. There are a series of papers by Robert A. Jarrow, Philip Protter, and Shimbo devoted to the theory of bubbles. Please, refer to [13] for the complete list of references. There are also a series of research papers published by Didier Sornette, who developed long-periodic power law (LPPL) model to describe market crashes. Please, refer to [14] for the complete list of references. Sornette along with other authors published a paper [15] in which they assessed the performance of the real-time diagnostic, available to the public on the website of the Financial Crisis Observatory (FCO) at ETH Zurich, of the bubble regime that began developing in Chinese stock markets in mid-2014 and started to burst in June 2015. Finally, Albert Shiryaev demonstrated how a well developed theory of change detection can be used in the bubbles identification [16].

Not only market misconceptions can turn market data into the trap. Markets can be rigged (as in the case of the Libor and foreign exchange scandals) or impacted unintentionally. There is a well known stock pinning[2] effect resulting from the market makers hedging activities. Recent market disruptions (they will be discussed later in the "Rise of the Models" section) such as Flash Crash and US Treasury intra-day crash are vivid examples of the operation risk caused by the high frequency algorithmic trading (HFAT). Interestingly, HFAT strategies can be viewed as models themselves. Hence, in case of HFAT, these models are built to take advantage of other models' limitations. As in case of the stock pinning effect, Marco Avellaneda and Michael Lipkin built a model [17] that is taking advantage of the option model limitations.

Chartis, in collaboration with IBM, performed an extensive research covering model risk management [18]. It has been noted that the top three sources of model risk include - poor quality data, insufficient data, and inadequate monitoring of model performance and usage. As in case of CDO modeling, market participants did not have sufficient data to accurately model correlations and used CDO pricing models in an uncontrolled manner.

In the next section we will describe the aforementioned model risk events in greater details.

2.2 Rise of the Models

2.2.1 The Copula That Killed Wall Street

As stated earlier, introduction of the CDO product caused some major issues in the financial markets. A CDO can be viewed as a pool of bonds or CDS (for synthetic CDO) broken down into tranches by seniority. Let's denote a number of bond/CDS issuers by N. An investor in a particular tranche receives cash flow $C_j = \sum_{i=1}^{N} C_j^i$ at time t_j. This cash flow is subject to the issuer's defaults. If τ_i is the default time for ith issuer, then $C_j = \sum_{i=1}^{N} C_j^i \chi_{\tau_i > t_j}$. The value of the tranche is the expectation of the future cash flows $\mathbb{E}\left[\sum_j e^{-rt_j} C_j\right]$. In order to price CDO tranche, one needs to model full joint risk neutral distribution for defaults

[2]It has been noted in Marco Avellaneda and Michael Lipkin's paper [17] that only minutes before options expire, many stock prices are near or at option strike prices. For some stocks, the subsequent evolution of the price until expiration is remarkably different from a random walk.

(let's denote it by $G(\tau_1, \ldots, \tau_N)$). The defaults corresponding to these tranches are correlated.

Correlated normally distributed random variables follow multivariate normal distribution. It is not clear how one can model correlation when dealing with other distributions. However, one can substitute non-normally distributed variables with normally distributed ones. For any random variable $V \sim F_V(x)$, one can map it to $F_V(V) \sim U(0,1)$ or $\Phi^{-1}(F_V(V)) \sim N(0,1)$. By using this mapping, one can map G-distributed random variables $\tau_1, \ldots, \tau_N$ to normally distributed ones $X_1, \ldots, X_N$ (where $X_i = \Phi^{-1}(F_{\tau_i}(\tau_i))$). David X. Li published a paper back in 2000 [19] demonstrating how to use Gaussian copula for CDO pricing. This approach became a market convention for the CDO pricing. When $N = 2$, we get bivariate normal copula with correlation parameter γ.

$$F_{\tau_1,\tau_2}(x, y) = \Phi_2(\Phi^{-1}[F_{\tau_1}(x)], \Phi^{-1}[F_{\tau_2}(y)], \gamma)$$

Gaussian copula is just one copula out of many. Following John Hull's paper on copulas [20], one can also use Student-t copula. The tail correlation in a bivariate t distribution is higher than in a bivariate normal distribution. So, the use of Gaussian copula has important implications for the model performance in the stressed environment. Also, when using Gaussian copula approach the correlation coefficient is assumed to be constant which is a critical assumption since correlations tend to change in stressful conditions. These model limitations have led to the misrepresentation of the correlation risk. When market practitioners started experiencing highly correlated defaults during the stressed period of 2008 that have not been predicted by the pricing model, the market crashed.

2.2.2 Stranded London Whale

JPMorgan Chase lost $2 billion on May 10, 2012 in trading. Jamie Dimon testified before the House Financial Services Committee in Washington on June 19, 2012. He explained that in December 2011, as part of a firmwide effort in anticipation of new Basel capital requirements, the bank instructed CIO (Chief Investment Office) to reduce risk-weighted assets and associated risk. To achieve this in the synthetic credit portfolio, the CIO could have simply reduced its existing positions; instead, starting in mid-January, it embarked on a complex strategy that entailed adding positions that it believed would offset the existing ones.

In Figure 1, one can see a snapshot of the JPMorgan's VaR report for the end of the first quarter of 2012. The highlighted row shows the VaR ($129 million) corresponding to the CIO portfolio. Consequently, JPMorgan reported a -$2,078 million P&L for the same portfolio in the second quarter of 2012. This is a vivid demonstration of the VaR model failure. The actual P&L turned out to be 16 times as large as the VaR.

So, what went wrong? Trader Bruno Iksil, nicknamed the London Whale, accumulated outsized CDS positions in the market. JPMorgan's CIO sold substantial amounts of IG (Investment Grade) CDX index exposure in the first quarter of the year. It also bought HY (High Yield) CDX protection, with total notional trade sizes running to tens of billions of dollars. In the economic downturn scenario, HY companies' spreads will widen more than those of IG companies'. A substantial divergence between IG and HY indices (Figure 2) occurred in 2012. The two indices moved in tandem in the past. The historical relationship between the indices has been broken.

Following JPMorgan's investigation report [21], "through January 2012, the VaR for the Synthetic Credit Portfolio was calculated using a "linear sensitivity model" also known within the

JPMORGAN CHASE & CO.

MARKET RISK-RELATED INFORMATION

(in millions)

		1Q12
95% CONFIDENCE LEVEL- AVERAGE IB TRADING VAR, CREDIT PORTFOLIO VAR AND OTHER VAR		
IB VaR by risk type:		
Fixed income	$	60
Foreign exchange		11
Equities		17
Commodities and other		21
Diversification benefit to IB trading VaR (a)		(46)
IB trading VaR (b)		63
Credit portfolio VaR (c)		32
Diversification benefit to IB trading and credit portfolio VaR (a)		(14)
Total IB trading and credit portfolio VaR		81
Other VaR:		
Mortgage Production and Servicing VaR (d)		11
Chief Investment Office VaR (e)(f)		129
Diversification benefit to other VaR (a)		(4)
Total other VaR		136
Diversification benefit to total IB and other VaR (a)		(47)
Total IB and other VaR (f)(g)	$	170

Figure 1: JPMorgan 1Q12 Report Extract
Source: 1Q12 Earnings Supplement

Firm as the "Basel I model," because it was used for purposes of Basel I capital calculations and for external reporting purposes. The Basel I model captured the major risk facing the Synthetic Credit Portfolio at the time, which was the potential for loss attributable to movements in credit spreads. However, *the model was limited in the manner in which it estimated correlation risk*: that is, the risk that defaults of the components within the index would correlate. As the tranche positions in the Synthetic Credit Portfolio increased, this limitation became more significant, as the value of the tranche positions was driven in large part by the extent to which the positions in the index were correlated to each other. The main risk with the tranche positions was that regardless of credit risk in general, defaults might be more or less correlated." Stress periods tend to deviate from historical correlations and typically at a time when they can have the most effect on models.

The important lesson to learn is that even in periods of relatively calm market, correlations between risk factors' movements can differ substantially from those seen in the past. This is so-called "correlation breakdown" effect. As in case of CDOs, the changes in the correlations were not captured by the VaR model.

2.2.3 Multi-Curve Valuation Puzzle

All financial instruments can be broken down into two major categories - over the counter (OTC) and exchanged traded. When two (or more) parties enter into a contract, the cash flows are subject to the default (or credit) risk. The exchanges developed an effective mechanism called margining to mitigate this risk. Clearing houses stand in the middle of each trade to guarantee financial performance of the contract. On the contrary, OTC instruments are

Figure 2: Historical CDX IG and HY Spreads
Source: Bloomberg

traded on a bilateral, principal-to-principal basis with your ultimate counterparty being the entity with whom you executed the trade. When entering into the OTC contract, one needs to account for the default risk.

In the OTC world, the International Swaps and Derivatives Association (ISDA) has developed a number of "master contracts" covering the range of OTC derivatives. ISDA master agreements also support bilateral netting arrangements that act to reduce counterparty exposures. Before the crisis, many financial institutions did not explicitly price default risk for OTC contracts. For the uncollateralized trades, banks used to charge a fee. And for the collateralized trades, many financial institutions assumed no default risk. With Lehman Brothers default on September 15th of 2008, it became apparent that this risk should be modeled explicitly even for the collateralized trades. The CVA (Credit Value Adjustment) became a buzzword.

The lack of transparency in the OTC markets was one of the main sources of the systemic risk. The Dodd-Frank Wall Street Reform and Consumer Protection Act of 2010 [22] has mandated central clearing for standardized OTC derivatives. Many classes of OTC derivatives are already being partially cleared through Central Counterparties (CCPs), e.g. LCH Clearnet for Interest Rate Swaps (IRSs), ICE Clear and CME for Credit Default Swaps (CDS), Fixed Income Clearing Corp (FICC) for Fixed-income OTC derivatives and many others. Central clearing exchanges have benefits and drawbacks as well since they concentrate risk in the CCPs.

The acknowledgement of the credit risk impacted pricing models in the interest rate area. Interest rate quotes for similar products started to diverge. Swap rates with the same maturity, but different payment frequency and Libor rate tenor (3-month Libor, 1-month Libor, etc.) exposed interest rates books to the basis risk. In terms of credit risk, a 2-year swap with quarterly 3-month Libor payments is riskier than a 2-year swap with monthly 1-month Libor payments. So, in order to price these two swaps one would need to build two different curves. When dealing with default-free counterparties, the no-arbitrage argument implies that these two swaps should be priced using a single curve. Modelers used to rely on the single curve pricing approach before the blow up in this basis risk. The swap books have always been exposed to the basis risk. Due to the size of the basis risk (under 5 bps[3] before crisis), the modelers found it acceptable to rely on the single curve modeling approach. One can refer to the Marco Bianchetti's paper [23] for further details and references regarding double-curve pricing formulas for basic plain vanilla interest rate derivatives, FRAs, swaps, caps/floors and swaptions.

Another caveat in the interest rate pricing theory is related to the discounting assumptions. Prior to the crisis, modelers used Libor curve for rates projections and discounting. The Libor curve was treated as a risk-free interest rate curve. Following the crisis, practitioners started using overnight index swap (OIS) rates as a risk-free interest rate curve. In the new framework, two curves are needed to price one swap. The Libor curve is used to project future payment rates and then all those projected payments are then discounted back at the OIS rate resulting in a present valued price of the instrument.

2.2.4 Rigged Markets - Libor and FX

As people started questioning models that failed during the crisis, more attention was brought to the quality and reliability of the market inputs. The market regulators discovered that Libor market was rigged. Libor rate is determined based on the largest banks' submissions of their borrowing rates. These submissions are just estimates, not the actual rates. The process has been administered by the British Banker's Association (BBA). In order to ensure the accuracy, BBA used the data collected from a number of banks and excluded the highest and lowest 25% of submissions. The rate was determined by a panel of 11 to 18 banks. As one can imagine, ability to artificially increase or decrease Libor rate by submitting faulty estimates could allow banks to take advantage of the Libor under/overestimation. This weakness in the system has been exploited by a number of traders from the largest banks. In the most famous case of Thomas Hayes from UBS, he was able to gain (for UBS) hundreds of millions over a three-year time period.

Another scandal is related to the Foreign Exchange (FX) market. Once again, there is a deficiency in the market quoting process. FX market is a 24-hour market, the 4 pm mark is used as an official quote for the day. In order to increase the 4 pm fix, traders submitted a rush of orders during the fix window (30 seconds before and after 4 pm). This allowed traders to enter the markets earlier knowing that their rush orders will drive prices higher at 4 pm. The Financial Conduct Authority (FCA) is the conduct regulator in the UK and it discovered cases when traders from different banks shared confidential information to coordinate a 4 pm fix distortion.

As of 2015, the banks paid $9 billion for rigging Libor. The administration of the Libor has been transferred to the ICE[4] Benchmark Administration (IBA). In order to restore the trust in markets, EU Commission kicked off a reform by implementing regulatory frameworks MAD/MAD II[5] and MAR[6] that address market manipulations. Furthermore, the Alternative

[3]BPS stands for basis point which is equal to the one hundredth of one percent.
[4]ICE stands for Intercontinental Exchange. It is a private exchange operator.
[5]MAD stands for Market Abuse Directive
[6]MAR stands for Market Abuse Regulation

Reference Rates Committee (ARRC) convened by the Federal Reserve has formed a new advisory group to assist it in developing input from a broad range of market participants as it finalizes its recommendations for an alternative reference rate and transition strategy. ARRC published interim report summarizing the results of its alternative rate searches. February 2017 was the first month in which the notional volume of US dollar overnight indexed swaps (OIS) in which the floating leg references the federal funds rate surpassed volumes of traditional Libor-referencing interest rate swaps [24].

Back in 2014, FCA fined five banks (Citibank N.A., HSBC Bank Plc, JPMorgan Chase Bank N.A., The Royal Bank of Scotland Plc, and UBS AG) $1.7 billion for FX failings and announced an industry-wide remediation program. The fix window has been widened to 5 minutes [25]. Over a five-minute fix period, actual trades executed and bid and offer order rates from the order matching systems are captured every second (from 2 minutes 30 seconds before to 2 minutes 30 seconds after the time of the fix). Trading occurs in milliseconds on the trading platforms and therefore not every trade or order is captured. However, it is much harder to manipulate the 4 pm fix with the new 5-minute fix window.

2.2.5 $7.2 Billion Equity Bet

In January 2008, the bank Société Générale lost approximately 4.9 billion Euro closing out positions over three days of trading beginning January 21, 2008, a period in which the market was experiencing a large drop in equity indices. The bank stated that these positions were fraudulent transactions created by Jérôme Kerviel, a trader with the company. The police stated they lacked evidence to charge him with fraud and charged him with breach of trust and illegally accessing computers. Kerviel stated that his actions were known to his superiors and that the losses were caused by panic selling by the bank.

Kerviel created fictitious positions to offset the risk posed by the real trades. The counterparties for the fictitious trades were entered so that the IT process could not classify them. This delayed settlement and and allowed Kerviel to cancel them before they were verified or identified by the middle office and back office personnel. This technique allowed him to hide the risk from the market risk management. In order to hide P&L, Kerviel created two offsetting fictitious trades with different purchase and sale prices. The scale of his trades was growing gradually, presumably, from November of 2004 through January of 2008. This is a very good example of how operational risk can sometimes be overlooked but it is very important.

2.2.6 Market Microstructure Risk

Imagine our life without a microscope. People lived without microscopes for a long time. The microscope invention goes back to the end of the XVIth century. Microscopes allow doctors to detect blood cells abnormalities, bacteria, and viruses. These creatures can't be detected with a naked eye, but have a huge impact on our lives. In the financial world, time can be compressed. A huge number of events can go unnoticed due to the high speed at which these events occur. Market microstructure is the field of study that explores trading mechanisms for financial securities. Some of these mechanisms can be only seen under a microscope. This point underscores the importance of taking the time to fully analyze the underlying details of the markets and its nuances. Quite often the small details get overlooked and can result in heightened risk.

2.2.7 38 Miles of Wire

The increase in the trading speeds created arbitrage opportunities for the high frequency trading (HFT) firms. HFT firms started exploiting different venues with different price updating speeds (PUS) by observing price movements on the exchanges with higher PUS and executing trades on the exchanges with lower PUS. A number of non-HFT participants in the lower PUS exchanges were loosing their money to HFT firms. Latency arbitrage is a trading technique that exploits differences in the data transferring and execution speeds between different markets and traders.

Brad Katsuyama has brought this issue to the public's attention. He noticed some issues when he was executing trades at Royal Bank of Canada (RBC). He co-founded IEX Group, a dark pool with a speed bump. The speed bump slows down the processing of the new orders to allow IEX to update the prices. The slow down is achieved by adding an extra 38-mile long coiled fiber-optic cable. This extra cable allows IEX to decrease execution speed by 0.35 ms[7].

2.2.8 Flash Crash of 2010

As discussed earlier, HFT algorithms are models themselves. These models can have a huge impact on the markets. Following U.S. Commodity Futures Trading Commission (CFTC) and U.S. Securities & Exchange Commission (SEC) reports [26], On May 6, 2010, the prices of many US-based equity products experienced an extraordinarily rapid decline and recovery. This is so-called flash crash. In the four-and-one-half minutes from 2:41 pm through 2:45:27 pm, prices of the E-Mini had fallen by more than 5% and prices of SPY suffered a decline of over 6%. At 2:45:28 pm, trading on the E-Mini was paused for five seconds when the Chicago Mercantile Exchange (CME) Stop Logic Functionality was triggered in order to prevent a cascade of further price declines. The sell algorithm continued to execute the sell program until about 2:51 pm as the prices were rapidly rising in both the E-Mini and SPY (SPDR S&P 500 ETF).

This event triggered implementation of the circuit breakers [27]. Trading in a stock would pause across US equity markets for a five-minute period in the event that the stock experiences a 10% change in price over the preceding five minutes. The pause, which would apply to stocks in the S&P 500 Index, would give the markets the opportunity to attract new trading interest in an affected stock, establish a reasonable market price, and resume trading in a fair and orderly fashion.

SEC also revised market-wide circuit breakers and implemented limit up-limit down (LULD) mechanism [28]. Market-wide circuit breakers provide for cross-market trading halts during a severe market decline as measured by a single-day decrease in the S&P 500 Index. A cross-market trading halt can be triggered at three circuit breaker thresholds - 7% (Level 1), 13% (Level 2), and 20% (Level 3). These triggers are set by the markets at point levels that are calculated daily based on the prior day's closing price of the S&P 500 Index. Limit up-limit down mechanism addresses market volatility by preventing trades in listed equity securities when triggered by large, sudden price moves in an individual stock.

[7] ms denotes a millisecond.

2.2.9 The Knight's $440 Million Nightmare

On August 1st in 2012 Knight Capital Group, a market-maker and trading firm, lost $440 million in 30 minutes (between 9:30 am and 10:30 am ET) due to the glitch in their program. The glitch resulted in 4 million extra trades in 550 million stocks. Knight's algorithms were generating a number of small losses at the very high speed by buying at the offer and selling at the bid. High frequency trading algorithms get deployed at the speed under 30 ms, where human's reaction time coupled with internet latency is 500 ms. As a result, these algorithms expose the users to severe risks. Additional automatic show stoppers such as stop loss limits are necessary.

2.2.10 Treasury Intra-Day Crash

On October 15th of 2014, the US Treasury market experienced a 12-minute (between 9:33 and 9:45 a.m. ET) 37 basis points swing. There were no significant news that could have caused such a swing. U.S. Department of the Treasury along with other agencies delivered a report [29] concerning this event. In this report they noted that during the event window, there was an imbalance between the volumes of buyer-initiated trades and seller-initiated trades - with more buyers in the 1st half of the event window (driving yields lower) and more sellers in the 2nd half (driving yields back). It is important to note that the Treasury market has experienced a large growth in high-speed electronic trading. The bank-dealers now account for less than a half of trading activity. In addition to the buyer-seller imbalance observed during the window event, the market depth[8] reduced significantly. A combination of these two events played an important role in the Treasury market flash crash on October 15th of 2014.

Following the crash, the Treasury Market Practices Group (TMPG) released a consultative paper [30] that contains best practices recommendations calling for the vigilant management of the sizable positions, detection and prevention of potentially disruptive trading activities and change controls for introducing new trading technologies and algorithms.

2.2.11 August 24th Volatility Test

The new mechanisms described above have been put to the real test on August 24th of 2015. A sharp drop in the US stock prices occurred after a panic caused by the Chinese stock market crash and Chinese economy performance. The panic resulted in an increased selling of shares. Stocks and ETFs trading was paused more than 1278 times due to the LULD halts [31]-[32] (773 Limit Up halts and 505 Limit Down halts). These pauses occur for 5 minutes when a stock jumps up or drops by 5% or more. Because the S&P 500 Index did not decline by 7% (the first level trigger) on August 24, the market-wide circuit breakers were not triggered [31].

2.2.12 Currency Wars

Currency wars became a common theme since the beginning of the 2008 crisis. Countries devaluate their currencies in order to gain a trade advantage. Following the interest rate parity formula, a decrease in the domestic interest rate allows central banks to devaluate their currencies. Rates not only hit near zero lows after the crisis, but went into the negative territory.

[8] The market depth is represented by the dollar amount of standing quotes in the central limit order books (CLOBs) on cash and futures trading platforms

There was a time when US treasury rates fell below 0 [33]. Currently, there are a number of central banks that moved their rates below 0 - Danmarks Nationalbank (DN), the European Central Bank (ECB), Sveriges Riksbank, the Swiss National Bank (SNB), and the Bank of Japan (BoJ) [33]. One of the 2016 Comprehensive Capital Analysis and Review (CCAR) scenarios assumed negative yields for short-term US Treasury securities [34].

2.2.13 Bank of Japan Ratesquake

The BOJ sent a shock wave through the markets on January 29th of 2016 when it announced that it would apply a rate of -10 bp to part of the balances in current accounts. In the long run, negative rates lead to the capital flight and saving money withdrawals. Interestingly, BOJ move drove up sales of storage safes.

2.2.14 The Swiss Euro Peg Abolishment

In the old days, most currencies were pegged to the U.S. dollar. Later on, a number of central banks shifted towards floating currencies. The number of pegged currencies decreased. Tables 1 and 2 demonstrate exchange rate regimes at the end of the year 2002 and 2011. Percentages represent shares of economies in each region. "Peg" includes currency board arrangements, other conventional fixed peg arrangements, pegged exchange rates within horizontal bands and conventional pegs. "Crawling peg" includes exchange rates within crawling bands, crawling pegs and crawl-like arrangements. "Managed" comprises managed floating with no pre-announced/predetermined path for the exchange rate and other managed arrangements. "Floating" includes both independently/free-floating and floating exchange rates.

Table 1: Exchange Rate Regimes (2002)

	Asia	**Latin America**	**EM Europe**	**Other**
Peg	33%	0%	20%	50%
Crawling peg	0%	0%	0%	25%
Managed	44%	14%	40%	0%
Floating	22%	86%	40%	25%

Source: Market Volatility and FX Intervention Analysis [35]

Table 2: Exchange Rate Regimes (2011)

	Asia	**Latin America**	**EM Europe**	**Other**
Peg	11%	14%	0%	50%
Crawling peg	11%	14%	0%	0%
Managed	22%	0%	20%	0%
Floating	56%	71%	80%	50%

Source: Market Volatility and FX Intervention Analysis [35]

As the Eurozone has been going deeper into recession, the European Central Bank (ECB) started implementing its quantitative easing (QE) program, to help bolster the economic growth. This move made the maintenance of the Swiss franc exchange rate peg impractical and expensive. It is worth noting that Swiss National Bank had accumulated about $480 billion worth of foreign currency in order to maintain the peg. On January 15th of 2015, the SNB announced that it would no longer hold the Swiss franc at a fixed exchange rate with the

Figure 3: CHF Currency Movements (01/15/2015)
Source: Bloomberg

euro. This triggered a panic in the markets. Figure 3 demonstrates CHF currency exchange rate movements on 01/15/2015.

2.2.15 Politicization of the Markets

Interest rate markets turned turbulent following the US presidential election of 2016. Treasury yields have increased by 75 bps following the win of Donald Trump of the presidency of the United States. Banking stocks rallied 30% in response to the election. On February 14th of 2017, Bloomberg News reported that Goldman Sachs climbed to a record high on optimism President Donald Trump's administration will spur trading and dealmaking, slash corporate taxes and roll back costly regulations after installing the firm's executives in top government posts. It still remains to be seen how much regulatory change can be pushed through very contentious political waters.

2.3 Regulatory Framework

In this paper we focus on the market risk modeling practices for the US banks that are subject to the market risk rule (i.e., gross trading assets and liabilities equal to \$1 billion or more, or gross trading assets and liabilities equal to 10 percent or more of total consolidated assets). The Federal Reserve's market risk rule establishes regulatory capital requirements for bank holding companies and state member banks. In the US, there are three main government agencies that oversee banking activities - Board of Governors of the Federal Reserve System

(FRB), the Federal Deposit Insurance Corporation (FDIC) and the Office of the Comptroller of the Currency (OCC). The USA is broken down into 12 Federal Reserve Districts [36] that provide oversight to the local banks. The main focus of our discussion will be modeling practices at the banks that are subject to the Market Risk Rule. The rules keep changing and it is the best practice to review the most current regulatory guidance regarding market risk modeling on the FRB page [37].

2.3.1 Model Validation Guidance

On April 4th of 2011, the Federal Reserve and OCC issued letters to the officers in charge of supervisions [38]-[39] accompanied by the Guidance on Model Risk Management [9]. It is worth noting that there was another model risk guidance issued prior to the famous SR 11-7, namely, OCC 2000-16 [40]. This guidance was issued to help financial institutions mitigate potential risks arising from reliance on computer-based financial models that are improperly validated or tested. In the pre-SR 11-7 era, banks' audit teams were obliged to scope in model validation for the audit exams. These teams focused on the validation activities around critical models only. SR 11-7 took model validation framework to a whole new level. Following the release of the SR 11-7 guidance, the banks started building their model validation teams. To this day, FDIC has not issued a model governance policy. Back in 2005, FDIC published supervisory insights regarding model governance, however.

SR 11-7 guidance is principle based. In other words, it is not prescribing the rules. This makes implementation of the guidance extremely difficult since they are open to interpretation. The banks have been developing model validation framework for 5 years, but there are still no banks that are compliant with SR 11-7.

2.3.2 Market Risk Rule

As the first international capital framework for banks was developed by the Basel Committee on Banking Supervision(BCBS) and endorsed by the G-10 central bank governors in 1988, the OCC, the Fed Reserve Board, and the FDIC implemented the 1988 capital accord in 1989 through the general risk-based capital rules. However, it was not until 1996 that capital charge over market risk exposure was first added to the 1988 Capital Accord through the Market Risk Amendment. The agencies implemented the market risk amendment by releasing the Market Risk Capital Rule[9] with an effective date of January 1st 1997.

In June 2004, BCBS issued the document entitled-International Convergence of Capital Measurement and Capital Standards:A Revised Framework, namely Basel II. Basel II retained much of the Market Risk Amendment but also announced that it would develop improvements to the market risk framework, especially with respect to the treatment of specific risk. BCBS made certain revisions in 2005 and began to work on significant changes to the market risk framework in 2007 to address the issues highlighted by the financial crisis.

All the significant changes were reflected in the 2009 revisions. At high level, the 2009 revisions call for additional prudential requirement on bank's internal models for measuring market risk and require enhanced qualitative and quantitative disclosures. Incremental risk capital and stressed Value-at-Risk(VaR) were introduced. The 2009 revisions also include changes to specific risk-weighting factors for rated and unrated securitization positions. In June 2010, the

[9]The agencies' market risk capital rules are at 12 CFR part 3, appendix B (OCC); 12 CFR parts 208 and 225, appendix E (Board); and 12 CFR part 325, appendix C (FDIC)

BCBS published additional revisions to the market risk framework including a floor on the risk-based capital requirement for modeled correlation trading positions.

To incorporate the 2005, 2009, and 2010 revisions, in January 2011, the agencies sought public comments on the proposed revisions to the agencies' market risk capital rule. The key objectives of the proposal were:

- To enhance the rule's sensitivity to risks not adequately captured
- To enhance modeling requirements that are consistent with advances in risk management
- To modify the definition of "covered position" to better capture positions for which treatment under the rule is appropriate
- To address shortcomings in the modeling of certain risks
- To address procyclicality
- To increase transparency through enhanced disclosures

Final Market Risk Rule was published in August 2012 and effective January 1,2013. The rule supplements both the agencies' general risk-based capital rules and the advanced capital adequacy guidelines by requiring any bank subject to the market risk capital rule to adjust its risk-based capital ratios to reflect market risk in its trading activities. It should be noted that the final rule does not include all of the methodologies adopted by the Basel Committee on Banking Supervision for calculating the standardized specific risk capital requirements for debt and securitization positions due to their reliance on credit ratings, which is impermissible under the Dodd-Frank Wall Street Reform and Consumer Protection Act (2010).

Final Market Risk Rule has the following requirements for market risk management:

- *Requirements for the Identification of trading positions and management of covered positions*
  The final rule requires a bank to have clearly defined policies and procedures for determining which of its trading assets and trading liabilities are trading positions as well as which of its trading positions are correlation trading positions. In determining the scope of trading positions, the bank must consider (1) the extent to which a position (or a hedge of its material risks) can be marked to market daily by reference to a two-way market; and (2) possible impairments to the liquidity of a position or its hedge.

- *General Requirement for Internal Models*
  The final rule requires a bank review its internal models periodically, but no less frequently than annually, in light of developments in financial markets and modeling technologies, and to enhance those models as appropriate to ensure that they continue to

meet the agencies' standards for model approval and employ risk measurement methodologies that are, in the bank's judgment, most appropriate for the bank's covered positions.

The final rule requires a bank to have a risk control unit that is independent of its business trading units and provides specific model validation standards similar to those in the advanced approaches rules. Also, the bank is required to have a rigorous process for assessing the overall capital adequacy in relationship to market risk. All material aspects of its internal models should be documented to facilitate the supervisory review and any internal audit or other review procedures.

- *Capital Requirement for Market Risk Determination of the Multiplication Factor*
  The final rule requires a bank to calculate its risk-based capital ratio denominator as the sum of its adjusted risk-weighted assets and market risk equivalent assets. However, the agencies are making changes to this calculation in the final rule for banks subject to the advanced approaches rules. Also, the final rule requires a bank, each quarter, to compare each of its most recent 250 business days of trading losses(excluding fees, commissions, reserves, net interest income, and intraday trading) with corresponding daily VaR-based measure calibrated to a one-day holding period and at a one-tail, 99.0 percent confidence level.

- *VaR-based Capital Requirement*
  The final rule does not change the existing quantitative requirements for the daily VaR-based measure. These include a one-tail, 99.0 percent confidence level, a ten-business-day holding period, and a historical observation period of at least one year. To calculate VaR-based measures using a 10-day holding period, the bank may calculate 10-business-day measures directly or may convert VaR-based measures using holding periods other than 10 business days to the equivalent of a 10-business-day holding period.

- *Stressed VaR-based Capital Requirement*
  The rule requires a bank to use the same model(s) used to calculate its VaR-based measure but with model inputs calibrated to reflect historical data from a continuous 12-month period that reflects a period of significant financial stress appropriate to the bank's current portfolio. The stressed VaR-based measure must be calculated at least weekly and be no less than the bank's VaR-based measure. The agencies generally expect that a bank's stressed VaR-based measure will be substantially greater than its VaR-based measure.

- *Modeling Standards for Specific Risk*
  The final rule allows a bank to use one or more internal models to measure the specific risk of a portfolio of debt or equity positions with specific risk. The internal models for specific risk are required to explain the historical price variation in the portfolio, be responsive to changes in market conditions, be robust to an adverse environment, and capture all material aspects of specific risk for debt and equity positions.

- *Incremental Risk Capital Requirement*
  The final rule requires that a bank that measures the specific risk of a portfolio of debt

positions using internal models must calculate an incremental risk measure for that portfolio using an internal model. Incremental risk consists of the default risk and credit migration risk of a position.The model must measure incremental risk over a one-year time horizon and at a one-tail, 99.9 percent confidence level, under the assumption of either a constant level of risk or of constant positions.

- *Comprehensive Risk Capital Requirement*
  The final rule requires a bank to have sufficient market data to ensure that it fully captures the material price risks of the correlation trading positions in its comprehensive risk measure.The final rule requires a bank's comprehensive risk model to capture all material price risk, including, but not limited to (1) The risk associated with the contractual structure of cash flows of the position, its issuer, and its underlying exposures ((2) credit spread risk, including nonlinear price risks; (3) volatility of implied correlations, including nonlinear price risks such as the cross-effect between spreads and correlations; (4) basis risks (for example, the basis between the spread of an index and the spread on its constituents and the basis between implied correlation of an index tranche and that of a bespoke tranche); (5) recovery rate volatility as it relates to the propensity for recovery rates to affect tranche prices; and (6) to the extent the comprehensive risk measure incorporates benefits from dynamic hedging, the static nature of the hedge over the liquidity horizon.

- *Disclosures Requirement*
  The final rule adopts disclosure requirements designed to increase transparency and improve market discipline on the top-tier consolidated legal entity that is subject to the market risk capital rule. The disclosure requirements include a breakdown of certain components of a bank's market risk capital requirement, information on a bank's modeling approaches, and qualitative and quantitative disclosures relating to a bank's securitization activities.

After the Final Market Risk Rule was effective, on Dec 6th 2013, Federal Reserve Board made technical changes to the market risk capital rule to align it with the Basel III revised capital framework.

2.3.3 Volcker Rule

Volcker Rule was named after Paul Volcker, a former U.S. Federal Reserve Chairman, who argued that proprietary trading by large financial institutions was a major contributing factor to the financial collapse in 2007-2008. Proprietary trading occurs when a trader trades stocks, bonds, currencies, commodities, their derivatives, or other financial instruments with the firm's own money, as opposed to depositors' money, so as to make a profit for itself. Congress included the Volcker Rule as part of the Dodd-Frank Act, which amended Section 13 of the Bank Holding Company Act of 1956. At the broadest level,the legislation prohibits banking entities from:

- engaging in short-term proprietary trading of securities, derivatives, commodity futures and options on these instruments for their own account

- owning, sponsoring or having certain relationships with hedge funds or private equity funds, referred to as "covered funds"

Final Volcker Rule requires 7 risk metrics for the trading desks:

- Risk and Position Limits and Usage
- Risk Factor Sensitivities
- Value-at-Risk and Stress Value-at-Risk
- Comprehensive Profit and Loss Attribution
- Inventory Turnover
- Inventory Aging
- Customer Facing Trade Ratio

The first three metrics(limit and usage, sensitivities, and VaR and SVaR) are intended to characterize the overall risk profile of trading activities and determine if this activity is permissible. The Comprehensive P&L attribution is to better understand the extent, scope, and type of profits and losses generated by the trading activities. While the last three metrics are aimed at characterizing trading activities and distinguishing customer transaction volumes as a fraction of overall business.

The reporting dates are based on a bank's gross sum of trading assets and liabilities over the previous year:

- Greater than $50 billion by June 30, 2014
- Between $25 billion and $50 billion by April 30, 2016
- Between $10 billion and $25 billion by December 31, 2016

The record-keeping requirements of Volcker require firms to maintain reported data and date used for metrics calculation for a period of five years.

2.3.4 CCAR

The Board's capital planning and stress testing regime consists of two related programs: The Comprehensive Capital Analysis and Review (CCAR), which is conducted pursuant to the Board's capital plan rule (12 CFR 225.8), and Dodd-Frank Act stress testing, which is conducted pursuant to the Board's stress test rules (subparts B, E, and F of Regulation YY).

In CCAR, the Board assesses the internal capital planning processes of large bank holding companies and their ability to maintain sufficient capital to continue their operations under expected and stressful conditions. Large bank holding companies must submit annual capital plans to the Board, which the Board may object to on either quantitative or qualitative grounds. In 2017, the FRB removed large and noncomplex firms (total consolidated assets between \$50 billion and \$250 billion) from the qualitative assessment. If the Board objects to a large bank holding company's capital plan, the large bank holding company may not make any capital distributions unless the Board indicates in writing that it does not object to such distributions.

Dodd-Frank Act stress testing is a forward-looking quantitative evaluation of the impact of stressful economic and financial market conditions on the capital adequacy of banking organizations. As part of Dodd-Frank Act stress testing, the Board conducts supervisory stress tests of large bank holding companies, and these bank holding companies also must conduct annual and mid-cycle company-run stress tests. In addition, bank holding companies with total consolidated assets of more than \$10 billion but less than \$50 billion, savings and loan holding companies with total consolidated assets of more than \$10 billion, and state member banks with total consolidated assets of more than \$10 billion must conduct annual company-run stress tests.

Supervisory Guidance on Stress Testing for Banking Organizations with more than \$10 Billion in Total Consolidated Assets, May 14, 2012 (SR 12-7).Supervisory Guidance on Dodd-Frank Act Company-Run Stress Testing for Banking Organizations with Total Consolidated Assets of More Than \$10 Billion but Less Than \$50 Billion, March 13, 2014 (SR 14-3).

The Model Validation Council was established in 2012 by the Board of Governors to provide expert and independent advice on its process to rigorously assess the models used in stress tests of banking institutions. The Dodd-Frank Wall Street Reform and Consumer Protection Act required the Federal Reserve to conduct annual stress tests of large bank holding companies and systemically important, nonbank financial institutions supervised by the Board. The Model Validation Council will provide input on the Board's efforts to assess the effectiveness of the models used in the stress tests. The council is intended to improve the quality of the Federal Reserve's model assessment program and to strengthen the confidence in the integrity and independence of the program.

Office of Inspector General conducted an evaluation of the Board's supervisory stress test model risk management practices. The objective was to assess the extent to which model risk management practices are consistent with supervisory guidance on model risk management previously issued by the Board. The report can be found here.

2.3.5 Fundamental Review of the Trading Book (FRTB)

The Basel Committee on Banking Supervision(BCBS) issued the final version of the Fundamental Review of Trading Book(FRTB) in January 2016 [41]. FRTB aims to contribute to a more resilient banking sector by strengthening the capital standards for market risks. The final standards require that national supervisory rule-making by January 2019 and banks to report under new standards by December 31st 2019.

The framework is built around two main measurements: a new standardized approach (SA) built around a sensitivity based calculation and an internal models approach (IMA) based on a liquidity adjusted expected shortfall calculation.

The highlights of new standards include:

- Revised internal models approach. The tail risk and market illiquidity risk will be better captured. The model approval process and model validation process will be more complex.

- Revised standardized approach. The new standardized approach is more risk-sensitive, and it will become mandatory even if the institution opts for IMA. SA result will serve as a fall-back and floor to the IMA.
- Shift from Value at Risk(VaR) to Expected Shortfall(ES). VaR and Stressed VaR measures will be replaced by the ES measure calibrated to a stress period.
- Incorporation of the risk of market illiquidity. Static 10 day horizon in Market Risk Rule will be replaced by varying liquidity horizons.
- A revised boundary between trading book and banking book. The regulatory arbitrage will be restricted.

Several model risk management related initiatives are discussed below:

2.3.6 Modellable vs. Non-modellable

Data integrity will now be a critical component in determining whether the risk factors are modellable or not by a bank. According to the final standards, there must be continuously available "real" prices for a sufficient set of representative transactions. A price will be considered "real", if:

- It is a price at which the institution has conducted a transaction
- It is a verifiable price for an actual transaction between other arms-length parties[10]
- The price is obtained from a committed quote

To be considered to have continuously available "real" prices, a risk factor must have at least 24 observable "real" prices per year (measured over the period used to calibrate the current expected shortfall model) with a maximum period of one month between two consecutive observations.

The criteria must be assessed on a monthly basis, and the above test must be applied to all risk factors. It's obvious that for many of the high volume trades(such as ED futures, swap rates, treasury), passing the test is easy. However, for the OTC market, many risk factors will not pass the test easily due to the lack of market depth(e.g. volatility, CDS spreads) .

For risk factors that do not meet the modellable criteria are by definition non-modellable and each risk factor has to be capitalized using a stress scenario calibrated to be at least as prudent as ES at 97.5% calibrated over an extreme stress period. Also, no correlation or diversification effect for non-modellable risk factors is permitted.

It should be noted that a bank needs to pass the real prices tests continuously to avoid the higher capital charge associated with non-modellable risk factors. There are other two important tests for the IMA to avoid the fall back to the standard approach(SA).

[10] An arm's length transaction is a transaction in which the buyers and sellers of a product act independently and have no relationship to each other

2.3.7 Model Approval Process

For the internal models approach, BCBS initial consultative paper proposed a model approval process consists of the following three tests:

- P&L attribution
- Back-testing
- Model-independent assessment tool

Under the final FRTB standards, the third requirement(model-independent assessment tool) was dropped as Basel committee did not want to go as far as imposing additional systems for the banks. Let's take a closer look at the two remaining tests: P&L attribution and back-testing:

P&L attribution tests: according to the standards "The risk factors for that portfolio that are included in the desk's risk management model must be used to calculate a 'risk-theoretical' P&L. This 'risk-theoretical' P&L is the P&L that would be produced by the bank's pricing models for the desk if they only included the risk factors used in the risk management model."

P&L attribution tests will reveal how well the risk factors included in the desk's risk management model capture the material drivers of the bank's P&L derived from the bank's pricing models.

The P&L attribution requirements are based on two metrics:

- The mean of the difference between the risk-theoretical and hypothetical P&L divided by the standard deviation of the hypothetical P&L; (-10% to 10%)
- The variance of the unexplained P&L divided by the variance of the hypothetical P&L (less than 20%)

The P&L attribution test will encourage the integration of front office system with the risk management system. And the P&L attribution test will serve as the primary validation test for IMA models.

Back testings: according to the standards "The Committee requires banks to develop the capability to perform these tests using both hypothetical and actual trading outcomes. In combination, the two approaches are likely to provide a strong understanding of the relation between calculated risk measures and trading outcomes. "

Per current Market Risk Rule, whereas capital calculation and back testing are both driven by Value-at-Risk measure, there is clear statistic interpretation. However, for the ES measure, there is no clear academic or supervisory guidance on how expected shortfall can be practiced in a statistically meaningful way.

The industry is prepared for a separation of capital measure and model performance measure, as capital is determined through ES measure calibrated to stress period but model performance is evaluated through VaR measure. The separation is not desirable, but it's superior to the pure VaR measure (capital and backtest using VaR) in the sense that the ES can produce more conservative capital level and to the pure ES measure(capital and backtest using ES) in the sense that backtest VaR is more theoretically sound.

2.3.8 IMA and SA

Per the final standards, under the standardized approach, banks must calculate the standardized capital charge for each trading desk as if it were a standalone regulatory portfolio. So the SA approach will be mandatory for all trading desks irrespective of IMA eligibility.

SA calculation must be performed at least monthly and will:

- Serve as an indication of the fallback capital charge for those desks that fail the eligibility criteria for inclusion in the banks internal model
- Generate information on the capital outcomes of the internal models relative to a consistent benchmark and facilitate comparison in implementation between banks and/or across jurisdictions
- Monitor over time the relative calibration of standardized and modelled approaches, facilitating adjustments as needed
- Provide macroprudential insight in an ex ante consistent format

The standard approach has three components:a sensitivities-based risk charge; the default risk charge(DRC); and the residual risk ad-on(RRAO). The sensitivities-based risk charge is the more prescriptive as the standards have specific guidance on how to decompose the portfolio into risk bucket, and calculate the three risk sensitivities: delta, vega, and curvature.

The implication for the standard approach is that even though the approach is sensitivities driven, there is still a need for valuation models which can produce satisfactory sensitivity measures. The valuation models themselves need to be validated. Thus, adopting the SA approach does not mean the model validation is no longer needed.

2.3.9 Validation Requirements for Internal Models Approach

The final standards have a standalone section for the model validation standards for the IMA. A summary of the requirements is:

Why: To ensure that they are conceptually sound and adequately capture all material risks

Who: Suitably qualified parties independent of the development process

When: When the model is initially developed and when any significant changes are made to the model, models must be periodically re-validated, particularly when there have been significant structural changes in the market or changes to the composition of the portfolio which might lead to the model no longer being adequate

What: Not limited to P&L attribution test and back testing. Model validation must not be limited to P&L attribution and backtesting, but must, at a minimum, also include the following:

- Tests to demonstrate that any assumptions made within the internal model are appropriate and do not underestimate risk. This may include the assumption of the normal distribution and any pricing models

- Further to the regulatory backtesting programmes, testing for model validation must use hypothetical changes in portfolio value that would occur were end-of-day positions to remain unchanged
- The use of hypothetical portfolios to ensure that the model is able to account for particular structural features that may arise

The new validation standards have also called for stronger data management. For example the bank could be required to use in validation and make available to the supervisor the following information for **each desk** for **each business day** over the **previous three years**, with no more than a 60-day lag:

- Two daily VaR's for the desk calibrated to a one-tail 99.0 and 97.5 percent confidence level , and a daily ES calibrated to 97.5
- The daily profit or loss for the desk
- The p-value of the profit or loss on each day for the desk

For the cases where the bank has to map these positions to proxies, then the bank must ensure that the proxies produce conservative results under relevant market scenarios.

3 Model Validation Clockwork

As discussed earlier, term *model* can be used in a number of ways. It can be used to describe a mathematical method (e.g., Monte Carlo simulation), a process (e.g., risk weighted assets calculation process), a calibration process (calculation of implied volatility based on the market quotes), etc. In this paper we will use a term model in the following way.

A model can be viewed as a triple $(\mathcal{F}, \mathcal{A}, \mathcal{U})$, where $\mathcal{F}$ is a set of mathematical functions, $\mathcal{A}$ is a set of both implicit and explicit assumptions, and $\mathcal{U}$ is a set of pre-defined uses of a model. Mathematical functions are mappings between a pre-defined set of terms and real numbers with a pre-defined set of parameters calibrated using the pre-defined criteria.

Let's consider the famous Black-Scholes model [43]. The model is used to calculate the value of a European option. A European option has the following terms - S is the spot price of the underlying asset, $T-t$ is the time to maturity, K is the strike price, r is the risk-free rate, σ is the volatility of returns of the underlying asset. The mapping between the terms and real numbers is defined by the Black-Scholes (BS) formula.

$$Value(S, T-t, K, r, \sigma) = \Phi(d_1)S - \Phi(d_2)Ke^{-r(T-t)},$$

where

$$d_1 = \frac{1}{\sigma\sqrt{T-t}}[\ln(S/K) + (r + \sigma^2/2)(T-t)]$$

and

$$d_2 = d_1 - \sigma\sqrt{T-t}$$

The assumptions have been identified by Black and Scholes in their seminal paper [43].

- The short-term interest rate is known and is constant through time.

- The stock price follows a random walk in continuous time with a variance rate proportional to the square of the stock price. Thus the distribution of possible stock prices at the end of any finite interval is log-normal. The variance rate of the return on the stock is constant.

- The stock pays no dividends or other distributions.

- The option is "European," that is, it can only be exercised at maturity.

- There are no transaction costs in buying or selling the stock or the option.

- It is possible to borrow any fraction of the price of a security to buy it or to hold it, at the short-term interest rate.

- There are no penalties to short selling. A seller who does not own a security will simply accept the price of the security from a buyer, and will agree to settle with the buyer on some future date by paying him an amount equal to the price of the security on that date.

These assumptions seem benign on first glance but some of them may not hold in the practice. Several of the items are assumed to be constant throughout the simulation process whereas, in fact, they are always changing.

In practice, when people use BS formula, the volatilities are calibrated to the market by solving BS equation with known value and unknown volatility. If the model is used to calculate the value of the option with terms identical to the instrument quoted in the market, the pricing error can only be caused by the deficiencies in the numerical procedure used to solve BS equation. If the terms of the option are different from the market quoted instruments, then one needs to use some sort of interpolation/extrapolation (along maturities and strikes) technique. It is only when one uses historical volatilities, the distributional assumption becomes important.

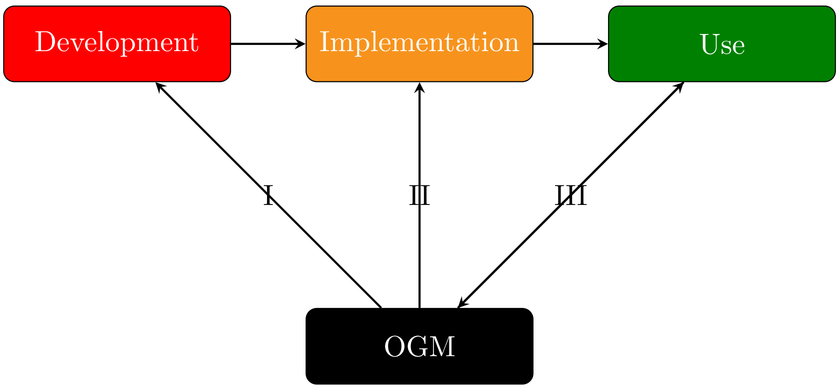
There are a number of procedures associated with the model validation process. Starting with the identification step in which one determines all components of a triple $(\mathcal{F}, \mathcal{A}, \mathcal{U})$ along with parameters set, calibration criteria and mathematical functions. This information constitutes model attributes. Model validation groups maintain these records in the model inventory.

It is important to implement procedures that keep this model inventory alive. The new models should be identified, the old models can be retired, changes in the models (mathematical functions, uses, assumptions, etc.) should be recorded. In order to identify new models, MV teams implement corporate policy that requires business units (BUs) to submit model candidates to the MoRM. It is common to include model risk questionnaire for the new business initiatives. This way one can assess whether these new initiatives will require internal and/or external model development. It is also best practice to have model owners review their model listing that is housed in the corporate model inventory on a periodic basis to attest that is their full listing of the models they use is included (quarterly, semi-annual, etc.).

As far as external models are concerned, it is critical to discuss model validation requirements and expectations with the vendors before the contract is signed. Model risk questionnaires can be integrated into the internal risk management process and/or vendor management process. In order to maintain independence, only MoRM can make determination whether the candidate qualifies to be a model or not. The retirement of the model is usually requested by the BU. Changes in the model attributes should be reported by the BU and MoRM. It is also important that all material changes be validated by MoRM before implementation to maintain alignment with SR 11-7.

Model validation team needs to establish ongoing monitoring framework and model performance metrics. These metrics can be both quantitative (assigning a score to each model) or qualitative (assigning a category). These metrics are early warning indicators that are measuring model risk. Model owners should be tasked with performing model monitoring and MoRM should provide oversight of the process.

The framework should capture modeling changes. Modeling changes can be broken down into the following three categories. Category I - pre-defined structural changes, undefined changes with significant impact on the model's output. These changes would need to validated prior to the implementation. Category II - pre-defined non-structural changes, undefined changes with small impact. These changes should be communicated to the MoRM, but do not necessarily require a full validation. Category III - no changes or pre-defined tuning/optimization. These changes are part of the normal business process (e.g., a daily re-calibration of the simulation models based on the new volatility information).



Models are used in the processes and as a result have dependencies. MoRM needs to evaluate aggregate model risk. From the processing perspective, it is important to identify upstream and downstream models. Furthermore, the same model can be used for different purposes (e.g., FICO model can serve an array of purposes withing a bank and can be used by the vendors). Different models can be used for the same purpose. A key to identifying and quantifying aggregate model risk is detailing model dependencies. If a problems were to occur in an upstream model, how likely are they to cascade into dependent (downstream) models and what might be the effects?

4 The Current State of Trading Activities

Trading book sizes vary significantly between different banks. There are banks that are relatively small in terms of assets, but have extremely large trading books. Commercial banks tend to have smaller trading books. OCC publishes quarterly reports showing trading volumes for the top 25 banks (available here). A snapshot of this report can be viewed in Table 3.

Table 3: Notional Amounts of Derivative Contracts (September 30, 2016) in Millions

RANK	BANK NAME	ASSETS	DERIVATIVES
1	JPMORGAN CHASE BANK	$2,118,497	$51,076,843
2	CITIBANK NATIONAL ASSN	$1,356,393	$48,140,013
3	GOLDMAN SACHS USA	$158,429	$38,053,388
4	BANK OF AMERICA NA	$1,659,793	$21,973,095
5	WELLS FARGO NA	$1,740,819	$7,363,786
6	HSBC NA	$203,705	$4,327,467
7	MORGAN STANLEY NA	$126,826	$1,571,981
8	STATE STREET BANK&TRUST CO	$251,545	$1,289,761
9	BANK OF NEW YORK MELLON	$299,651	$957,904
10	PNC BANK NATIONAL ASSN	$357,859	$351,043
11	SUNTRUST BANK	$200,201	$272,538
12	US BANK NATIONAL ASSN	$448,401	$269,493
13	NORTHERN TRUST CO	$119,702	$266,164
14	MUFG UNION BANK NA	$116,912	$178,192
15	TD BANK NATIONAL ASSN	$264,528	$176,011
16	CAPITAL ONE NATIONAL ASSN	$279,255	$88,747
17	REGIONS BANK	$124,196	$83,609
18	KEYBANK NATIONAL ASSN	$101,265	$77,400
19	CITIZENS BANK NATIONAL ASSN	$114,605	$74,208
20	FIFTH THIRD BANK	$140,771	$68,701
21	BRANCH BANKING&TRUST	$217,378	$58,801
22	BOKF NATIONAL ASSN	$32,669	$50,849
23	HUNTINGTON NATIONAL BANK	$100,416	$38,153
24	CAPITAL ONE BANK USA NA	$105,930	$36,871
25	COMPASS BANK	$84,983	$36,129
TOP 25		$10,724,731	$176,881,147
OTHER		$4,461,122	$579,691
TOTAL		$15,185,854	$177,460,838

A number of banks that were among top 25 in 2007 have defaulted - Lehman Brothers, Wachovia, National City, etc. Despite a significant drop in the derivative activities after the credit crunch of 2007, the current notional amount derivative contracts exceeds the pre-crisis level (Table 4). It looks like a big reason for the change has been consolidation. The top financial institutions have gotten larger but have reduced their derivative exposure while the smaller institutions have increased their derivative exposure.

BIS publishes semiannual and triennial surveys regarding derivative activities listed below. Following the decision to reform the over-the-counter (OTC) derivative market[11], CCP Central clearing now predominates the over-the-counter (OTC) interest rate derivatives markets. BIS reported that, as of end-June 2016, 75% of reporting dealers' outstanding OTC interest rate derivatives were cleared through CCPs, compared with 37% for credit derivatives and less than 2% for OTC foreign exchange and equity derivatives. Overall, 62% of the $544 trillion

[11] G-20 2009 Pittsburgh Agreement

Table 4: Notional Amounts of Derivative Contracts (March 31, 2007) in Millions

RANK	BANK NAME	ASSETS	DERIVATIVES
1	JPMORGAN CHASE BANK	$1,224,104	$70,817,340
2	CITIBANK NATIONAL ASSN	$1,076,949	$30,069,982
3	BANK OF AMERICA NA	$1,204,472	$28,535,873
4	HSBC BANK USA NATIONAL ASSN	$169,010	$5,649,176
5	WACHOVIA BANK NATIONAL ASSN	$518,753	$5,454,856
6	BANK OF NEW YORK	$83,608	$959,681
7	WELLS FARGO BANK NA	$396,847	$879,779
8	STATE STREET BANK&TRUST CO	$97,978	$588,222
9	PNC BANK NATIONAL ASSN	$90,405	$244,870
10	SUNTRUST BANK	$184,810	$204,169
11	MELLON BANK NATIONAL ASSN	$25,201	$133,299
12	NATIONAL CITY BANK	$131,742	$133,170
13	NORTHERN TRUST CO	$51,028	$112,021
14	KEYBANK NATIONAL ASSN	$89,408	$96,882
15	LASALLE BANK NATIONAL ASSN	$75,052	$76,639
16	US BANK NATIONAL ASSN	$219,825	$74,822
17	MERRILL LYNCH BANK USA	$61,366	$72,376
18	BRANCH BANKING&TRUST CO	$118,083	$43,711
19	REGIONS BANK	$133,224	$40,941
20	FIFTH THIRD BANK	$51,561	$35,407
21	FIRST TENNESSEE BANK NA	$38,523	$31,553
22	DEUTSCHE BANK TR CO AMERICAS	$37,533	$26,881
23	UNION BANK OF CALIFORNIA NA	$54,003	$24,213
24	CAPITAL ONE BANK	$28,691	$23,491
25	LEHMAN BROTHERS COML BK	$3,521	$23,489
TOP 25		$6,165,695	$144,352,843
OTHER		$2,527,836	$436,780
TOTAL		$8,693,531	$144,789,624

in notional amounts outstanding reported by dealers was centrally cleared.

- Triennial Central Bank Survey of foreign exchange and OTC derivatives markets in 2016

- Semiannual OTC derivatives statistics

- Exchange-traded derivatives statistics

References

[1] FRB (2016, May 17). *Supervisory Policy and Guidance Topics*. Available here

[2] Pablo Triana, *The Flawed Maths of Financial Models*, Financial Times, November 29, 2010.

[3] Steven Shreve, *Don't Blame the Quants*, Forbes Blog, October 7, 2008.

[4] Nassim N. Taleb, *Report on the Effectiveness and Possible Side Effects of the Office of Financial Research (OFR)*, Congressional Testimony, 2009.

[5] Nassim N. Taleb, *Errors, Robustness, and The Fourth Quadrant*, International Journal of Forecasting, Vol. 25, No. 4, 2009.

[6] Wilmott, P. and Derman, E. (2009, January 7). *Financial Modelers' Manifesto*. Available here

[7] National Community Reinvestment Coalition (2016). *A Brief Description of CRA*. Available here

[8] Lo, A.W., *Reading About the Financial Crisis: A 21-Book Review*, January 9, 2012.

[9] FRS, OCC, *Supervisory Guidance on Model Risk Management*, April 4, 2011.

[10] Derman, E., *Model risk*, Technical Report, Goldman Sachs, 1996.

[11] Rama Cont, *Model Uncertainty and its Impact on the Pricing of Derivative Instruments*, Mathematical Finance, Vol. 16, No. 3, July 2006, pp. 519-547.

[12] Dudley., W. C. (2010, April 7). *Asset Bubbles and the Implications for Central Bank Policy*. Available here

[13] Protter, P., *A Mathematical Theory of Financial Bubbles*, SSRN, November 3, 2012.

[14] Sornette, D., Woodard, R., *Financial Bubbles, Real Estate bubbles, Derivative Bubbles, and the Financial and Economic Crisis*, May 2, 2009.

[15] Sornette, D., Demos, G., Zhang, Q., Cauwels, P., Filimonov, V., Zhang, Q., *Real-time Prediction and Post-mortem Analysis of the Shanghai 2015 Stock Market Bubble and Crash*, Journal of Investment Strategies, 4(4), pp. 77-95, 2015.

[16] Shiryaev, A. N., Zhitlukhin, M. V., Ziemba, W. T., *Land and Stock Bubbles, Crashes and Exit Strategies in Japan Circa 1990 and in 2013*, October 28, 2013.

[17] Avellaneda, M., Lipkin, M. D., *A Market-induced Mechanism for Stock Pinning*, Quantitative Finance, Volume 3, pp. 417-425, 2003.

[18] Chartis, *Model Risk Management*, 2014.

[19] Li, D. X., *On Default Correlation: A Copula Function Approach*, Journal of Fixed Income, 9 (4), pp. 43-54, 2000.

[20] Hull, J., *Defining Copulas*, Risk Magazine, October 2006, pp. 62-64.

[21] JPMorgan Chase (January 16, 2013). *Report of JPMorgan Chase & Co. Management Task Force Regarding 2012 CIO Losses.* Available here

[22] The Senate and House of Representatives of the United States of America, *Dodd-Frank Wall Street Reform and Consumer Protection Act*, January 5, 2010.

[23] Bianchetti, M. (August 1, 2012) *Two Curves, One Price: Pricing & Hedging Interest Rate Derivatives, Decoupling Forwarding and Discounting Yield Curves.* Available here

[24] Risk, *Monthly Swap Data Review: Libor Dominance Challenged*, April 2017.

[25] WM/Reuters (2012). *Spot & Forward Rates Methodology Guide.* Available: here

[26] CFTC, SEC (September 30, 2010). *Findings Regarding the Market Events of May 6, 2010.* Available here

[27] SEC (June 10, 2010). *SEC Approves New Stock-by-Stock Circuit Breaker Rules.* Available here

[28] SEC (May 31, 2012). *Investor Bulletin: Measures to Address Market Volatility*. Availabe: https://www.sec.gov/investor/alerts/circuitbreakersbulletin.htm

[29] US Department of the Treasury, FRB, SEC, CFTC (July 13, 2015). *The US Treasury Market on October 15, 2014*. Available here

[30] TMPG (June 2015). *Automated Trading in Treasury Markets*. Available here

[31] SEC (December 2015). *Equity Market Volatility on August 24, 2015*. Available here

[32] BlackRock (October 2015). *US Equity Market Structure: Lessons from August 24*. Available here

[33] BIS (March 2016). *How Have Central Banks Implemented Negative Policy Rates?*. Available here

[34] FRB (January 28, 2016). *2016 Supervisory Scenarios for Annual Stress Tests Required under the Dodd-Frank Act Stress Testing Rules and the Capital Plan Rule*. Available here

[35] BIS, *Market Volatility and FX Intervention in EMEs - What has Changed*, October, 2013.

[36] FRB (December 13, 2005). *The Twelve Federal Reserve Districts*. Available here

[37] FRB (May 17, 2016). *Market Risk Management*. Available here

[38] FRB (April 4, 2011). *A Letter Regarding Guidance on Model Risk Management*. Available here

[39] OCC (April 4, 2011). *Sound Practices for Model Risk Management*. Available here

[40] OCC (May 30, 2000). *Bulletin OCC 2000-16, "Model Validation."* Available here

[41] Basel Committee on Banking Supervision (January 2016), *Minimum Capital Requirements for Market Risk*. Available here

[42] FDIC (December 5, 2005). *Supervisory Insights, "Model Governance"*. Available here

[43] Black, F. and Scholes M. B., *The Pricing of Options and Corporate Liabilities*, Journal of Political Economy, 81 (3), pp. 637-654. Available here