Sensitivity Analysis and Empirical Validation of a Black-Box Asset Model

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Résumé

Dans un contexte de marchés financiers de plus en plus complexes, les modèles d'actifs et la gestion du risque ont gagné de l'importance dans les institutions financières. Alors que la recherche existante a été surtout dédiée à la conception de modèles de risque d'actifs et au développement de méthodes statistiques adéquates pour mesurer le risque, moins d'études ont été consacrées au sujet de la validation d'un modèle d'actifs existant de type boîte noire, c'est-à-dire des modèles d'actifs dont l'utilisateur ne connaît pas tous les détails. PartnerRe est une entreprise de réassurance relativement petite qui utilise un modèle d'actifs d'un vendeur externe. Il est d'autant plus important pour PartnerRe de s'assurer d'une forte confiance dans la pertinence du modèle. Ce travail propose une démarche pragmatique pour la validation de bout en bout d'un modèle d'actifs de type boîte noire. L'approche proposée consiste en une validation interne et externe du modèle d'actifs : Dans la validation interne, la plausibilité et la robustesse des sorties du modèle sont vérifées par une analyse de sensibilité. Ceci se fait par une analyse de l'impact des paramètres en entrée du modèle d'actifs sur le risque de baisse prédit par le modèle. Dans la validation externe, la validité empirique du modèle d'actifs est étudiée en le comparant à des données historiques. La crise financière de 2008 est comparée aux valeurs extrêmes sortant du modèle afin d'évaluer la période de retour à laquelle la crise financière de 2008 correspond selon le modèle d'actifs. Il est également vérifié que la fréquence de changements adverses des taux de change générés par le modèle correspond aux données historiques de taux de change. Les connaissances acquises par la validation interne et externe sont utilisées afin d'affiner l'approche de modélisation d'actifs et pour palier à certains défauts du modèle, tels que des limitations sur la granularité des classes d'investissements ou sur le nombre de devises qui peuvent être modélisées.

Mots-clés : modèle d'actifs, validation, boîte noire, analyse de sensibilité, validation empirique

Abstract

In the context of increasingly complex financial markets, asset models and risk management have gained importance within financial institutions. While existing research has been mostly dedicated to the design of asset risk models and to the development of adequate statistical measures of risk, fewer studies have focused on the validation of a black-box asset model, i.e., an asset model for which not all details are known to the end user. PartnerRe is a relatively small reinsurance company which uses an asset model from an external vendor. It is therefore crucial that PartnerRe has strong confidence into the quality of the model. This study proposes a pragmatic end-to-end approach to validate a black-box asset model without knowing all of its underlying mechanisms. The proposed framework consists of an internal and external validation of the asset model: In the internal validation, the plausibility and robustness of the model outputs are verified through a sensitivity analysis. This is done by studying the impact of changing asset model parameters on the predicted downside risk. In the external validation, the empirical validity of the asset model is studied by comparing the model outputs to historical data. The 2008 financial crisis is compared to the most severe model outputs in order to determine the matching return period for observed historical losses. It is also verified that the frequency of adverse FX rates projected by the asset model matches historical FX data. The insights gained from the internal and external model validation are used to refine the modeling approach and to propose improvements to the model where it is limited, either in terms of the granularity of asset classes or in the number of currencies that can be modeled.

Keywords: Asset model, validation, black box, sensitivity analysis, empirical validation

1 Introduction

Partner Re (PRE) is a global and diversified reinsurance company which invests its capital into a broad range of financial assets. Within its investment portfolio, PRE distinguishes between assets held to support liabilities and excess capital funds: While the liability fund is invested in high-quality, liquid, investment-grade fixed-income securities, the excess capital fund may be invested in other asset classes of riskier nature while being subject to limits and control. In order to balance between a high return on investment and sufficient liquidity to cover liabilities, PRE has established risk limits which it monitors on a quarterly basis using an internal asset model.

The overall purpose of this study is to provide a validation of the asset model used to quantify the downside risk of PRE's investment portfolio. The main motivation for the asset model validation is to give a risk manager confidence in the accuracy of the model. For the purpose of this analysis, the following requirements have been defined to assess the overall validity of the asset model:

1. *Plausible*: The expected annual return of each asset class should be within a meaningful range defined by the expert running the model.

2. *Robust*: The variation of the annual return of each asset class should be consistent with expert expectations as model parameters are changed.

3. *Empirically valid*: The downside tail of the risk distributions produced by the model should match expert expectations on the frequency and severeness of adverse historical events.

As asset models are increasingly complex, a rapid validation approach is needed in order to gain confidence in the modeled returns. Therefore, this study treats PRE's asset model as a black box, taking into account all the available historical and current economic data in order to assess the plausibility of the model's output. Doing so, the findings of this report can be used to refine the modeling approach over time.

In this study, explanations on the methodology of determining a risk appetite are limited to a minimum, as they have been described in other studies [2, 16, 6]. Similarly, due to the wealth of research on risk metrics [9, 3], their description and comparison is not in the focus of this study either. Overall, numerous publications exist on risk appetite setting, risk tolerances, risk metrics as well as topics related to implementing and comparing capital models [16, 13, 14, 8].

Yet, there is relatively little literature on end-to-end validation of an asset model. The focus of this study lies on the analysis of the standalone downside asset risk due to the investment portfolio. In this context, standalone means that correlations between asset risks and other risks, such as a hurricane leading to a market crash, are ignored. The aim of this thesis is to provide a pragmatic methodology for validating an existing internal asset model to measure the downside risk of an investment portfolio.

Three approaches are used to validate PRE's asset model:

1. A sensitivity analysis of the asset model's projected returns and, in particular, downside tail risk, with respect to changes in the model parameters.

2. A comparison of the asset model's projected returns against historical data.

3. A comparison of different modeling approaches within the asset model.

2 Asset Classes and Risk Types

PartnerRe invests its capital into a diversified and broad portfolio of assets spanning fixed income, equities, real estate as well as other financial assets. Counterparties issuing an investment instrument have a certain likelihood to default or experience a credit rating downgrade, leading to a partial or full loss of the asset value. Other factors linked to financial markets may lead to a devaluation of an asset.

Amongst other risk factors, the risk of a devaluation of PRE's assets may lead to the company's inability to settle liabilities due to insufficient liquidity. This may ultimately lead to a downgrade of PRE's credit rating or, in the worst case, defaulting. To foresee the impact of a devaluation of PRE's assets, it is important to measure and model asset risk.

Each asset in PRE's investment portfolio can be categorized into one of the following four broad asset classes:

1. *Risk-free fixed income*: e.g., U.S. government & government-backed securities, AAA foreign government securities and cash
2. *Credit-risky fixed income*: corporate bonds, foreign government securities rated below AAA, municipal bonds and principal finance
3. *Equity or equity-like investments*: public equity, private equity and strategic ventures
4. *Real estate*: investments in real estate property

Table 1 summarizes the asset classes represented in PRE's portfolio and their relevant risk components under the Solvency II framework.

Broad Asset Risk Category	**Asset Class**	**Asset Subclass**	**Risks**
Standard Fixed Income	Cash & Cash Equivalents excl. Working Capital		Cash Risk
	Sovereign Government	US Govt	Interest Rate Risk Spread Risk (rating-dependent)
		EUR Govt	
		CAD Govt	
		US TIPS	
		Non-EUR Govt	
	US Municipal Bonds		Interest Rate Risk Spread Risk
	Corporate	USD Corp	Interest Rate Risk Spread Risk
		EUR Corp	
		GBP Corp	
		CAD Corp	
	MBS	US Agency MBS	Interest Rate Risk Spread Risk
		Canadian Gov Guar MBS	
		Other ABS / MBS	
Financial Investments	(ILS)		(Not modeled)
	Alternative Credit	Bank Loans	Interest Rate Risk Spread Risk
		High Yield US and EUR	
		Principal Finance	
	Financial Assets	Private Equity	Private Equity Risk
		Public Equity	Equity Risk
		Real Estate	Real Estate Risk
		Strategic Ventures	Private Equity Risk
(Other)	(Liabilities)		(Interest Rate Risk)
	(Net Asset Value)		(FX Risk)

Table 1 – Asset Classes represented on PRE's Balance Sheet and associated risk types. Asset classes not studied within this paper are indicated in parentheses.

Every asset carries risks coming from one or several asset risks [6]:

1. *Interest Rate Risk (IR Risk)* (fixed income): the risk of an exposure to losses arising from changes in interest rates. Lower interest rates generally increase the opportunity cost of holding money as there is less return on it, thus creating demand for investment and increasing bond prices. Interest Rate Risk of a security usually depends on the maturity and the coupon rate of a security.

2. *Spread risk* (non-standard fixed income): the risk due to market perception of an increased risk on either a macro (industry sector) or micro (company) basis. Sometimes, spread risk is divided into two components, reflecting migration risk (downgrading to a lower credit rating) and default risk (the risk of the company becoming insolvent). Spread risk usually correlates strongly with the credit rating of a company, reflecting its financial strength.

   Generally, US government and other AAA-rated foreign government bonds have no spread component and are considered risk-free due to government's ability to print money or raise more taxes, making it much more unlikely for a government to default than for a company. The risk-free rate is therefore often chosen as the U.S. Treasury Bill rate.

   One measure to calculate the expected return on a security is the Capital Asset Pricing Model (CAPM), which is based on the risk-free return rate and a risk premium [11]:

$$ER_i = \underbrace{R_f}_{\text{Risk-free}} + \underbrace{\beta_i(ER_m - R_f)}_{\text{Risk Premium}} \tag{1}$$

   where ER_i is the expected return on the security i, R_f is the risk-free rate, β_i is the beta of security, ER_m is the expected return of the market and $ER_m - R_f$ is the market risk premium. The risk-free rate R_f accounts for the time value of money. The β is an indicator whether the investment will reduce or increase the risk associated to a portfolio that looks like the market (lower or greater than 1). The market risk premium indicates the rate of return which the market expects above the risk-free rate.

3. *Equity risk*: Generally, equity is considered more risky and volatile than bonds. A measure of equity risk for a given company is the beta:

$$\beta = \frac{\text{Covariance}(R_e, R_m)}{\text{Variance}(R_m)}$$

   Where R_e is the return on an individual stock and R_m is the return on the overall market.

4. *Property risk*: The risk of an exposure to losses in real estate investments. Similar to equity, the beta is used as a measure of property risk.

5. *Foreign Exchange (FX) Risk*: The risk of an exposure to a change on the value of an investment due to the effect of change in the exchange rates between currencies [10]. FX risk can be hedged against using derivatives.

This work omits discussions around concentration risk, defined as the risk arising from having a relatively higher weight assigned to a sector or an issuer within the investment portfolio.

In order to assess which level of tail risk is acceptable, a company has to define its risk appetite, meaning its willingness to assume risks up to a certain threshold [9, 16]. The notion of *Risk Appetite* can be somehow misleading, as it suggests a positive "appetite" for taking risks. In reality, *Risk Appetite* signifies rather a level of risk an individual or company is willing to assume in order to achieve a return [2]. The dependency between risk and return is called the risk-return trade-off, which is reflected in the popular phrase "Eat well, sleep well", meaning that you can either eat well (high return), but sleep little (high risk) or vice-versa.

According to Mahoudeau [9], three notions can be linked to the notion of Risk Appetite:

1. *Risk Preferences*: qualitative notion denoting the types of risk a company wants to assume within its activities.

2. *Risk Tolerances*: quantitative notion specifying the risk levels that a company is willing to assume within a given perimeter of activity.

3. *Risk Limits*: quantitative notion, composed of both *Risk Preference* and *Risk Tolerance*, meaning the operational risk limits by risk type that are imposed to each legal entity or branch.

The sum of all characteristics of the company related to risks can be called the *Risk Profile*.

Within the following report, particular focus is placed on the topic of modeling and validating *Risk Tolerances* and *Risk Limits*. The leading metric will be the maximum overall risk tolerance defined by the owner of PartnerRe, EXOR, and the Enterprise Risk Committee as a 20% loss of economic capital every 100 years due to financial asset risks and 35% every 100 years across all risk sources of PRE.

From a return distribution on a given asset, the downside risk can be calculated in terms of the risk of being at the lower end of the distribution. For these purposes, a widely-spread indicator is Value at Risk (VaR), which is defined as follows by Capinski and Kopp [3] for a given quantile p:

$$\mathrm{VaR}_p[X] = \inf\{x \in \mathbb{R} | F_X(x) \geq p\}, \quad p \in (0,1) \tag{2}$$

With $F_X(x) = \mathbb{P}[X \leq x]$.

This measure has been criticized for not being coherent by ignoring the tail risk past the quantile p. Other measures have been proposed to reflect the overall tail risk more appropriately, among which the most popular is Tail Value-at-Risk (TVaR), defined as:

$$\mathrm{TVaR}_p[X] = \frac{1}{1-p} \int_p^1 \mathrm{VaR}_q[X] \, \mathrm{d}q, \quad p \in (0,1) \tag{3}$$

These two metrics are most widely used in insurance for measuring downside risk. As the purpose of asset modeling at PRE it to ensure that the limit on the maximum loss for a given return period is respected, the VaR is used across all asset classes and risk types.

3 Methodology

3.1 Asset Model

The purpose of an asset model is to model the market risks faced by a particular company in a coherent way, capturing dependencies between risks [13]. In particular, the two principal requirements of PRE for its asset model are to project the expected annual returns on its investments and to quantify the downside risk of its investments portfolio at given return periods.

PRE relies on Willis Towers Watson (WTW) to model total returns by asset class and risk type. The model is widely used in the industry and is subject to regular validation by WTW. The asset model used by PRE is based on an Economic Scenario Generator (ESG). According to the Society of Actuaries [12], an ESG is a software tool used to simulate future paths of economies and financial markets, taking into account the risks inherent to the economy which drive financial variability. As there is significant complexity in real-world economic dynamics captured in ESG, statistical sampling from a set of possibilities is required in order to produce a realistic distribution of potential outcomes, which is also known as a Monte Carlo process. WTW's ESG produces a pre-defined number of Monte Carlo simulations of the economy, capturing real world dynamics such as the economic environment, the historical relationships between macroeconomic variables as well as returns by risk type. Usually, several thousands of simulations are generated in order to avoid bias from outliers in the distribution.

For each economic simulation generated by the ESG, the asset model produces one return projection at a specified moment in the future. Using many different economic projections, a distribution of the asset return can be calculated, from which a downside risk (VaR) can be derived. Many of the asset model's assumptions and characteristics are described by Stephan [13]. Although other approaches have been proposed to measure tail risk, such as using historical approaches or parametric mappings, return projections based on Monte Carlo simulations remain the most widely-spread approach in the reinsurance industry [7, 5, 8, 13].

All numerical results of the model used in the Sensitivity Analysis and in the Empirical Validation are available in appendix A.

3.2 Sensitivity Analysis

The purpose of the sensitivity analysis applied to PRE's asset model is to evaluate the sensitivity of modeled returns and, in particular, asset risks, to changes in the relevant model parameters, both in terms of direction and magnitude. All return projections are made over a period of one year. The tested parameters and parameter ranges for each asset class are indicated in Table 2.

Asset Class	Default Parameters	Tested Parameter Range	Attached Risks
Government Bonds	C=3% M=5	C={1%, 2%, ..., 10%} M={1, 2, ..., 5}	Interest Rate Risk
Corporate Bonds	C=3% M=5 R=A	C={1%, 2%, ..., 10%} M={1, 2, ..., 5} R = {BB, BBB, ..., AAA}	Interest Rate Risk Spread Risk
Property	B=1	B={0.2, 0.4, ..., 3}	Property Risk
Equity-Like	B=1	B={0.2, 0.4, ..., 3}	Equity Risk
Mortgage-Backed Security (MBS)	APP=60 C=5% Curve=R M=30 PSA_f=100% Rating=AAA	APP={0, 20, ..., 116} C={3%, 4%, ..., 7%} Curve={Rf, R} M={3, 5, 10, ..., 30} PSA_f={50%, 100%, ..., 300%} Rating={BBB, A, ..., AAA}	Prepayment Risk, Measured as Interest Rate Risk + Spread Risk

Table 2 – Tested parameters and parameter ranges for each modeled asset classes and risks arising from each asset class. C = Coupon Rate, M = Maturity, R = Rating, B = Beta, Rf = Risk-free, R=Risk, APP = Active Payment Periods, PSA_f = PSA factor (see appendix B for an explanation of special parameters tested for MBS)

3.3 Empirical Validation

The empirical validation of the asset model aims at validating the plausibility of all modeled returns for each asset class by risk type and, in particular, the validation of modeled downside risk, by comparing the model outputs to historical data. In particular, we want to compare the impact of the 2008 financial crisis on total returns against the modeled risks of asset classes. To simplify the analysis, a range of meaningful parameters have been selected per asset class, excluding parameter ranges that would be too extreme or rare to find in financial markets:

1. **Government Bonds**: USD Government Bonds (M = {2, 5, 10 years}), TIPS (M = 5 years)
2. **Corporate Bonds**: USD Corporate Bonds (R = {BB, BBB, A}, M = 5 years, C = 2%)
3. **MBS**: USD MBS (R = AAA, M = 5 years, C =5%)
4. **Equity and equity-like**: USD Public Equity, USD Private Equity, USD Emerging Equity, USD Hedge Fund (Beta = 1)
5. **Property**: USD Real Estate, GBP Real Estate (Beta = 1)
6. **Currencies**: USD to GBP, EUR, CAD, JPY, CHF and SGD

The aim is to compare historical returns during the crisis to modeled returns for each asset class. The strength and moment of the impact of the 2008 financial crisis may vary for each asset class, conclusions on the plausibility of the model are therefore made separately for each asset class and risk type.

Empirical data on returns, spread widening and yields for different asset classes were obtained from the Federal Reserve Economic Data (FRED) (`https://fred.stlouisfed.org/`) and from Bloomberg. Time frames of the studied empirical data are indicated in table 3.

Asset Class	Parameters	Index	Type	Time Frame
US Treasury	M = 2Y	H15T2Y	Y	1976/06/01 - 2017/11/29
	5Y	H15T5Y		
	10Y	H15T10Y		
TIPS	M = 5	BXIIUL05	P	2006/04/28 - 2017/11/30
Corporate Bonds	R = A	C5A3	S	1996/12/31 - 2017/11/30
	BBB	C5A4		
	BB	H0A1		
MBS	D = 4	M0A0	S	2004/01/02 - 2019/06/30
Equity	Public Equity	SPX	P	1927/12/30 - 2017/11/30
	Private Equity	SPLPEQTR	P	2003/11/28 - 2017/11/30
	Emerging Equity	MXEF	P	1987/12/31 - 2017/11/30
	Hedge Fund	HFRXGL	P	1997/12/31 - 2019/07/31
Property	USD	US HPI	HPI	1975/01/01 - 2017/09/01
	GBP	UK HPI	HPI	1968/01/04 - 2017/01/09
Currencies	USD - GBP	USDGBP	FX	1972/01/31 - 2017/11/30
	USD - EUR	USDEUR	FX	1976/01/31 - 2017/11/30
	USD - CAD	USDCAD	FX	1972/01/31 - 2017/11/30
	USD - JPY	USDJPY	FX	1972/01/31 - 2019/07/31
	USD - CHF	USDCHF	FX	1972/01/31 - 2019/07/31
	USD - SGD	USDSGD	FX	1982/01/31 - 2019/07/31

Table 3 – Time Frames of Data Sources used for Empirical Validation. Data types can be given as Yield (Y), Spread (S), Price (P), Housing Price Index (HPI) or FX Rates. All indices are from Bloomberg, with the exception of US HPI and UK HPI, which are from Standard & Poor's (S&P) [1] and the from the UK HM Land Registry [15], respectively.

All historical data sources have been transferred to total return [%] in order to compare them to the modeled returns on a same scale. Transformations were made according to the nature of the source data:

- **Spread** S [4]:

$$\delta P\ [\%] = \frac{(P_t - P_{t-1})}{P_{t-1}} = -D \times \underbrace{\delta S}_{(S_t - S_{t-1})/10000} \tag{4}$$

  Where P is the price, D is the spread duration and S is the spread in bps. Convexity is not included in this formula, assuming it to be equal to 0.

- **Yield** Y: The calculation of total return was done similarly to spread widening:

$$\delta P\,[\%] = \frac{(P_t - P_{t-1})}{P_{t-1}} = -M \times \underbrace{\delta Y}_{(Y_t - Y_{t-1})} \tag{5}$$

  Where M is the maturity and Y is the Yield To Maturity.

- **Price levels** P:

$$\delta P\,[\%] = \frac{(P_t - P_{t-1})}{P_{t-1}} \tag{6}$$

Regarding property, the HPI used to assess the returns of the property market at a given time needs to be adjusted for inflation as follows:

$$HPI_{adj,t} = 100 \times \frac{HPI_{raw,t}/CPI_t}{HPI_{raw,0}/CPI_0} \tag{7}$$

For the empirical validation of downside returns, particular attention is given to the 2008 financial crisis. The assumption is made that this crisis corresponds roughly to a 1/100 downside event for the equity markets, while some other asset classes like Treasury Inflation-Protected Securities (TIPS) may have been positively impacted by the crisis. For all comparisons, it is important to notice that the 2008 financial crisis and other historical data may only be one potential source of information used in the asset model to predict total returns. The asset model may also take into account many other factors, such as other real-world data, monetary policy, political outlook and further factors that could influence the future development of total returns and tail risks. Therefore, no perfect correspondence between historical returns and model returns should be expected.

For this part of the empirical validation, we define the time span of the 2008 financial crisis as going from 12/2007 until 06/2009. Historical price changes were calculated with the following indices:

- **Maximum change**: *maximum* percentage change of the average monthly price of the asset class over a time frame of x months (backward-looking) on any month during the 2008 financial crisis, for $x = 1$ (monthly change), $x = 3$ (quarterly change), $x = 12$ (annual change) or $x = 18$ (change over entire time span of crisis).
- **Mean change**: *mean* percentage change of the average monthly price of the asset class over a time frame of x months (backward-looking) on any month during the 2008 financial crisis, for $x = 1$ (monthly change), $x = 3$ (quarterly change), $x = 12$ (annual change) or $x = 18$ (change over entire time span of crisis).
- **Change 2008/12 - 2007/12**: annual percentage change between the mean price of the asset class in December 2008 and the mean price in December 2007.
- **Change 2008/10 - 2007/10**: annual percentage change between the mean price of the asset class in October 2008 and the mean price in October 2007.

In summary, the first two indicators above measure the change in price of an asset, calculated as the **maximum** or the **mean** change in price over time periods ending in any month of the crisis and starting 1, 3, 12 or 18 months earlier (rolling window approach). In order to account for the different natures of the source data, for spread data, the maximum increase in spreads was taken in order to calculate the maximum change in price over a given time, whereas for yield data, the minimum increase in yield was taken (eq. 4, 5).

Quantifying the impact of the 2008 financial crisis as the maximum loss incurred at any moment of the crisis might be strongly conservative, as yields, spreads and asset prices fluctuated during the crisis. Depending on the considered moment within the 2008 financial crisis, strong losses of the asset value compared to the previous year can be observed.

Overall, it is a desirable property for the asset model to be conservative. Therefore, the baseline indicator used in the empirical validation is the maximum yearly percentage change (the maximum percentage change over each 12-month shift), unless otherwise indicated.

3.4 Modeling Approach Assessment

The purpose of the modeling approach assessment is to study the appropriateness of modeled results *between* different asset classes and subclasses. Sensitivities, returns and downside risk between asset subclasses and currencies are studied in order to understand which asset subclasses and currencies follow similar risk profiles and return distributions. In addition to insights gained into risk profiles of asset classes and currencies, information on return properties between asset classes can be used to determine meaningful proxies for asset classes when needed. Substituting asset classes or currencies by proxies can be especially useful when there is either no exact information on the nature of a security and an assumption has to be made for the modeling choice, or if there is a limitation in the model due to high run-times requiring asset class to be bucketed and aggregated. In these cases, it is important to have confidence in the plausibility of the risk profile of the proxy used.

First, sensitivities are compared between assets classes which can be modeled using different indices in the asset model. Prior to the comparison of the returns for different asset subclasses, it is verified that the modeled return of these asset subclasses indeed follows the actual, historical returns of the underlying indices used for modeling them. The purpose of studying the risk profiles of these indices is to enable a wider range of modeling possibilities.

All indices of the “Extra Indices” section in the asset model are modeled like equity, with beta as the only varying parameter. Yet, some non-equity-like indices such as “High Yield” (global high yield corporate bonds) and “US High Yield” are also available for use. It is assumed that these indices, which are modeled like equity but are of a non-equity-like underlying asset class, are provided in order to model riskier assets which have a risk profile similar to equity.

The underlying asset classes of each index in the Extra Indices class of IGLOO as well as the data source are shown in table 4.

Extra Index (IGLOO)	**Underlying Asset Class**	**Data Source**
Emerging Equity	Equity	GDUEEGF (MSCI Barra 1988)
Global Equity	Equity	GDDUWI (MSCI Barra 1984)
Hedge Fund	Equity	HFRXGL (HFR Asset Management LLC 1998)
Private Equity	Equity	LPXCMPTR (LPX GMBH 2002)
High Yield	Corporate Bond	IM00 (Merrill Lynch 1999)
US HY	Corporate Bond	HWXC (Merrill Lynch Global HY BB-B rated)

Table 4 – Extra Indices: Underlying asset classes and Bloomberg Index of the data source.

Validation of the equity-like and non-equity-like indices is achieved by matching the return distribution, and, in particular, the downside risk, of each of the indices to the return distribution of their underlying asset class. For equity-like indices, the underlying asset class is US Dollar (USD) equity, while for the non-equity-like indices, the underlying asset type is a USD Corporate Bond. Therefore, the validation of the indices is split into sub-analyses for equity-like indices and for non-equity-like indices.

For equity-like indices, the closeness of the return distribution and downside risk is compared to the modeled return distribution of USD equity using a corresponding beta value. Corresponding beta values for each index have been retrieved from Bloomberg by comparing index performance against the S&P 500 Index (SPX) within the time window 1999-2019. The resulting betas for each index are shown in table 5 and a sample screenshot of the data extraction process using the Bloomberg Terminal is shown in appendix C.

Extra Index (IGLOO)	**Bloomberg Data**	
	Index	**Raw Beta**
Emerging Equity	GDUEEGF	1.126
Global Equity	GDDUWI	0.994
Hedge Fund	HFRXGL	0.221
Private Equity	LPXCMPTR	1.172

Table 5 – Bloomberg Data for **equity**-like Asset Classes modeled as Extra Indices in IGLOO.

For instance, table 5 indicates that the downside risk of emerging equity at a beta of 1 should correspond to the downside risk of USD equity at a beta of 1.126.

For each non-equity-like index return, it is verified that the tail risk matches the modeled tail risk of a corporate bond with parameters corresponding to the index, using a beta equal to 1. Corresponding parameters for each non-equity-like index have been obtained from Bloomberg and are shown in table 6.

Extra Index (IGLOO)	Bloomberg Data			
	Index	**Composite Rating**	**Years to Maturity**	**Coupon**
High Yield	IM00	B1 (S&P: B+)	9.33	6.45
US HY	HWXC	BB3 (S&P: BB-)	5.68	5.87

Table 6 – Bloomberg Data for **fixed-income** Asset Classes modeled as Extra Indices in IGLOO and corresponding bond characteristics derived from Bloomberg.

For instance, table 6 shows that the High Yield index provided in the asset model should have the properties a B1-rated corporate bond with 9.33 years to maturity and a coupon rate of 6.45.

Second, total return sensitivities with respect to currency are compared for public equity, private equity and property. For each currency, asset class and parameter set, the comparison is made to USD as a baseline currency, as it is the most strongly represented currency across all asset classes in PRE's investments portfolio. The purpose of the comparison of total returns and downside risk by currency is to understand the relative sensitivity to model parameters for each currency.

Last, we look at currencies present in PRE's invested assets which are currently not modeled due to limitations in the asset model runtime. Due to high calculation times of the asset model, only a limited set of five currencies is currently modeled in the asset model: USD, Canadian Dollar (CAD), Euro (EUR), Pound sterling (GBP) and Singapore Dollar (SGD). However, there are more currencies in PRE's balance sheet, such as Chinese Yuan (CNY), Japanese Yen (JPY) and Swiss Franc (CHF). Therefore, for currencies which are present in PRE's investment portfolio but cannot be modeled due to computation time limitations, we find the modeled currency which matches the non-modeled currency most closely in terms of downside tail risk. For a number of selected asset classes with same parameters modeled in different currencies, the closest matching currency is determined by comparing the VaR 1/100 and VaR 1/250 downside risk values of the modeled currency to the downside risk values of the non-modeled currency. Doing so, non-modeled currencies can then be modeled as one of the five modeled currencies which matches the non-modeled currency most closely for a given asset class. Results for the tests are shown in appendix E for government bonds, for A- and B-rated corporate bonds as well as for equity, for currencies CNY and JPY. For CHF, there are only liabilities and no invested assets on PRE's balance sheet, therefore, the only comparison with respect to other currencies is done for Zero-Coupon Bond (ZCB).

4 Results

4.1 Sensitivity Analysis

4.1.1 Government Bonds

Figure 1 shows the sensitivity of the modeled return and interest rate risk of government bonds after one year to coupon rate and maturity. All the figures below show projected returns after a period of one year.

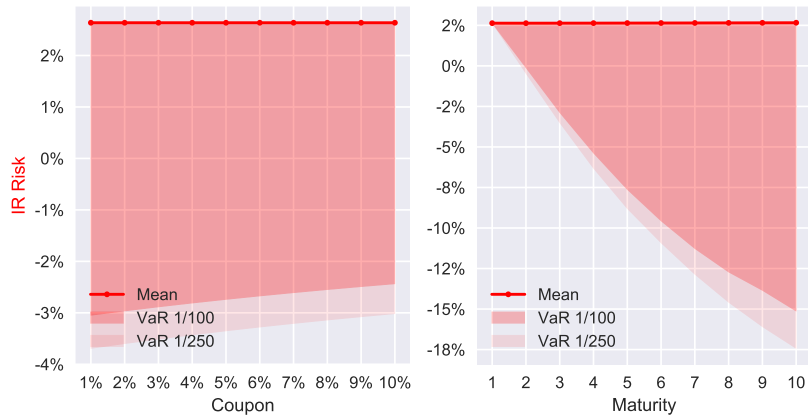


Figure 1 – Sensitivity test results for government bonds **Base Case: USD, C=3%, M=3**

Figure 1 shows a negative correlation between tail risk and coupon rate and a positive correlation between tail risk and maturity.

Since the model scope does not exceed one year, the model showed no difference in sensitivities with respect to the parameter "holding type", which indicates whether a bond is sold, kept, or sold and reinvested into the same security type after a period of one year.

4.1.2 Corporate bonds

Figures 2 and 3 show the sensitivity of an A-rated a B-rated corporate bond, respectively, to changes in Coupon Rate, Maturity and Rating in terms of Interest Rate Risk, Spread Risk and Total Risk (diversified return) after one year.

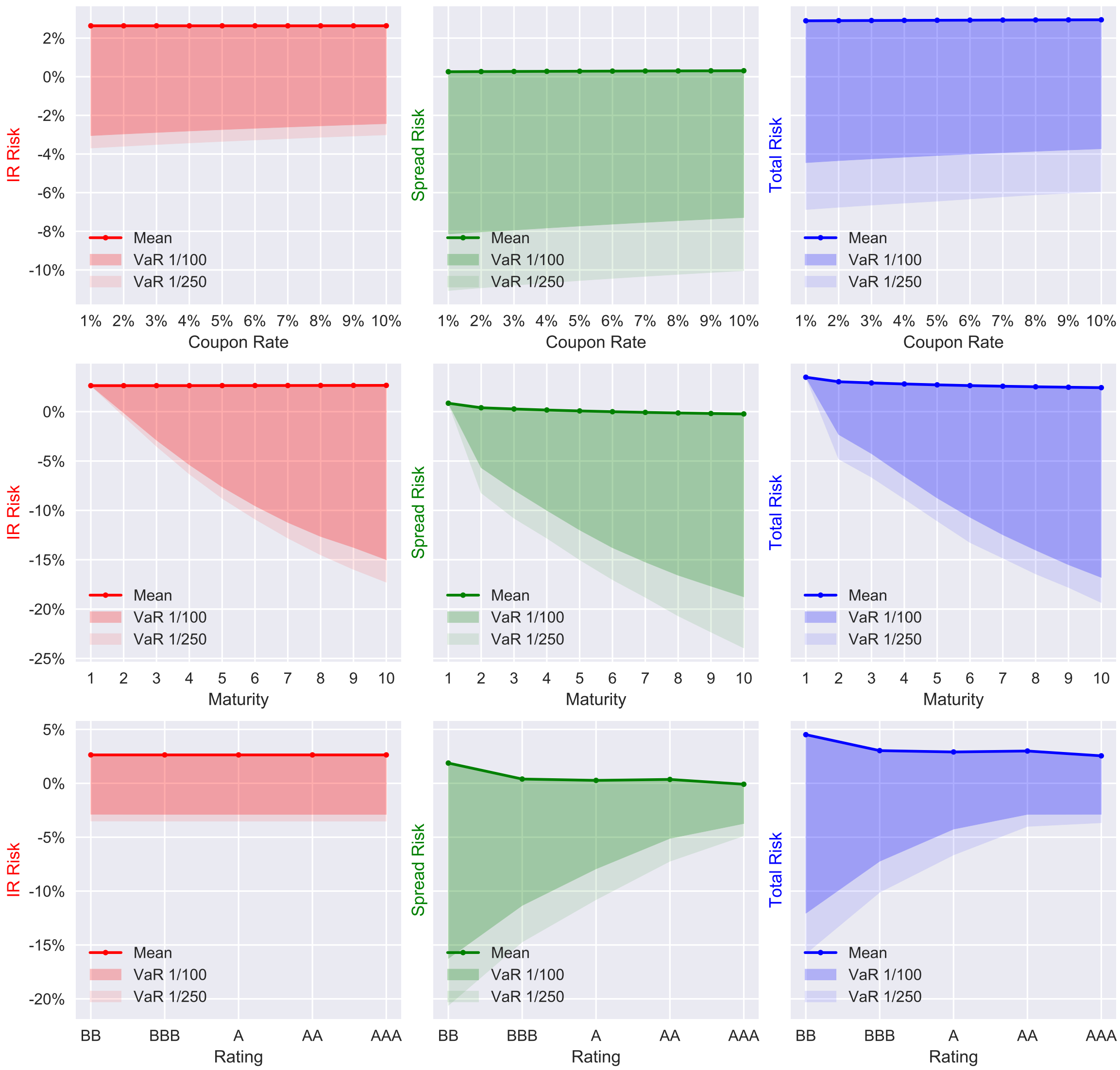


Figure 2 – Sensitivity test results for A-rated corporate bonds (**Base Case: USD, C=3%, R=A, M=3**)

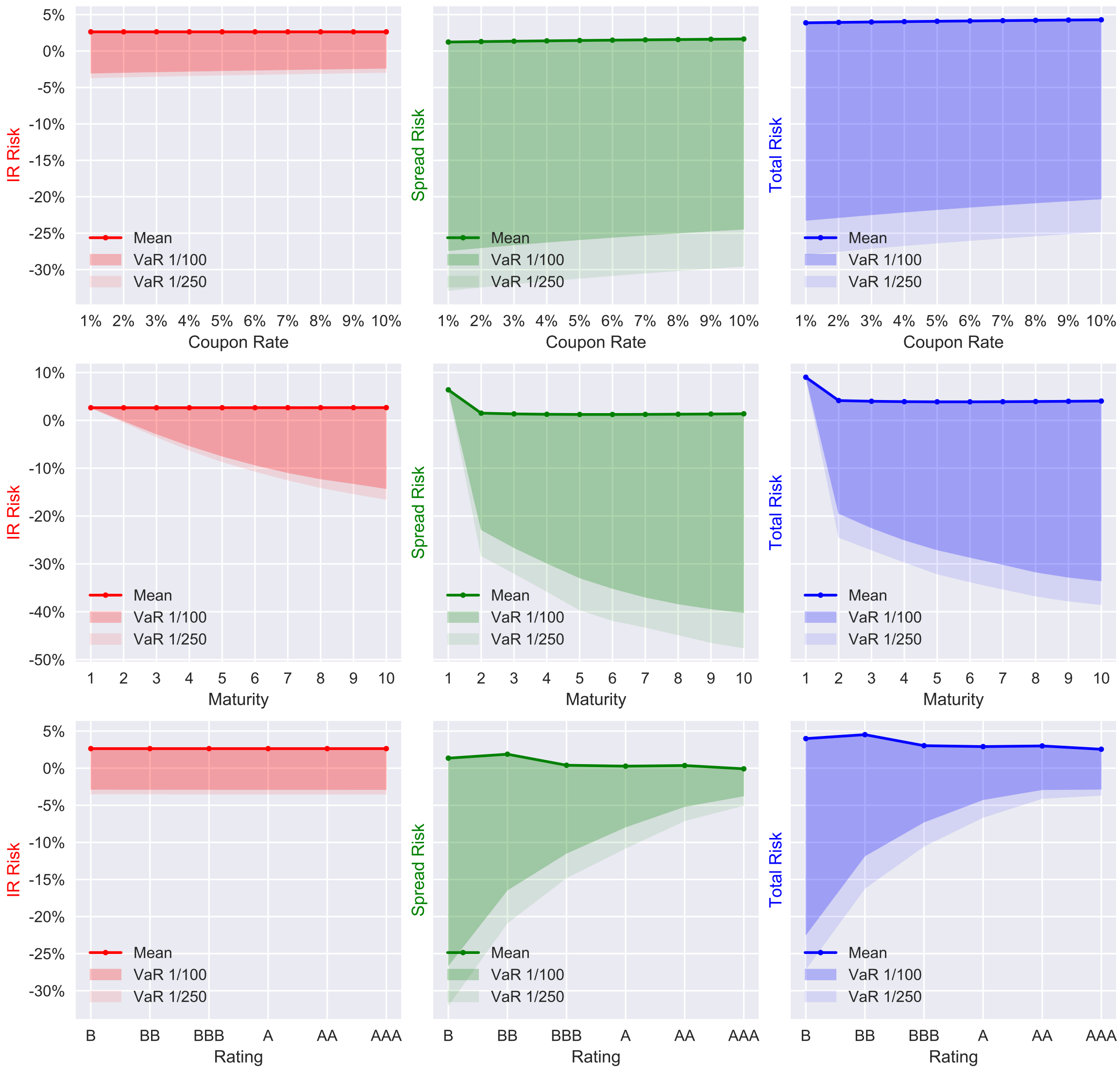


Figure 3 – Sensitivity test results for B-rated corporate bonds (**Base Case: USD, C=3%, R=B, M=3**)

Figures 2 and 3 both show a negative correlation between rating and spread risk, no correlation between rating and interest rate risk, a positive correlation between maturity and all risk types, and a negative correlation between the coupon rate and all risk types. Additionally, it confirms that interest rate risk is a diversifier of spread risk particularly in the tail. Figure 3 shows a stronger downside risk in all risk dimensions for the B-rated corporate bond compared to the A-rated corporate bond in figure 2.

4.1.3 MBS

Figures 4 and 5 show the sensitivity of MBS to changes in Active Payment Periods (APP), Coupon Rate and Current Market Value (fig. 4) as well as Risk Curve, Maturity, PSA Factor and Credit Rating (fig. 5) in terms of Interest Rate Risk, Spread Risk and Total Risk (diversified return) after one year.

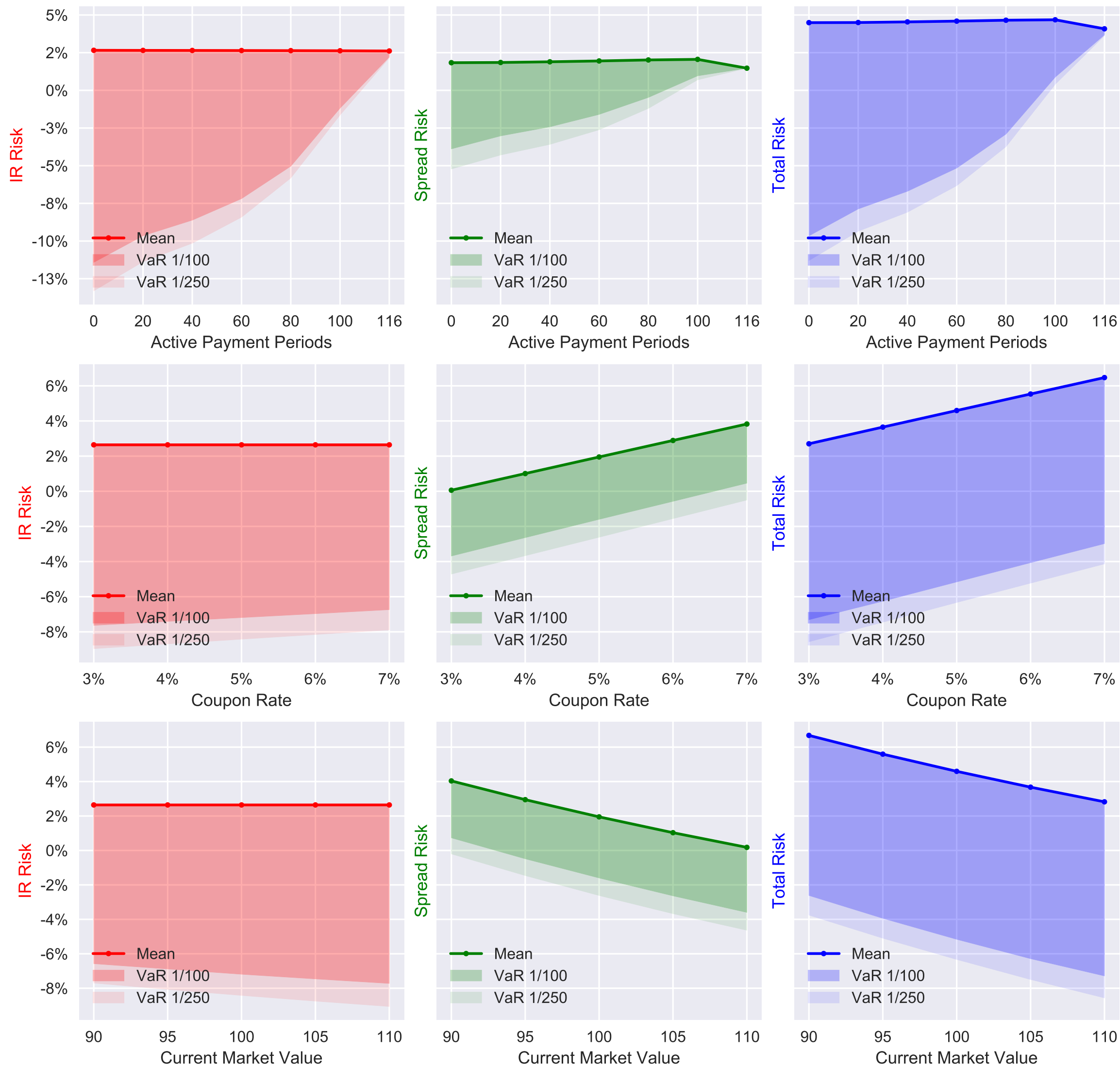


Figure 4 – Sensitivity test results for MBS (**Base Case: USD, APP=60 (0 for Maturity), C=5%, CMV=100, Curve=Risk, M=30 years, PSA$_f$=100%, R=AAA, 4 payments / year**)

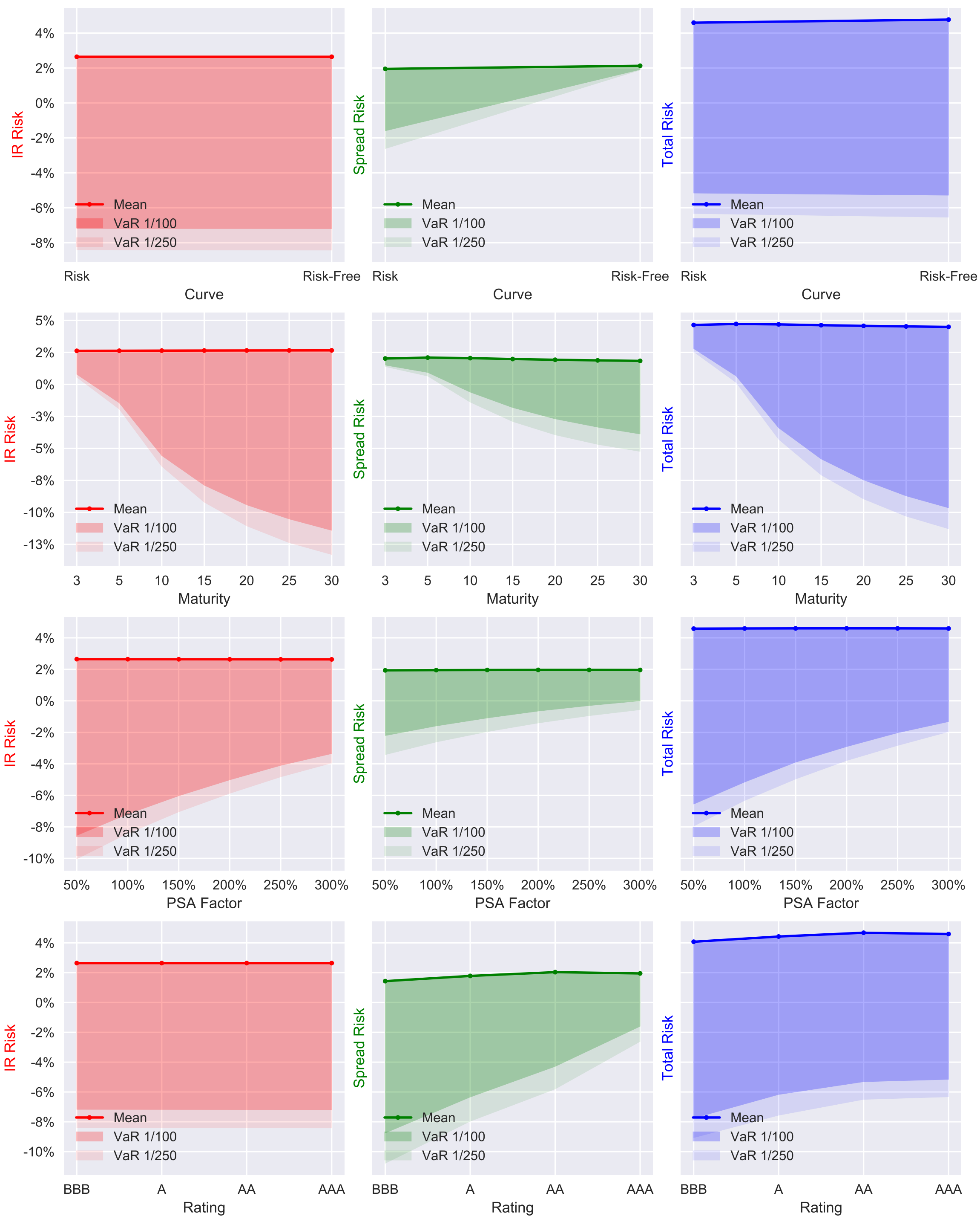


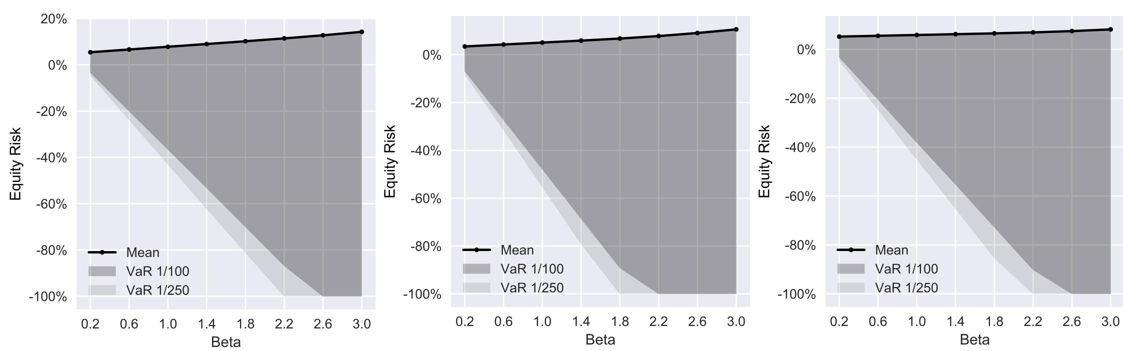
Figure 5 – Sensitivity test results for MBS (**Base Case: USD, APP=60 (0 for Maturity), C=5%, CMV=100, Curve=Risk, M=30 years, PSA$_f$=100%, R=AAA, 4 payments / year**)

The following correlations are observed for MBS:

- A positive correlation between all asset tail risks and current market value as well as between all asset tail risks and maturity.
- A negative correlation between all asset tail risks and APP as well as coupon rate, and a negative correlation between spread risk and rating.
- An absence of spread component if the underlying risk curve is to be chosen risk-free.
- The correlation between tail risk and PSA could be either negative if the bond is bought at discount or positive if the bond is bought at premium.

4.1.4 Equity

Figure 6 shows the total return sensitivity of USD, EUR and GBP equity to changes in beta.



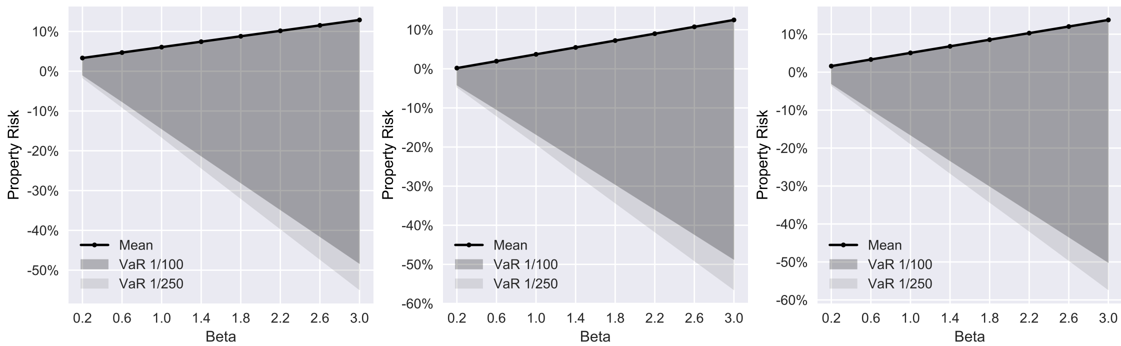
(a) USD (b) EUR (c) GBP

Figure 6 – Sensitivity test for Equity Risk with respect to Beta for different currencies.

Figure 6 shows a positive correlation of the beta parameter with return and with tail asset risk for all currencies. Among the modeled currencies, EUR shows the strongest tail risk and USD a slightly lower tail risk than GBP, while USD equity also shows the highest return relative to beta.

4.1.5 Property

Figure 7 show the total return sensitivity of USD, EUR and GBP property to changes in beta.



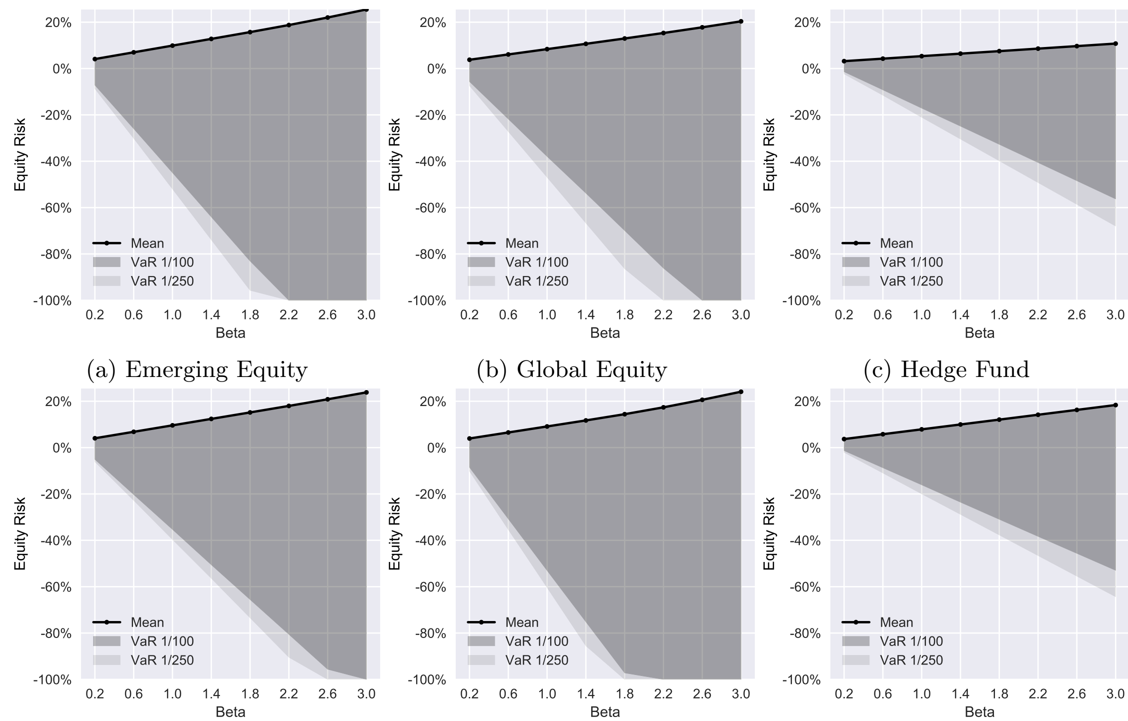
(a) USD (b) EUR (c) GBP

Figure 7 – Sensitivity test for Property Risk with respect to Beta for different currencies.

Similar to equity, the beta of property in all currencies is positively correlated with return and with tail asset risk. The effect of beta on total return and tail risk is stronger for equity than for real estate.

4.1.6 Extra Indices

Additional equity-like asset categories can be modeled using so-called "Extra Indices" in the asset model, which comprise several equity-like asset classes. Figure 8 shows the sensitivity of total return to beta for Emerging Equity, Global Equity, Hedge Funds, High Yield Bonds, Private Equity and US High Yield.



(a) Emerging Equity (b) Global Equity (c) Hedge Fund

(d) High Yield (e) Private Equity (f) US HY

Figure 8 – Extra Indices: Sensitivity Results for Extra Indices (all in USD)

As can be seen in figure 8, all indices show a positive correlation of varying strength between beta and return as well as between beta and tail risk. It is noteworthy to mention that Hedge Funds show the lowest tail risk and the lowest return for any chosen beta value, while Emerging Equity has the greatest tail risk and return of all studied indices. Private Equity has a similar yet slightly lower tail risk compared to Emerging Equity, after which follows (Global) High Yield, Global Equity and US High Yield Bonds.

4.2 Empirical Validation

4.2.1 Government Bonds

Figure 9 shows the price change for US treasury government bonds of different maturities and highlights the 2008 financial crisis. Figure 10 compares the historical returns during the 2008 financial crisis to projected model returns.

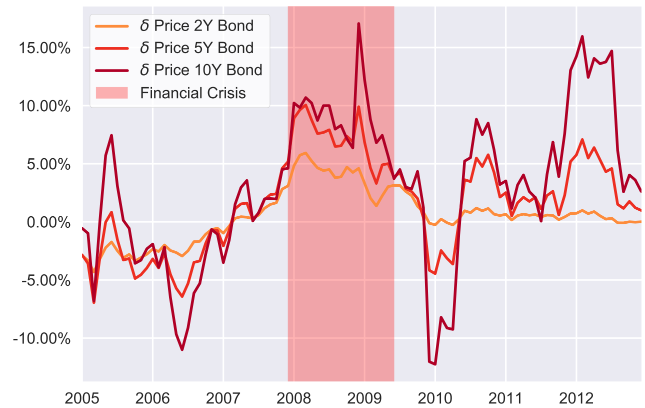
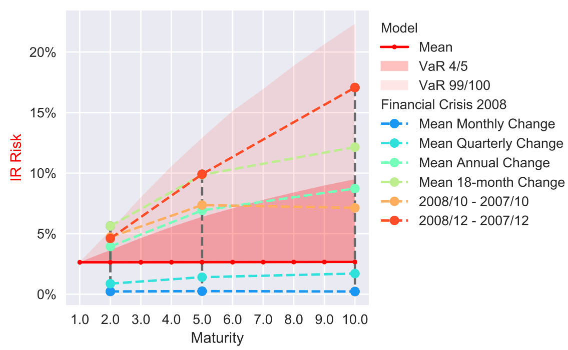
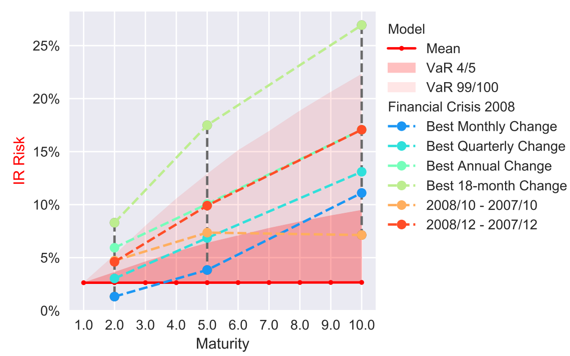


Figure 9 – Historical Data for USD Government Bonds Bonds: Price Change (yearly)



(a) Model and historical returns (**Mean increase**)



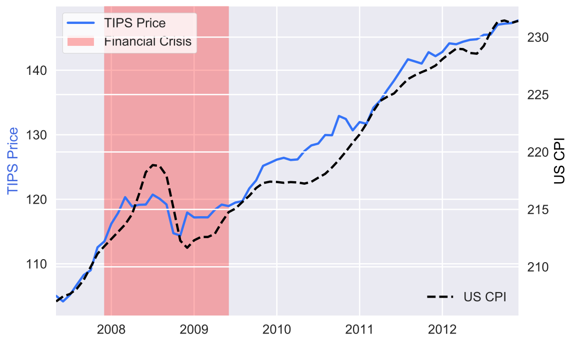
(b) Model and historical returns (**Maximum increase**)

Figure 10 – Downside risk predicted by the model compared to historical returns during the 2008 financial crisis (**USD Government Bonds**, for 2-year, 5-year and 10-year treasury bonds)

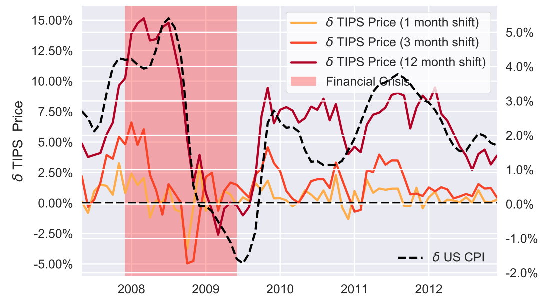
As can be seen on figure 9, returns on government bonds due to price appreciation were higher during the crisis thanks to higher demands driven by investors seeking for safe assets. Figure 10 confirms that bonds returns during the crisis match the VaR 4/5 upside tail of the return distribution provided by the model.

Since the interest rates were high before the crisis, there was a lot of room for US treasury bonds' price to appreciate and yield to decline. Due to the low interest rates environment now, no such major gains corresponding to the ones preceding the 2008 financial crisis can be expected anymore in the near future.

Figure 11 shows the historical price for US TIPS and the change in price using different time lags. Figure 12 compares the historical return of TIPS to returns of the model output.



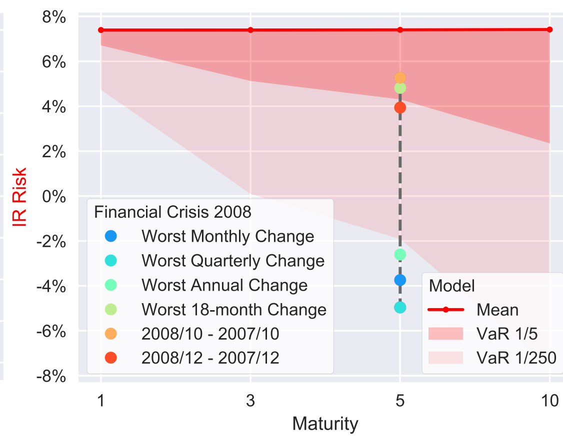
(a) Historical Data: Price Level



(b) Historical Data: Price Change

Figure 11 – Historical Data for **TIPS** (M=5) with CPI overlaid

(a) Mean change



(b) Maximum change

Figure 12 – Downside risk predicted by the model compared to historical returns during the 2008 financial crisis for TIPS (M=5)

The historical data for TIPS in figure 11 shows minor, short-term drops in return during the 2008 financial crisis. It is for this reason that the change in market value is at times negative when looked at on a monthly basis (yellow line in figure 11), but on a yearly basis there are only a few very slightly negative observation available for TIPS (dark red line on figure 11). Therefore, according to the rolling window and aggregation function chosen (mean or maximum of change), the return on TIPS varies strongly. This is reflected in figure 12, which shows that short-term, monthly returns seem to correspond to a 1/250 downside tail event in the model, while long-term, annual returns are more in the area of 1/5 events (positive return).

4.2.2 Corporate Bonds

Figure 13 shows historical yearly returns for three different USD corporate bonds, rated A, BBB and BB, respectively, highlighting the period of the 2008 financial crisis. Figure 14 compares the historical return of these Corporate Bonds to the returns of the model output. The average duration of the three corporate bond indices used was between 3.7 and 4.3 and maturities between 5.4 and 7.5 years, it was chosen to compare them against a corporate bond with a maturity of 5 years and a coupon rate of 2% across all ratings.

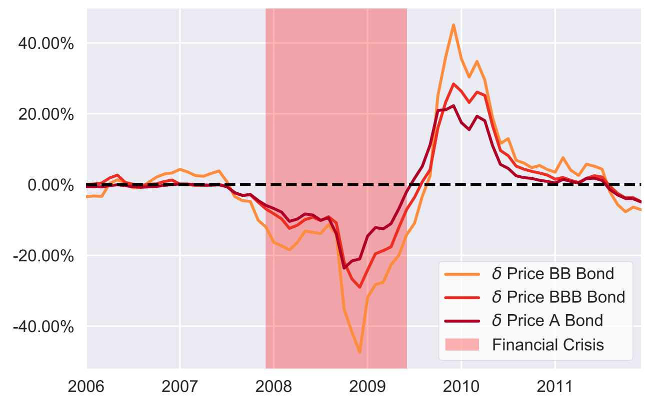
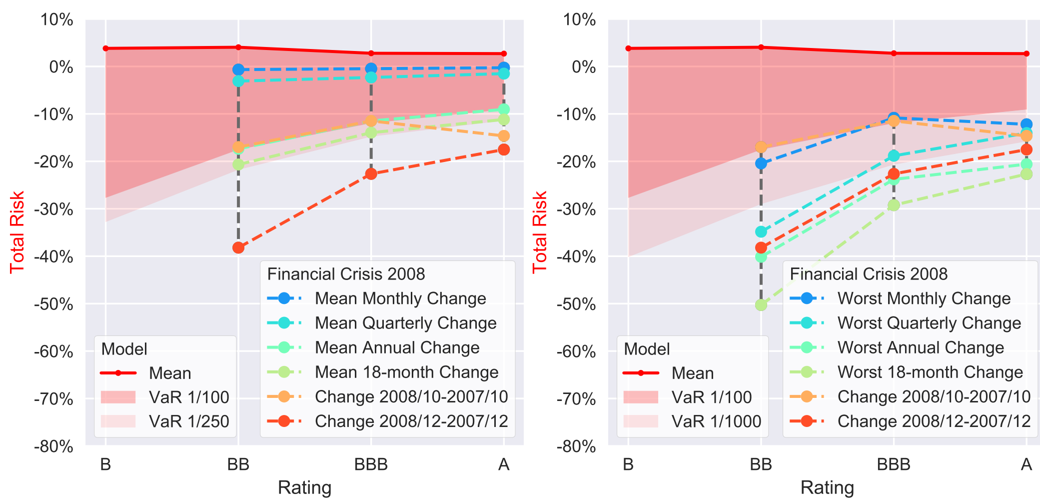


Figure 13 – Historical Data for USD Corporate Bonds: Price Change (yearly)



(a) **Mean change** (b) **Maximum change**

Figure 14 – Downside risk predicted by the model compared to historical returns during the 2008 financial crisis (**USD Corporate Bonds, M=5 years, C=2% annual**)

As can be seen in figure 13, corporate bonds experienced a sharp drop in returns during the 2008 financial crisis, with the higher rated bonds preserving most of their value.

The historical data seems to correspond roughly to the 1/100 and 1/250 downside risk predicted by the model when looking at the mean change indicator, while for the maximum change indicator, the historical data is matched more closely by the VaR 1/1000 downside risk of the distribution predicted by the model.

4.2.3 MBS

Historical price changes for MBS are shown in figure 15 and a comparison to the model output is shown in figure 16.

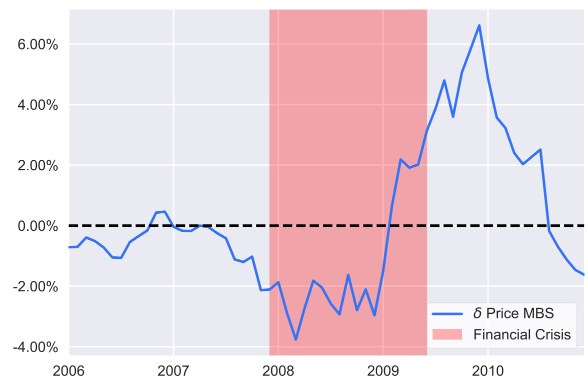
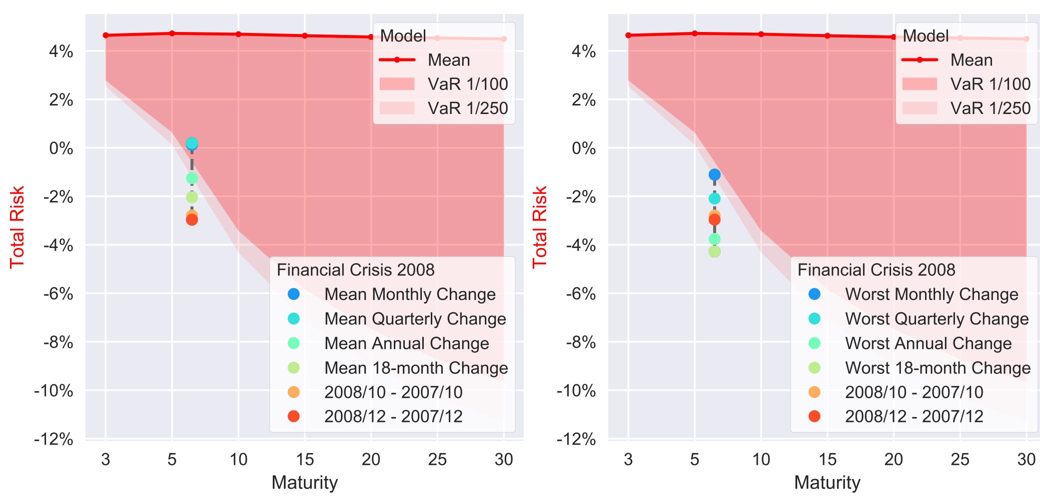


Figure 15 – Historical Price Change (yearly)



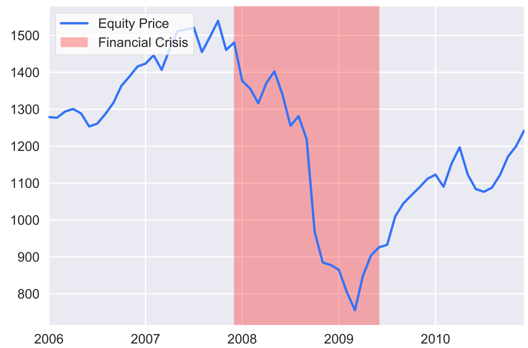
(a) **Mean Change** (b) **Worst Change**

Figure 16 – Downside risk predicted by the model compared to historical returns during the financial crisis 2008 (**MBS**, D=5 years, C=5% annual, R=AAA)

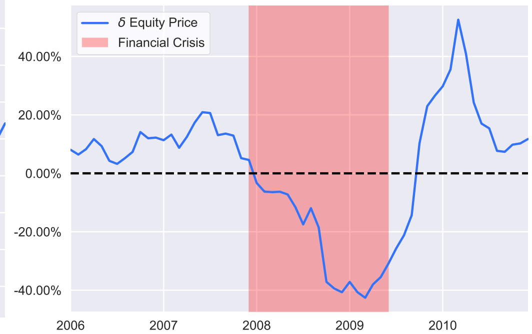
MBS returns during the crisis seem slightly below the VaR 1/250 downside risk of the return distribution provided by the model, indicating that MBS securities took a particularly hard hit during the 2008 financial crisis.

4.2.4 Equity

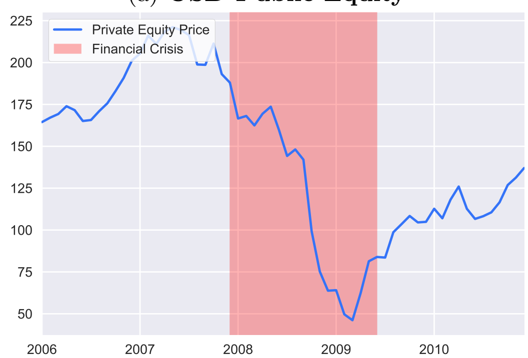
Historical price and return data for different types of equity investments is shown in figure 17 and comparisons to the model outputs are shown in figure 18.



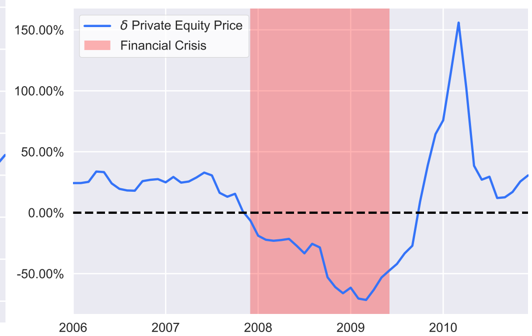
(a) **USD Public Equity**



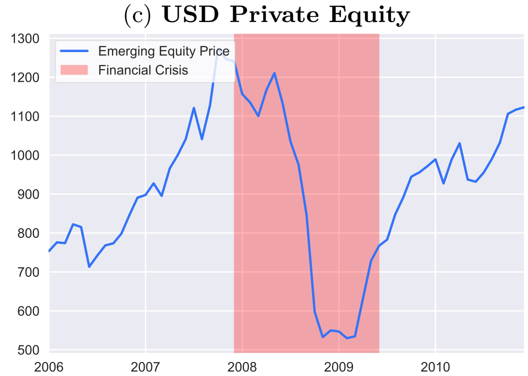
(b) δ **USD Public Equity**



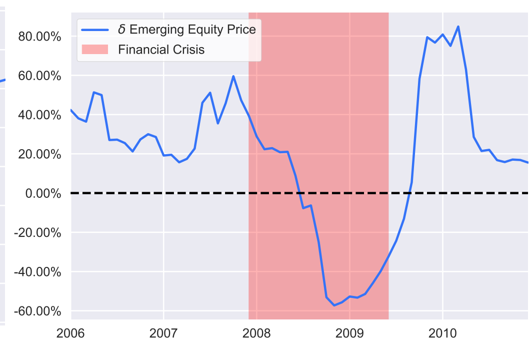
(c) **USD Private Equity**



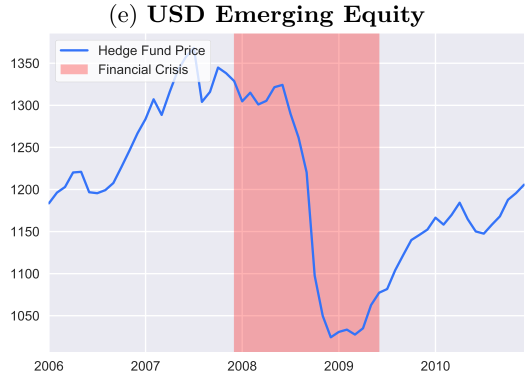
(d) δ **USD Private Equity**



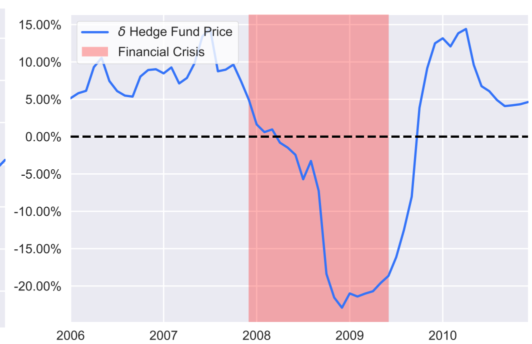
(e) **USD Emerging Equity**



(f) δ **USD Emerging Equity**

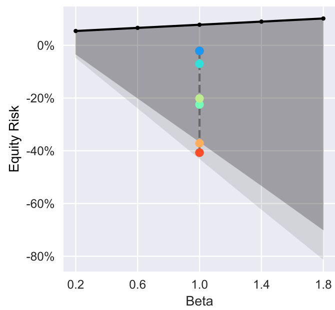


(g) **USD Hedge Fund**

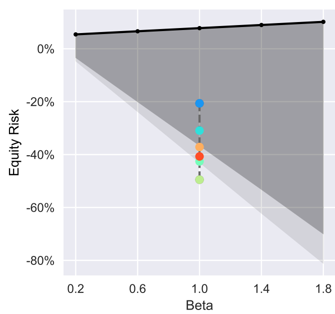


(h) δ **USD Hedge Fund**

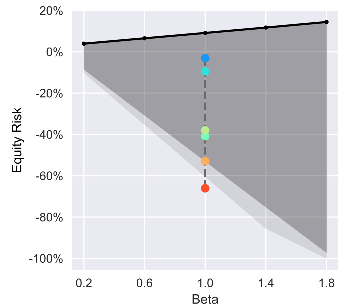
Figure 17 – Historical price and price change for equity-like asset classes during the 2008 financial crisis



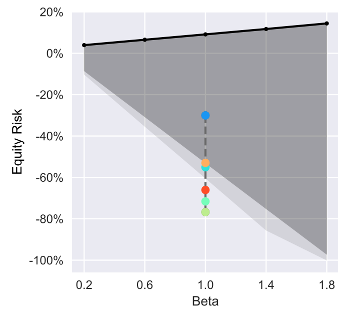
(a) **USD Public Equity**: mean



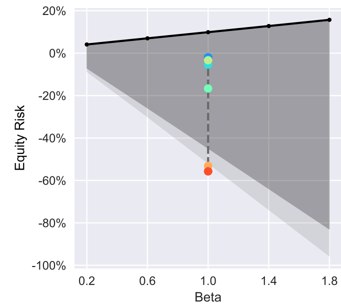
(b) **USD Public Equity**: max



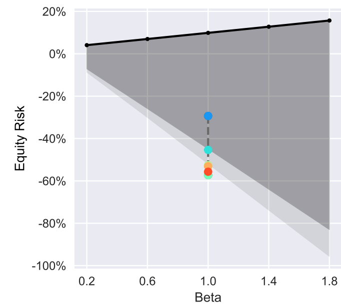
(c) **USD Private Equity**: mean



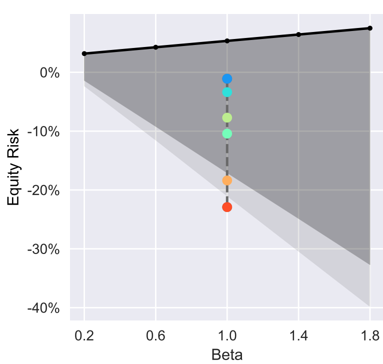
(d) **USD Private Equity**: max



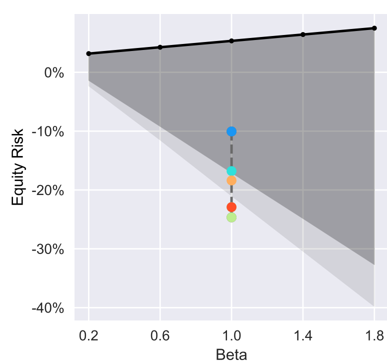
(e) **USD Emerging Equity**: mean



(f) **USD Emerging Equity**: max



(g) **USD Hedge Fund**: mean



(h) **USD Hedge Fund**: max

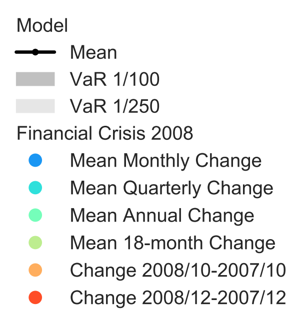


Figure 18 – Downside risk predicted by the model compared to historical returns during the 2008 financial crisis

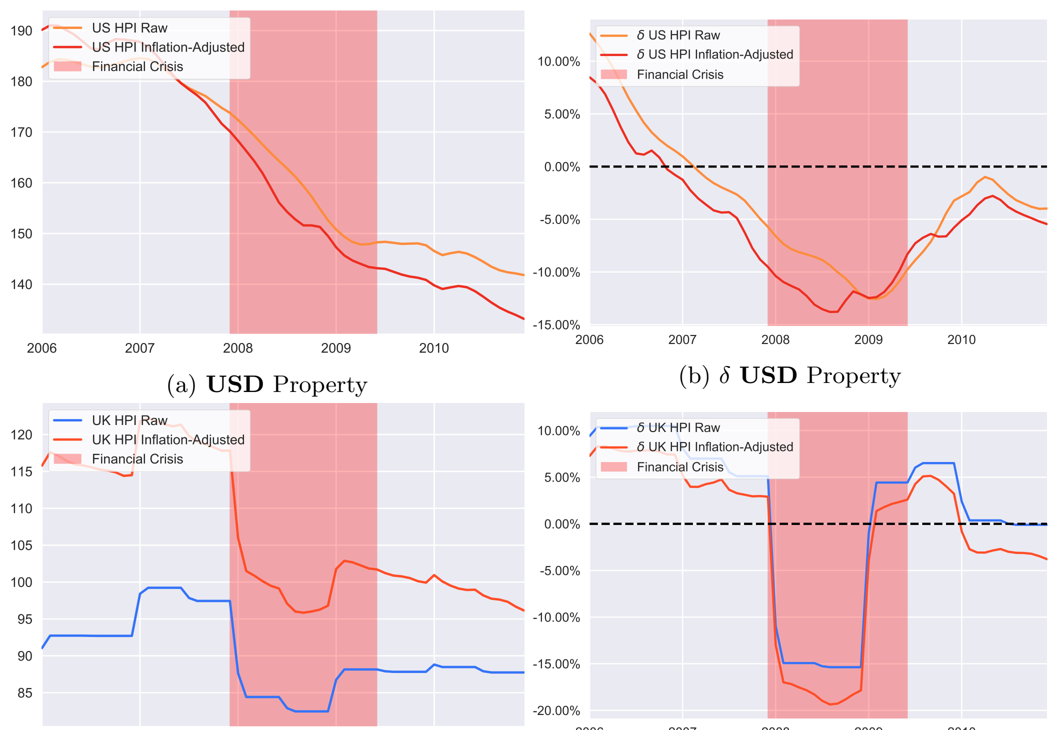
Figure 17 indicates losses in the order of -40% to -60% for different equity indices during the 2008 financial crisis.

Figure 18 indicates that returns of equity-like asset classes during the crisis match the VaR 1/100 -

VaR 1/250 downside risk of the return distribution provided by the model. Figure 18 also indicates that Hedge Funds, Private Equity and Emerging Equity were hit particularly hard during the 2008 financial crisis (shock in the order of a 1/250 event or greater) while the public equity market experienced a less severe drop (shock in the order of a 1/100 - 1/250 event).

4.2.5 Property

Figure 19 shows historical data for the GBP and USD Housing Price Index before and after inflation adjustment. Figure 20 and 21 compare historical returns of the Housing Market to returns produced by the model.



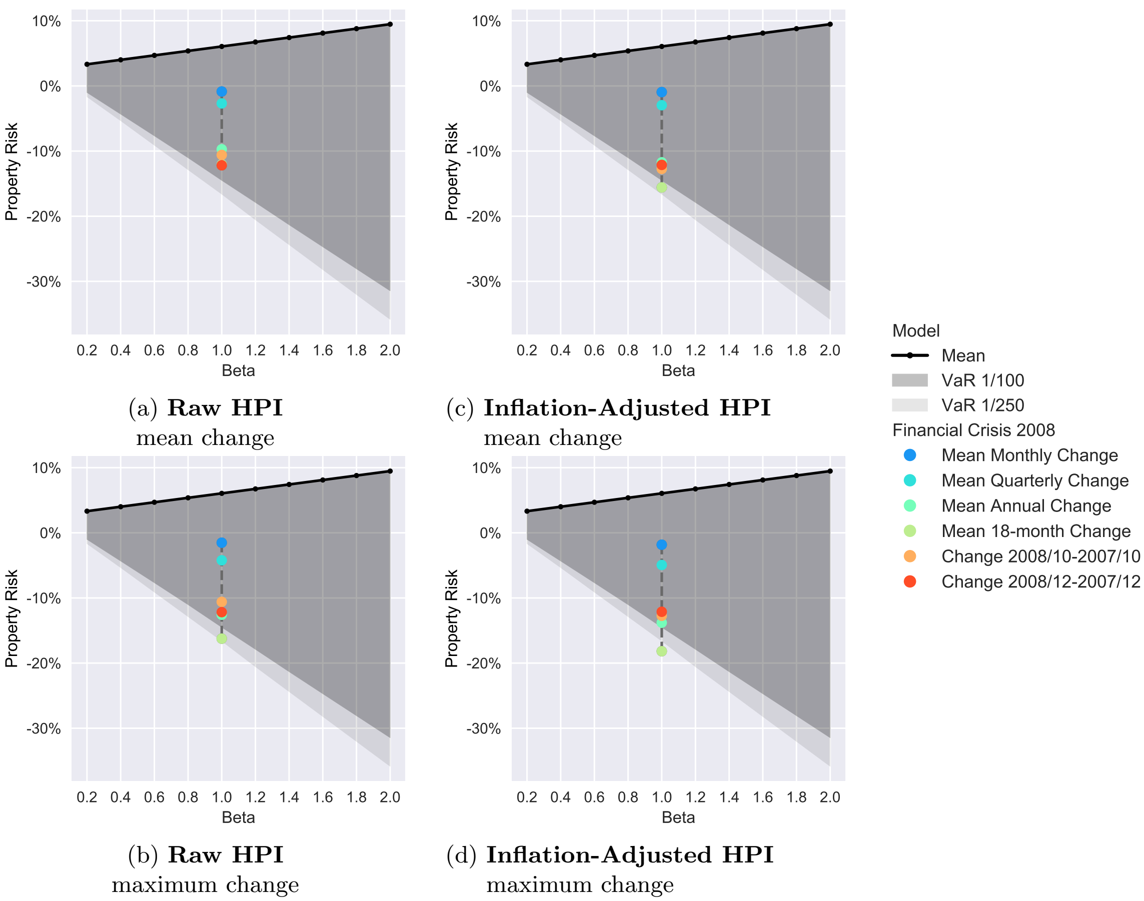
(a) **USD** Property

(b) δ **USD** Property

(c) **GBP** Property

(d) δ **GBP** Property

Figure 19 – Historical Price and Price Change Data for Property (Raw and Inflation-Adjusted)



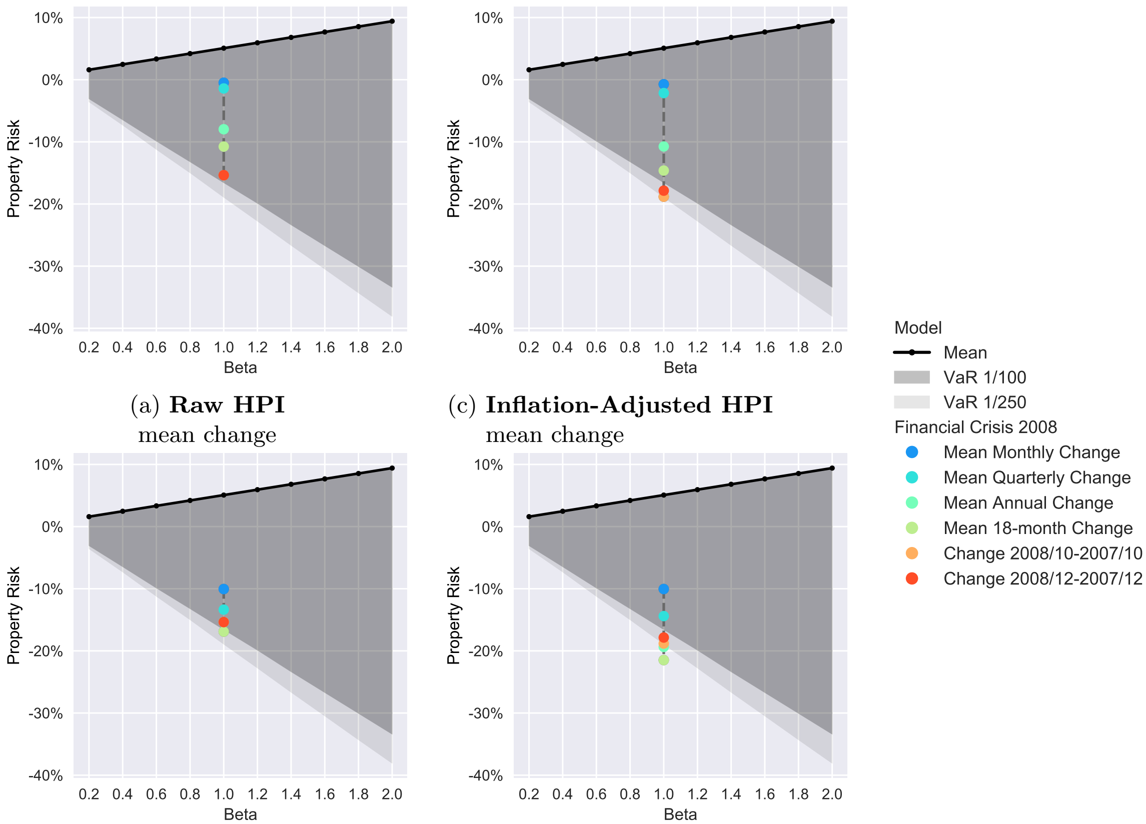
(a) **Raw HPI** mean change

(c) **Inflation-Adjusted HPI** mean change

(b) **Raw HPI** maximum change

(d) **Inflation-Adjusted HPI** maximum change

Figure 20 – Property Risk predicted by the model compared to historical returns during the 2008 financial crisis (**USD Property**)



(a) **Raw HPI** mean change

(c) **Inflation-Adjusted HPI** mean change

(b) **Raw HPI** maximum change

(d) **Inflation-Adjusted HPI** maximum change

Figure 21 – Property Risk predicted by the model compared to historical returns during the 2008 financial crisis (**GBP Property**)

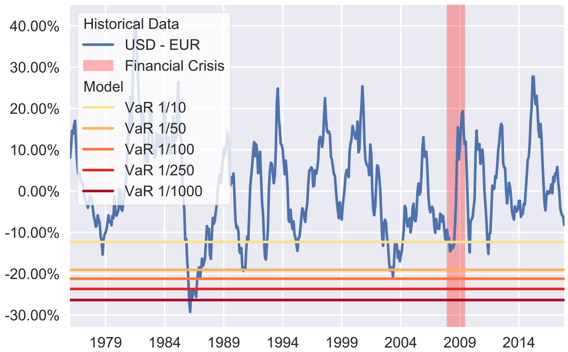
Figure 19 shows a pronounced decline in the HPI for both the USD and GBP markets. Although the GBP housing market experiences a more severe drop during the crisis, it experiences a more rapid recovery after the crisis compared to the USD housing market.

Figure 20 shows a drop in the housing returns during the 2008 financial crisis roughly corresponding to a 1/100 downside tail event predicted by the model. The drop for the GBP market corresponds more to a 1/250 downside tail event, which confirms the sharper decline in returns for the UK housing market during the 2008 financial crisis as seen in figure 19.

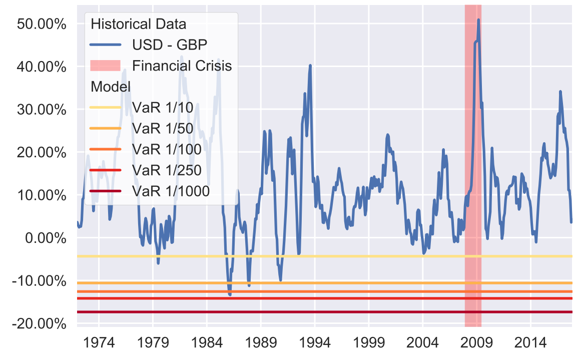
Overall, returns of USD and GBP Property during the crisis correspond to a VaR 1/100 - VaR 1/250 downside risk of the return distribution predicted by the model.

4.2.6 FX Risk

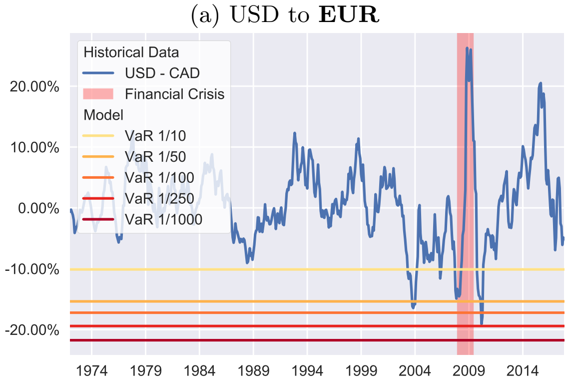
Historical FX rates from USD to EUR, GBP, CAD, SGD, JPY and CHF are shown in figure 22. FX downside tail risk thresholds predicted by the model are indicated in horizontal lines (yellow to red).



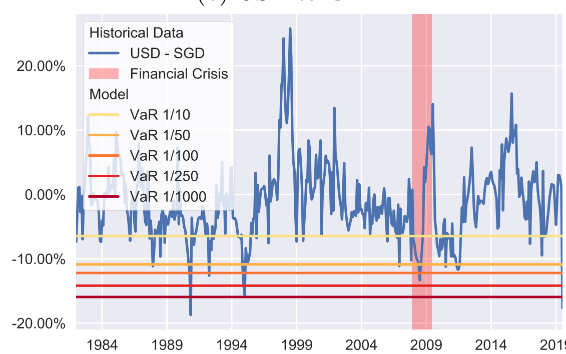
(a) USD to **EUR**



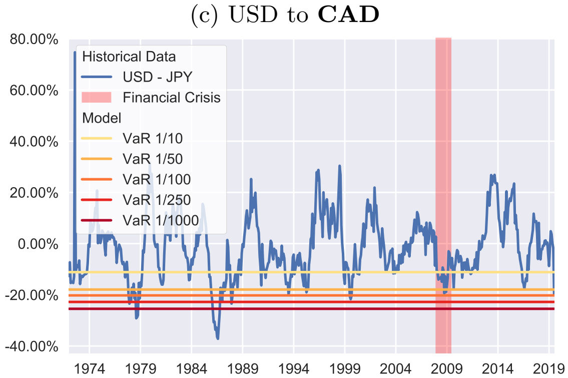
(b) USD to **GBP**



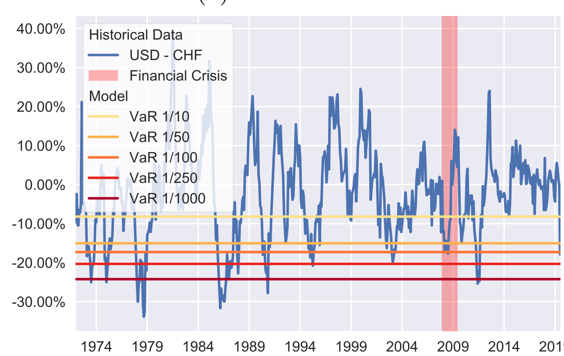
(c) USD to **CAD**



(d) USD to **SGD**



(e) USD to **JPY**



(f) USD to **CHF**

Figure 22 – Downside risk in predicted by the model compared to historical data (**FX Risk**, measured as percentage change of exchange rate over one year)

Historical FX seems to be well aligned with the model for all the modeled currencies. Yet, for some currencies, the VaR 1/100, which is used here as a baseline risk indicator for FX Risk, is exceeded several times, such as for SGD and CHF. This might be due to the fact that the model parameters are not only based on historical data but also on economic outlook. Given the uncertainties around the Brexit at the time of the run, it seems that GBP might have to be modeled more conservatively in future runs.

4.3 Modeling Approach Assessment

4.3.1 Comparison of Sensitivities across Asset Subclasses

First, it is verified that the return distribution and downside risk of USD equity are within a meaningful range, for which the modeled return distribution is compared against the historical return distribution of the S&P 500 index, which, due to the length of the time series and sector diversification is considered a reliable indicator for the purposes of this report. The comparison of modeled return periods for USD equity against historical shocks during the 2008 financial crisis as well as against historical return indicators according to the S&P 500 index is shown in fig. 23.

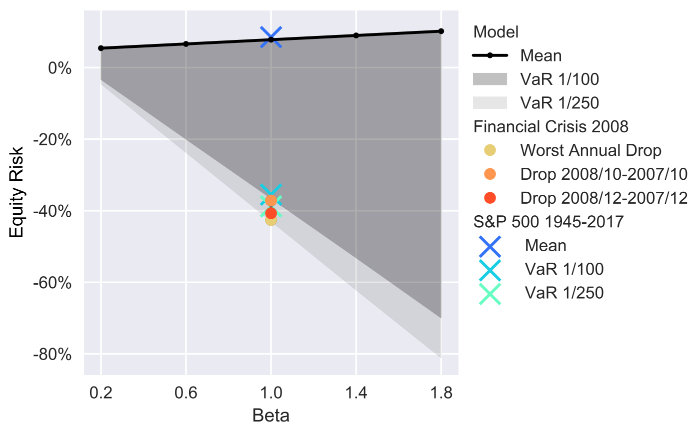
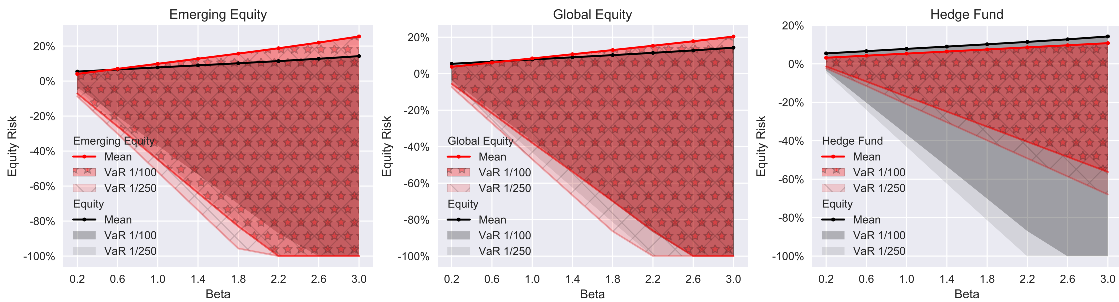


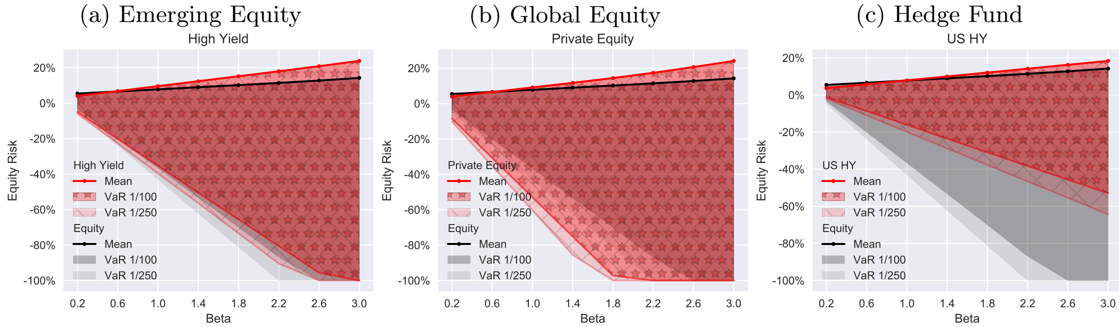
Figure 23 – USD Equity according to the asset model compared to S&P 500 from 1945 until 2017. Returns during the 2008 financial crisis are also indicated for comparison.

Figure 23 shows that the USD equity return distribution of the asset model closely matches the historical distribution of the S&P 500 index and can therefore be considered to be a validated baseline indicator.

Extra Indices Figure 8 compares the total return sensitivity of indices within "Extra Indices" to the total return sensitivity of USD equity.



(a) Emerging Equity (b) Global Equity (c) Hedge Fund



(d) High Yield (e) Private Equity (f) US HY

Figure 24 – Extra Indices: Sensitivity Results for Extra Indices, compared to USD equity (all in USD)

The indices showing an overall higher return and higher risk than USD equity are Emerging Equity, Global Equity and Private Equity. The Hedge Fund index shows a lower return and lower risk. The indices Global High Yield and US High Yield show a higher return, yet lower risk compared to US equity.

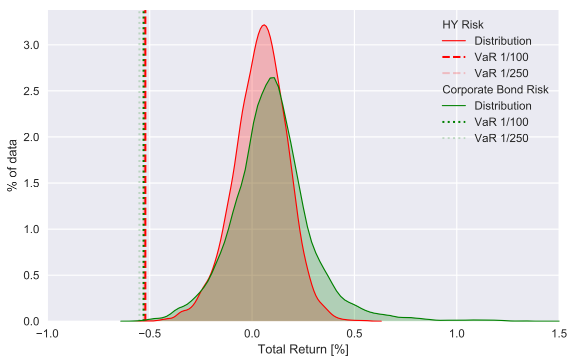
Equity-Like Indices The apparent matching betas between equity and each extra index are shown in table 7. Appendix figure D.1 shows the process of finding a matching beta for each equity-like index.

Extra Index	**Bloomberg Data**	**Apparent Matching Beta**
Emerging Equity	1.13	1.06
Global Equity	0.99	1.05
Hedge Fund	0.22	0.70
Private Equity	1.17	1.25

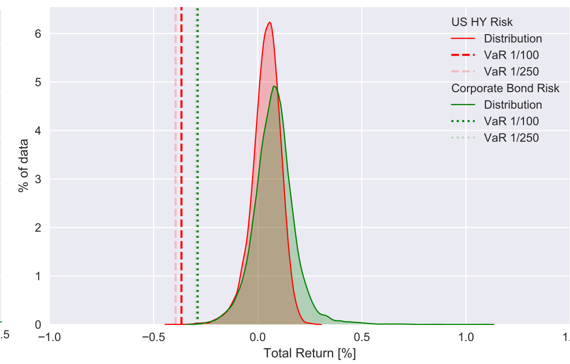
Table 7 – Index beta and apparent beta according to model for each equity-like index

The beta calibration of all extra indices seem to roughly match the index betas found on Bloomberg, with the exception of Hedge Funds. For the Hedge Fund index, the apparent matching beta is too high compared to the beta from the Bloomberg index. The lower beta of the Bloomberg index could be due to the time frame within which it is calculated, from 1998-2018. Including the pre-crisis period for the beta calculation might overstate the performance of Hedge Funds, therefore it was concluded that a beta around 0.7 as produced by the model matches the real Hedge Fund beta more accurately.

Fixed-Income Indices Figure 25 shows the modeled return distribution of non-equity-like indices versus modeled return distribution of a corporate bond with corresponding parameters.



(a) HY vs corporate bond (B, M=9, C=6%)



(b) US HY vs corporate bond (BB, M=5.5, C=6%)

Figure 25 – Comparison of Extra Indices against original asset class

The distributions of the original asset class with the parameters of table 6 match the fixed-income type extra indices. From figure 25, we can conclude that the tail risk of the fixed income securities is similarly close to the tail risk of the fixed-income-like indices.

4.3.2 Comparison of Sensitivities across Currencies

Public Equity Figure 26 shows mean return and downside tail risk for EUR and GBP compared to USD equity.

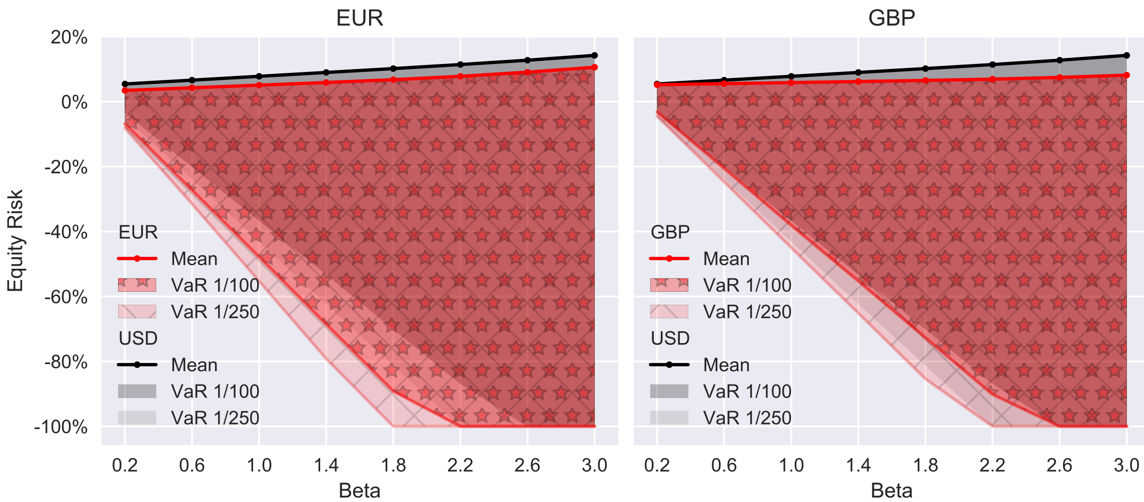


Figure 26 – Sensitivity test results for EUR and GBP Equity with respect to Beta, compared to the sensitivity of USD Equity with respect to beta.

Figure 26 shows lower expected returns and higher risk for both EUR and GBP equity compared to USD equity. EUR equity shows the highest risk of all modeled currencies. Although GBP has a lower return for high beta compared to EUR and USD, its return for low beta values is similar to the one of USD and higher than the return of EUR for a low beta value.

Private Equity Fig. 27 compares mean return and tail risk for EUR and USD private equity.

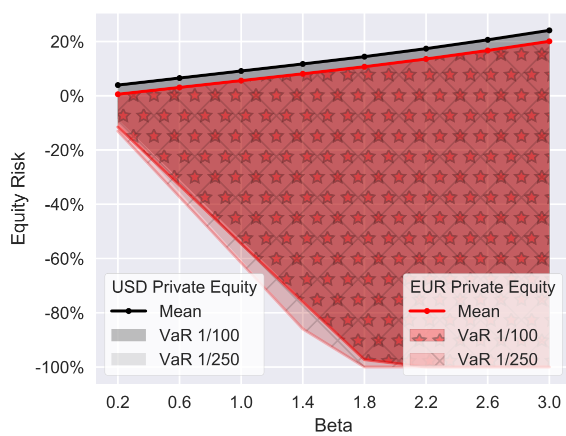


Figure 27 – Sensitivity test results for EUR Private Equity compared to USD Private Equity

EUR private equity shows a lower average return and similar tail asset risk compared to USD private equity.

Property Figure 28 shows mean return and downside tail risk for EUR and GBP property compared to USD property.

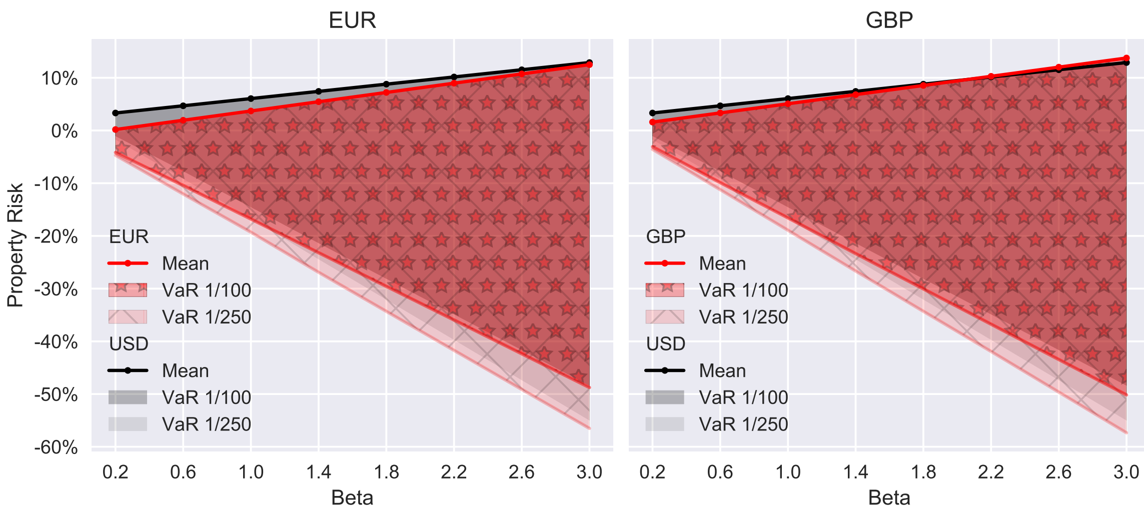


Figure 28 – Sensitivity test for EUR and GBP Property with respect to Beta, compared to the sensitivity of USD Property with respect to beta.

Similar to public equity, EUR Property and GBP Property have a lower return and higher risk compared to USD Property, with GBP property being slightly riskier than EUR property for high beta values. EUR Property shows the lowest return of all modeled currencies.

4.3.3 Matching of Non-Modeled Currencies

Table 8 shows the closest matched currency for all currencies which are present in PRE's investment portfolio but which cannot be modeled due to computation time limitations. Detailed figures showing the process of matching currencies are shown in appendix E.

Original currency	⟶	Proxy currency
Government Bonds		**fig. E.1, E.2, E.3**
CNY	⟶	SGD
JPY	⟶	SGD
CHF	⟶	EUR
Corporate Bonds		**fig. E.4, E.5, E.6, E.7**
CNY	⟶	CAD
JPY	⟶	(CAD)*
Equity		**fig. E.8, E.9**
CNY	⟶	(EUR)*
JPY	⟶	(CAD)*

* Based on numerical comparisons between distributions, requiring additional expert judgment

Table 8 – Closest overall match by asset class from each unmodeled currency to one of the modeled currencies

It is possible to further split up the closeness of unmodeled currencies to modeled currencies into the risk sources of each asset class:

1. **CNY**
   (a) **Government Bond** (fig. E.1): SGD seems to match the IR Risk of CNY best for government bonds.
   (b) **Corporate Bond** (fig. E.4, E.5)
      - IR Risk: SGD most closely matches CNY
      - Spread Risk: Again, SGD and CAD most strongly match CNY
      - Total Risk: CAD most closely matches CNY both for A- and B-rated corporate bonds
   (c) **Equity**, Equity Risk (fig. E.8): EUR seems to match CNY best in terms of VaR 1/250.
2. **JPY**
   (a) **Government Bond** (fig. E.2): SGD seems to match the IR Risk of JPY best for government bonds.
   (b) **Corporate Bond** (fig. E.6, E.7)
      - IR Risk: No other currency matches JPY well, however SGD matches its mean return quite well, while CAD seems to perform best for downside risk, given that it is slightly more conservative in the downside than SGD.
      - Spread Risk: Again, no other currency matches JPY well.
      - Total Risk: Again, no other currency matches JPY well, but CAD seems to be closest overall.

(c) **Equity**, Equity Risk (fig. E.9): JPY seems to be best matched by CAD.

3. **CHF**, **ZCB**, Interest Rate Risk (fig. E.3): EUR seems to best reproduce the risk distribution and tail asset risk of CHF, although CAD also shows a similar tail asset risk.

5 Discussion

Overall, the asset model currently used by PRE correctly assesses risks for the asset classes in PRE's portfolio of invested assets both in terms of parameter sensitivity and in terms of its relation to empirical data. In particular, the sensitivity analysis yielded the following insights:

- Section 4.1.1, Government Bonds: the findings on government bonds make sense as higher coupon leads to a shorter duration with all other parameters the same and thus negative correlation, longer maturity leads to longer duration and thus positive correlation.
- Section 4.1.2, Corporate Bonds: the findings on corporate bonds make sense, lower credit rating leads to a wider spread and higher spread volatility and thus higher spread risk, interest rate risk is not dependent on credit rating but durations, longer maturity also leads to higher spread duration, i.e., more sensitive to spread movement. Higher coupon also leads to a shorter spread duration, i.e., less sensitive to spread movement. Interest Rate and spread risk usually are diversifiers with an exception of 1970s and 1980s hyperinflation when both the interest rate and spread spiked.
- Sections 4.1.4 and 4.1.5, Equity and Property: the findings on Equity and Property make sense as higher beta means higher volatilities relative to market, i.e., higher downside risk.
- Section 4.1.3, MBS: the findings on MBS make sense in terms of the magnitude and direction of the sensitivites.
- Section 4.1.6, Extra Indices: all the findings make sense and show that higher beta leads to higher risk for all indices.

From the results above, we conclude that the direction and magnitude of changes in parameters make sense in all cases for the modeled asset classes. In terms of the Empirical Validation, the following insights can be gained:

- Section 4.2.1, Government Bonds: The findings on government bonds make sense, as returns on government bonds increased during the crisis thanks to higher demands driven by investors seeking for safe assets.
- Section 4.2.2, Corporate Bonds: The findings on corporate bonds make sense, as corporate bond returns were negative during the crisis.
- Section 4.2.3, MBS: The findings on MBS make sense, as MBS returns were negative during the crisis.
- Sections 4.2.4 and 4.2.5, Equity and Property: The findings on equity and property make sense, as equity and property returns were negative during the crisis.
- Section 4.2.6, FX Risk: The findings on FX risk make sense given the historical drops in conversion rates and the current economic outlook for the modeled currencies.

All mentioned studies taken together, we conclude that the current modeling approach is accurate overall and in line with expectations of the Risk Operations team. Yet, there are a number of important limitations on the asset model which are mentioned in table 9. Specifically, it lists a number of technical and conceptual limitations of the asset models, the potential impact of these limitations and possible improvements.

Limitation	**Potential Impact of the Limitation**	**Possible Improvements**
Non-agency and agency MBS are currently modeled in the same way	Non-agency MBS may have a higher risk due to possible defaulting of security issuer	Model as MBS with underlying curve of type "risk" and a rating below AAA
Non-rated alternative credit (principal finance) is currently modeled as corporate bonds with a BB rating	Non-rated assets may have highly different attached total return distributions and downside tail risks	Scenario modeling using risk summary tables to assess vulnerability (using appendix A)) / Manual refinements into more granular risk categories by searching for company credit ratings
All private equity is currently modeled as USD	Emerging markets may have a higher volatility than the US equity market. Non-USD private equity only makes up 0.25% of the total portfolio and 10% of all the private equity ($\sim$ 40 mio \$)	Modeling EUR equity as USD equity with corresponding beta (fig. 27) / model separately / Software solution
Only 5 currencies at a time can be modeled currently in IGLOO	Assets in unmodeled currencies may show different returns than assets in modeled currencies. Around 1.5% of the total portfolio of invested assets are in other currencies ($\sim$ 250 mio \$)	Scenario modeling using risk summary figures to assess vulnerability (using appendix E) / Use closest matching currency

Table 9 – Current limitations of the asset model, potential impacts and improvements

Further applications may be based on the model outputs and loss distributions given in the summary tables in appendix A:

1. Calculation of economic returns per asset classes using single or multiple economic scenarios.
2. Stress testing using scenario modeling, such as a financial crisis, a real estate crisis or an inflation spike.
3. Dynamic visualization and monitoring of risks present in the portfolio given the current economic environment.

6 Conclusion

Due to the changing market environment of reinsurance and a more aggressive investments strategy leading to newer, more exotic investments, asset models are becoming increasingly complex. In order for decision makers to gain confidence in the increasingly complex asset models provided by commercial software vendors, there is a need for a simple, yet coherent methodology allowing company stakeholders to validate an asset model.

This work aims at contributing to the purpose of validating an asset model without knowing all its internal details. In particular, the following contributions have been achieved:

1. A methodology for identifying relevant parameter ranges in order to compare the sensitivities of common asset classes.
2. An empirical validation has been performed on all major asset classes represented in PRE's investment portfolio, specifically comparing returns of the 2008 financial crisis to the downside risk predicted by the model. A simple methodology has been proposed to validate the FX risk predicted by the model against historical returns.
3. A methodology for comparing model outputs has been proposed, in particular:
    (a) Comparing downside risk between different currencies
    (b) Comparing downside risk between different indices provided to model asset subclasses
    (c) Comparing the returns of asset classes in non-modeled currencies to asset classes in modeled currencies

While the results shown have been produced under the mandate of PRE's Risk Operations team, the results of this work aim at generalizing the methodology used for the validation procedure and providing a baseline for future asset model validation studies. Ultimately, this work sets the stage for the end-to-end validation of a black-box asset model, using simple statistical tools which can be applied to the most widely-spread asset models.

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7 Appendix

A Model Results

The following tables contain downside risks according to the asset model for each modeled asset class.

Asset Class	Currency	Asset Maturity	VaR 1/100 IR	VaR 1/250 IR	VaR 4/5 IR
Government Bond, ZCB	**USD**	**3**	-3.14%	-3.79%	4.71%
		5	-8.44%	-9.64%	6.64%
		10	-17.70%	-20.34%	10.45%
	EUR	**3**	-4.52%	-5.18%	0.64%
		5	-7.87%	-8.79%	1.85%
		10	-14.78%	-16.83%	4.63%
	CAD	**3**	-3.19%	-3.94%	3.53%
		5	-6.91%	-7.99%	4.90%
		10	-12.98%	-14.78%	7.37%
	CHF	**3**	-4.19%	-4.63%	0.36%
		5	-6.81%	-7.91%	1.40%
		10	-13.41%	-15.18%	4.03%
Government Bond	**USD**	**3**	-2.89%	-3.51%	4.62%
		5	-7.63%	-8.81%	6.37%
		10	-15.13%	-17.43%	9.48%
	EUR	**3**	-4.36%	-4.99%	0.58%
		5	-7.41%	-8.25%	1.68%
		10	-13.14%	-14.85%	4.02%
	CAD	**3**	-2.98%	-3.70%	3.46%
		5	-6.34%	-7.32%	4.69%
		10	-11.37%	-12.98%	6.67%
TIPS	**USD**	**3**	1.26%	0.11%	9.61%
		5	-0.68%	-1.90%	10.41%
		10	-5.75%	-7.54%	12.44%

Table A.1 – Total Return (in %) by risk type for **Government Bonds**

Asset Class	Currency	Asset Maturity	VaR 1/100 IR	VaR 1/100 Spread	VaR 1/100 Total	VaR 1/250 IR	VaR 1/250 Spread	VaR 1/250 Total	δS VaR 1/100[1]	δS VaR 1/250[1]
Corporate Bond, R=B	**USD**	**3**	-2.86%	-26.62%	-22.48%	-3.49%	-31.98%	-27.10%	917.80	1,102.75
		5	-7.50%	-32.94%	-27.08%	-8.67%	-39.65%	-32.12%	716.04	862.02
		10	-14.28%	-40.20%	-33.57%	-16.54%	-47.58%	-38.53%	490.30	580.19
	EUR	**3**	-4.34%	-30.42%	-29.96%	-4.97%	-36.53%	-36.02%	1,049.10	1,259.49
		5	-7.30%	-38.84%	-37.02%	-8.13%	-45.35%	-42.62%	844.35	985.79
		10	-12.22%	-42.40%	-40.36%	-13.73%	-48.54%	-46.37%	517.13	591.97
	CAD	**3**	-2.96%	-23.42%	-20.41%	-3.68%	-28.74%	-25.40%	807.59	991.21
		5	-6.25%	-28.46%	-24.10%	-7.22%	-33.97%	-28.86%	618.79	738.55
		10	-10.89%	-34.49%	-29.79%	-12.42%	-40.46%	-33.77%	420.59	493.46
Corporate Bond, R=BB	**USD**	**3**	-2.87%	-16.44%	-11.84%	-3.50%	-20.87%	-16.21%	566.87	719.54
		5	-7.55%	-22.83%	-16.99%	-8.73%	-27.43%	-21.22%	496.22	596.29
		10	-14.63%	-31.75%	-25.29%	-16.90%	-38.35%	-30.01%	387.19	467.72
	EUR	**3**	-4.35%	-21.60%	-20.60%	-4.98%	-26.76%	-26.31%	744.79	922.80
		5	-7.35%	-29.15%	-27.35%	-8.18%	-35.22%	-33.60%	633.60	765.73
		10	-12.72%	-36.64%	-35.03%	-14.32%	-42.38%	-40.53%	446.83	516.77
	CAD	**3**	-2.97%	-14.71%	-11.41%	-3.69%	-19.98%	-16.28%	507.40	688.87
		5	-6.29%	-18.98%	-15.15%	-7.26%	-24.30%	-19.79%	412.60	528.16
		10	-11.10%	-25.37%	-21.08%	-12.64%	-31.05%	-25.79%	309.39	378.60
Corporate Bond, R=BBB	**USD**	**3**	-2.88%	-11.48%	-7.28%	-3.51%	-14.78%	-10.53%	395.92	509.79
		5	-7.60%	-16.30%	-11.59%	-8.77%	-20.06%	-14.38%	354.35	436.03
		10	-14.91%	-23.82%	-19.76%	-17.19%	-29.25%	-23.47%	290.52	356.66
	EUR	**3**	-4.36%	-11.65%	-10.97%	-4.99%	-15.85%	-15.58%	401.78	546.69
		5	-7.39%	-18.85%	-17.34%	-8.22%	-23.89%	-22.30%	409.89	519.36
		10	-12.95%	-27.71%	-26.67%	-14.61%	-33.63%	-32.45%	337.93	410.10
	CAD	**3**	-2.97%	-8.20%	-4.95%	-3.70%	-10.91%	-7.74%	282.71	376.06
		5	-6.31%	-11.13%	-8.16%	-7.28%	-14.55%	-10.62%	242.00	316.25
		10	-11.20%	-16.50%	-14.00%	-12.77%	-20.44%	-16.73%	201.26	249.29
Corporate Bond, R=A	**USD**	**3**	-2.88%	-7.94%	-4.25%	-3.51%	-10.79%	-6.65%	273.65	372.20
		5	-7.61%	-11.99%	-8.75%	-8.79%	-15.01%	-11.07%	260.65	326.23
		10	-15.00%	-18.76%	-16.79%	-17.28%	-23.94%	-19.34%	228.79	291.97
	EUR	**3**	-4.36%	-7.69%	-7.11%	-4.99%	-11.04%	-10.03%	265.03	380.56
		5	-7.39%	-13.14%	-12.05%	-8.23%	-17.35%	-15.61%	285.57	377.10
		10	-13.03%	-21.86%	-21.90%	-14.71%	-27.02%	-25.88%	266.63	329.56
	CAD	**3**	-2.98%	-4.69%	-2.59%	-3.70%	-6.50%	-4.05%	161.76	224.19
		5	-6.31%	-7.26%	-5.77%	-7.29%	-9.91%	-7.36%	157.75	215.38
		10	-11.24%	-12.17%	-11.83%	-12.82%	-15.23%	-13.72%	148.46	185.74
Corporate Bond, R=AA	**USD**	**3**	-2.88%	-5.19%	-2.91%	-3.51%	-7.09%	-4.09%	178.81	244.60
		5	-7.61%	-9.07%	-7.48%	-8.79%	-11.72%	-9.46%	197.20	254.79
		10	-15.03%	-15.98%	-15.83%	-17.31%	-20.56%	-18.37%	194.85	250.71
	EUR	**3**	-4.36%	-5.21%	-4.94%	-4.99%	-7.64%	-7.00%	179.64	263.38
		5	-7.40%	-10.66%	-9.88%	-8.24%	-13.71%	-12.44%	231.75	298.05
		10	-13.08%	-19.93%	-20.14%	-14.77%	-24.33%	-23.51%	243.02	296.73
	CAD	**3**	-2.98%	-4.70%	-2.96%	-3.70%	-6.86%	-4.17%	161.93	236.39
		5	-6.32%	-6.86%	-6.16%	-7.31%	-9.35%	-7.36%	149.13	203.24
		10	-11.31%	-10.92%	-11.81%	-12.90%	-13.60%	-13.68%	133.21	165.79

Table A.2 – Total Return (in %) by risk type for **Corporate Bonds** and spread widening (in bps)

Asset Class	Currency	Asset Maturity	VaR 1/100 IR	VaR 1/100 Spread	VaR 1/100 Total	VaR 1/250 IR	VaR 1/250 Spread	VaR 1/250 Total	δS VaR 1/100[1]	δS VaR 1/250[1]
MBS	**USD**	**5**	-1.45%	-1.92%	-0.09%	-1.94%	-2.57%	-0.77%	41.82	55.82
		10	-5.57%	-4.97%	-4.19%	-6.40%	-6.24%	-5.60%	60.59	76.09
	EUR	**5**	-3.40%	0.80%	0.19%	-3.84%	0.20%	-0.41%	-17.38	-4.38
		10	-5.96%	-2.20%	-3.47%	-6.74%	-3.33%	-4.43%	26.84	40.58
	CAD	**5**	-1.67%	-1.25%	0.33%	-2.10%	-1.86%	-0.33%	27.13	40.42
		10	-4.49%	-4.13%	-2.93%	-5.32%	-5.44%	-4.03%	50.35	66.40

Table A.3 – Total Return (in %) by risk type for **MBS** and spread widening (in bps)

Asset Class	Asset Currency	VaR 1/100 Equity	VaR 1/250 Equity
Public Equity	**USD**	-36.60%	-42.99%
	EUR	-47.85%	-55.29%
Private Equity	**USD**	-52.99%	-60.33%
	EUR	-54.55%	-61.57%

Table A.4 – Total Return (in %) by risk type for **Equity**

Asset Class	Asset Currency	VaR 1/100 Property	VaR 1/250 Property
Real Estate	**USD**	-14.50%	-16.61%
	EUR	-16.79%	-19.30%
	GBP	-16.57%	-18.92%

Table A.5 – Total Return (in %) by risk type for **Real Estate**

Asset Class	Asset Currency	VaR 1/100 Equity	VaR 1/250 Equity
Hedge Fund	**USD**	-17.08%	-21.02%
Emerging Market Equity	**USD**	-44.92%	-51.95%

Table A.6 – Total Return (in %) by risk type for **Extra Indices**

[1] using the following mapping from maturity to duration:

M	3	5	10
↓	↓	↓	↓
D	2.9	4.6	8.2
(C=	2%	3%	5%)

(discount rate = 2%)

B Special Parameters

For the sensitivity analysis of MBS total returns, the following parameters have been tested in addition to the parameters listed in table 2

- **APP**: The number of payments that have already taken place at the date of the model
- **PSA**: The used method for measuring the probability of repayment of a loan for a given year as a probability rising year-by-year by a constant factor $PSA_f \times 0.2$ and reaching a threshold level at which it stays after t =30 years. Where PSA_f determines the slope of the curve and the prepayment probability level reached after year 30. PSA is calculated as follows:

$$PSA(t) = \min(t, 30) \times 0.2 \times PSA_f$$

A visualization of PSA for different factors is shown in figure B.1.

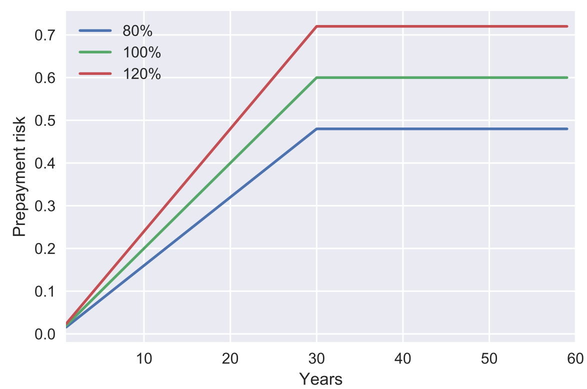


Figure B.1 – PSA parameter for prepayment risk, using different PSA factors

- **Refinancing Spread**: This parameter only applies to the OTS prepayment method, which is an alternative model for prepayment risk (see asset model documentation, p. 62), therefore, it can be safely ignored.

C Bloomberg Data

Sample Bloomberg Data for an equity-like index used in section 4.3 is shown in figure C.1.

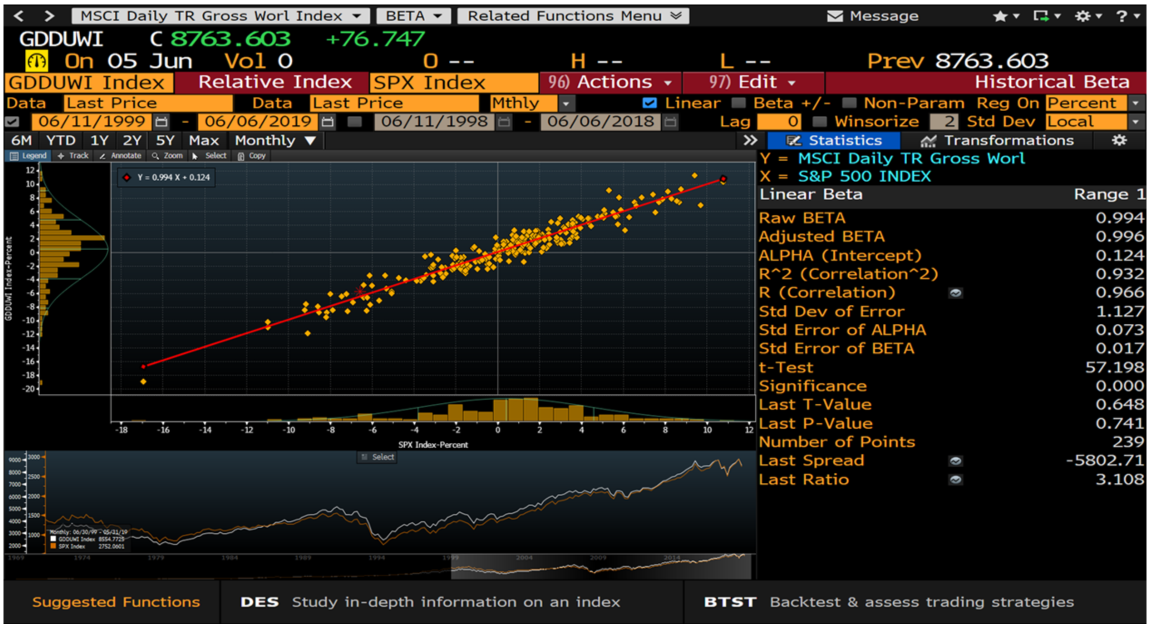
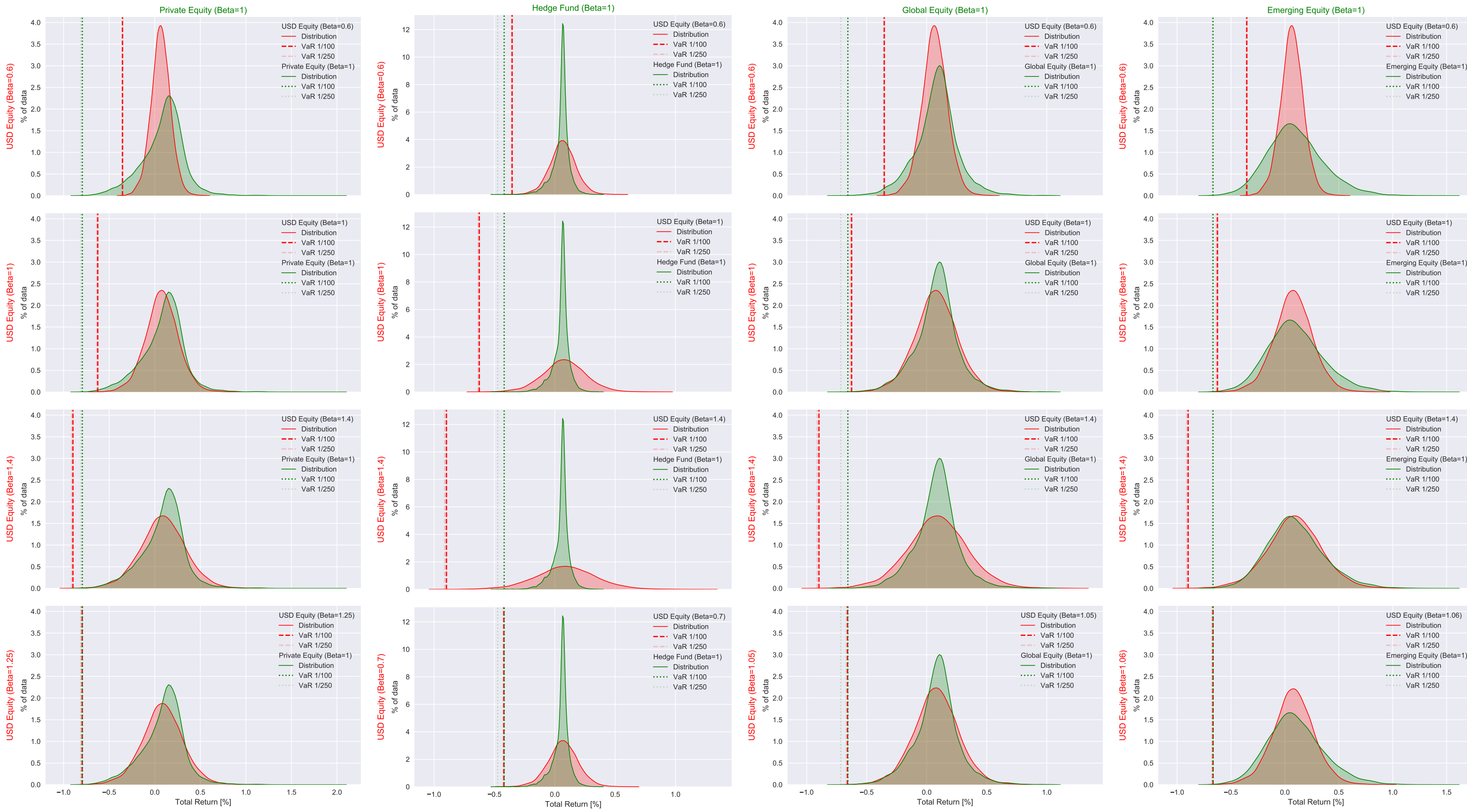


Figure C.1 – Sample Bloomberg Data Screenshot for Global Equity (GDDUWI)

D Asset Class Matching



(a) Private Equity (b) Hedge Fund (c) Global Equity (d) Emerging Equity

Figure D.1 – Equity-like indices compared against US equity for several betas (apparent matching beta on bottom line)

E Currency Matching

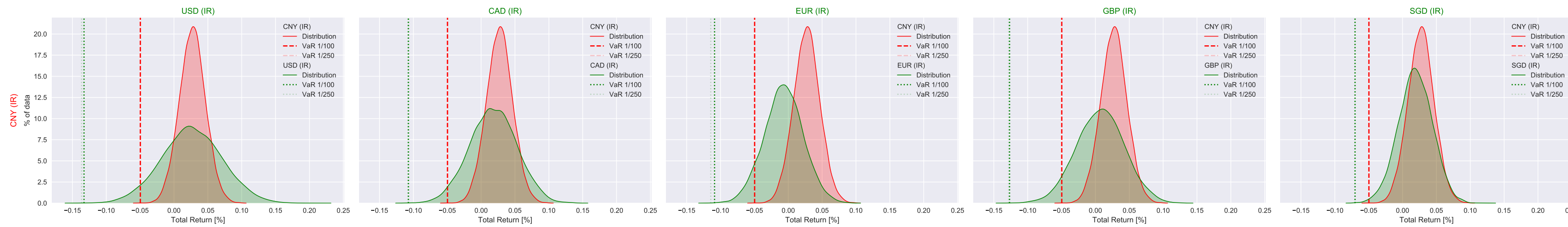


Figure E.1 – Compared Currencies for **CNY** (**government bond**, M=5 years, C=3% annual, Hold & Reset)

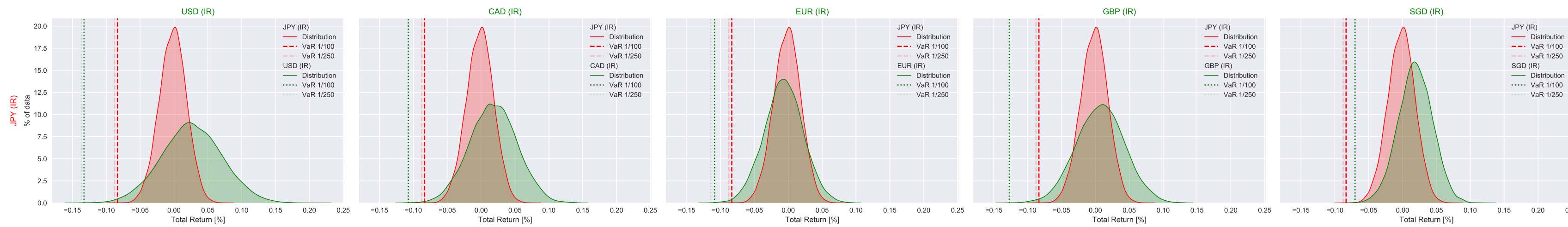


Figure E.2 – Compared Currencies for **JPY** (**government bond**, M=5 years, C=3% annual, Hold & Reset)

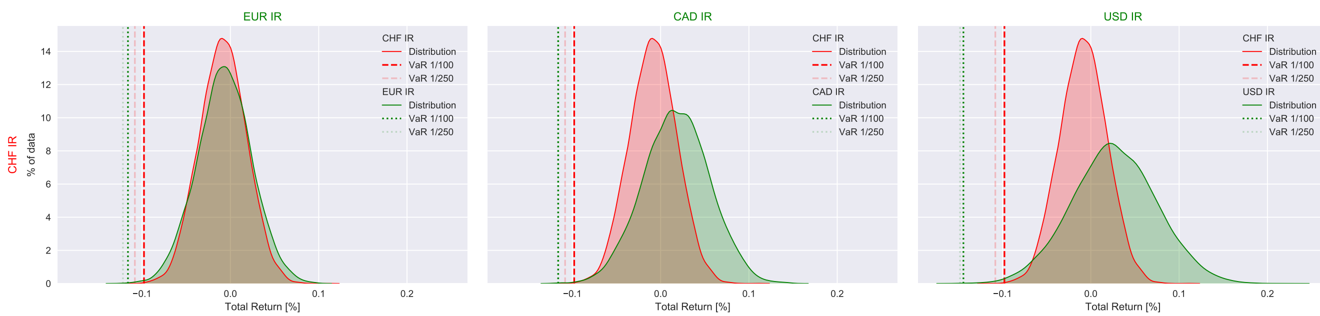
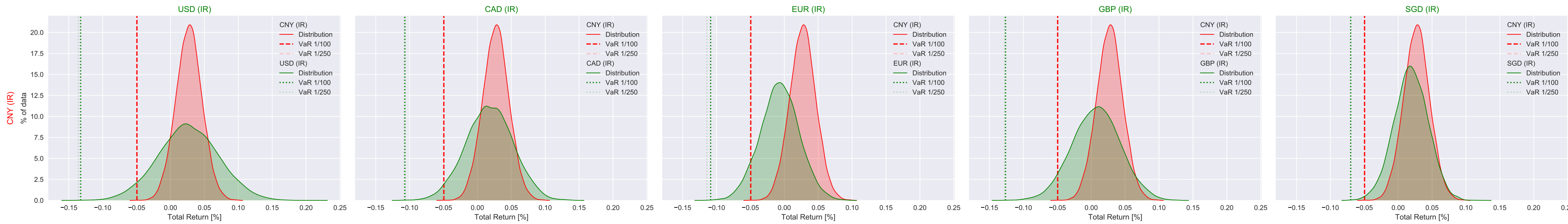
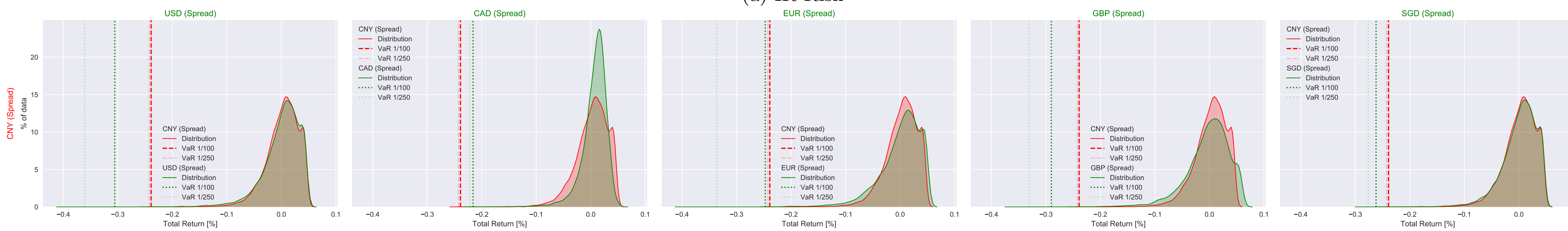


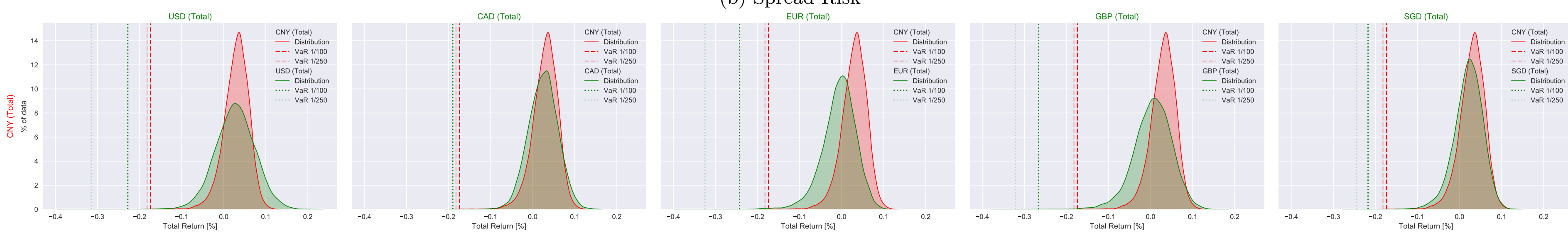
Figure E.3 – Compared Currencies for **CHF** (**Government ZCB**, M=5 years, Hold & Reset)



(a) IR Risk

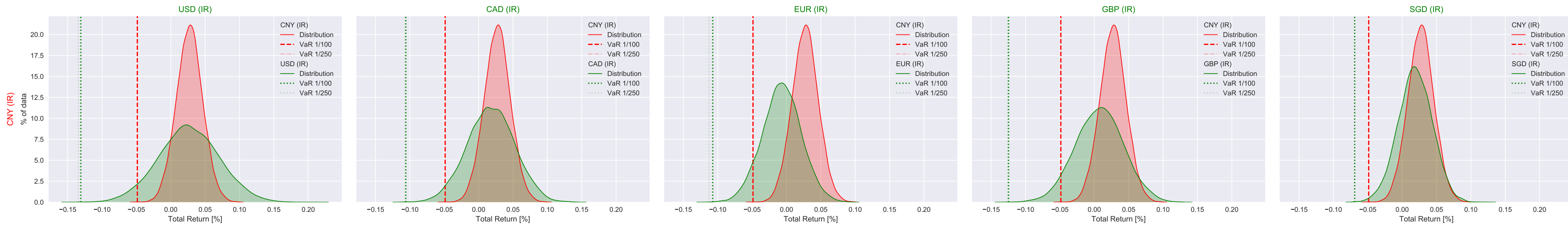


(b) Spread Risk

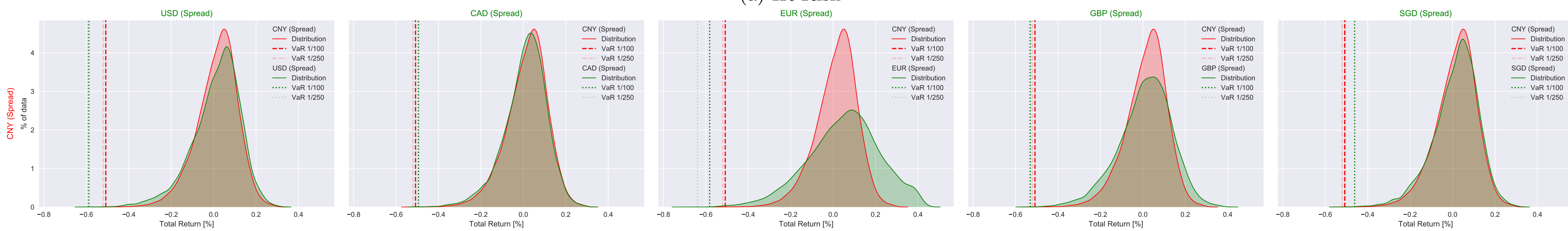


(c) Total Risk

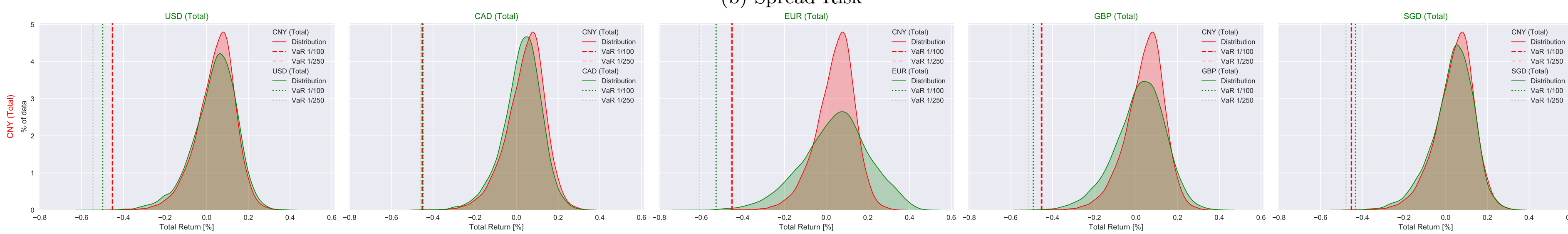
Figure E.4 – Compared Currencies for **CNY** (**corporate bond**, **R=A**, M=5 years, C=3% annual)



(a) IR Risk

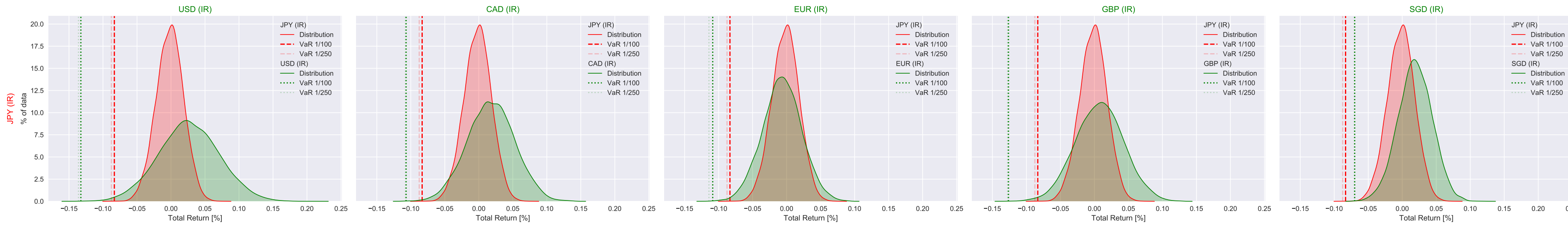


(b) Spread Risk

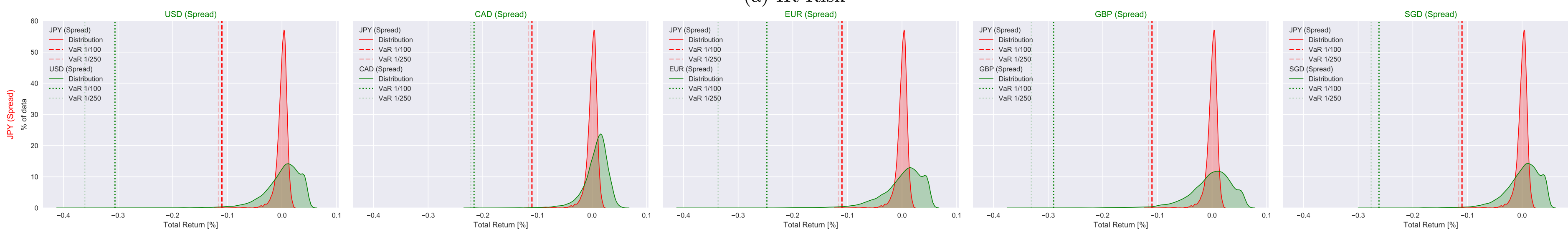


(c) Total Risk

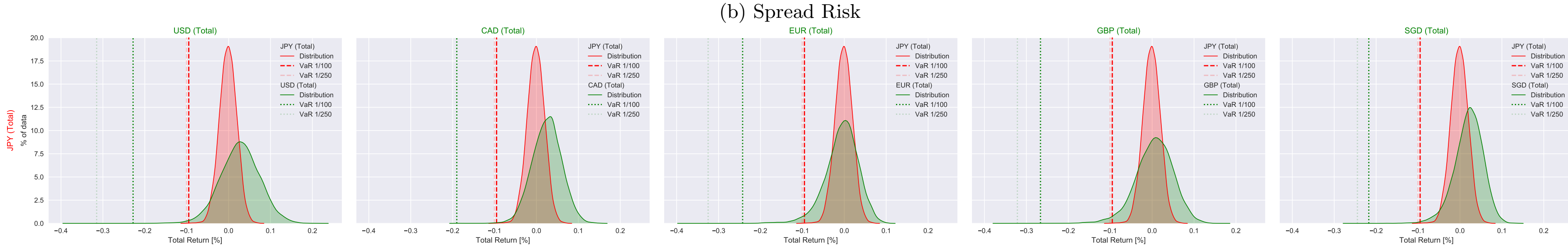
Figure E.5 – Compared Currencies for **CNY** (**corporate bond**, **R=B**, M=5 years, C=3% annual)



(a) IR Risk

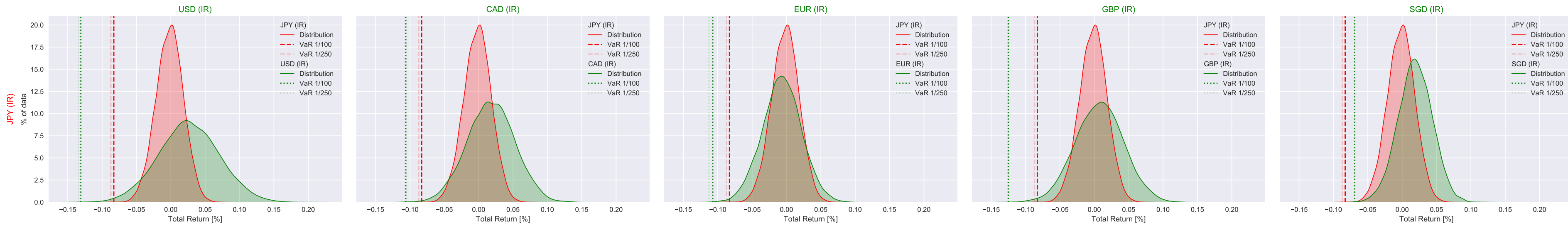


(b) Spread Risk

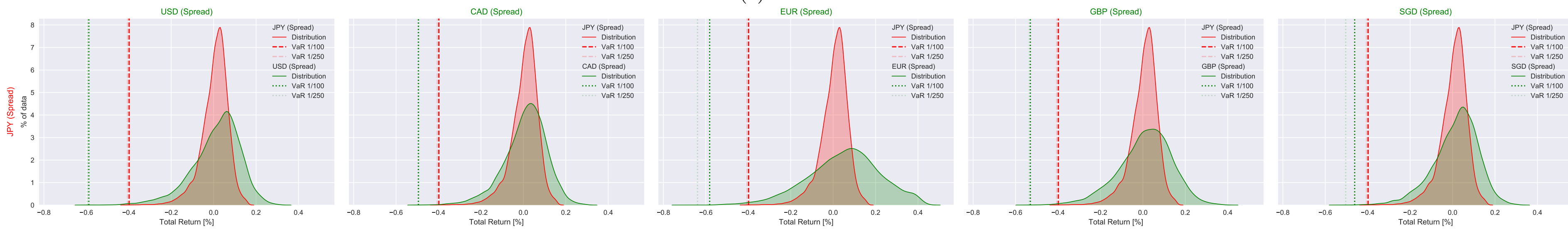


(c) Total Risk

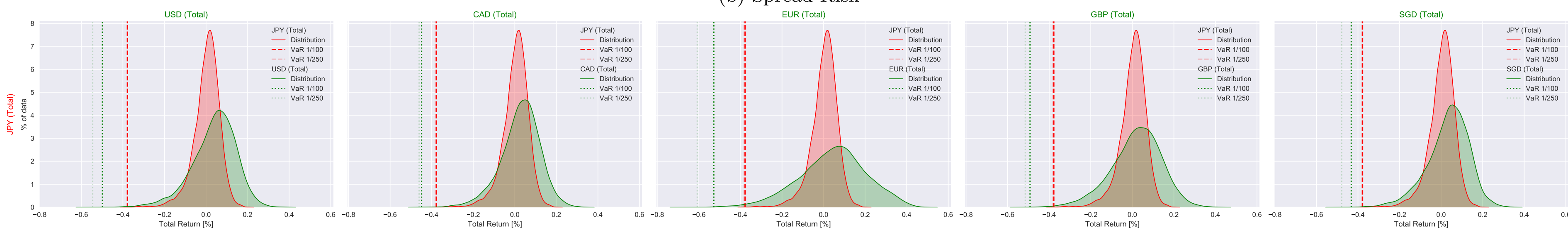
Figure E.6 – Compared Currencies for **JPY** (**corporate bond**, **R=A**, M=5 years, C=3% annual)



(a) IR Risk



(b) Spread Risk



(c) Total Risk

Figure E.7 – Compared Currencies for **JPY** (**corporate bond**, **R=B**, M=5 years, C=3% annual)

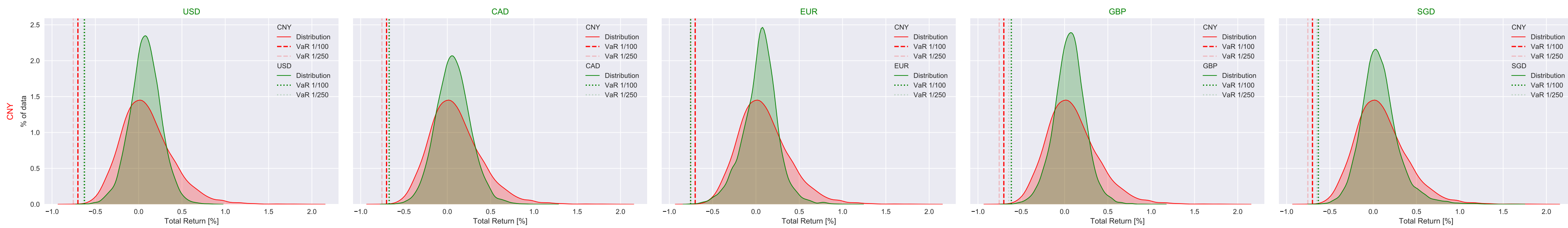


Figure E.8 – Compared Currencies for **CNY** (**equity**, Beta=1)

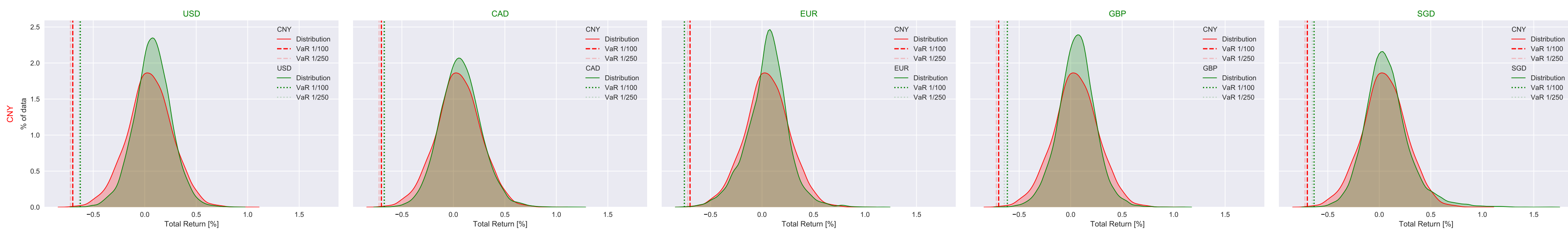


Figure E.9 – Compared Currencies for **JPY** (**equity**, Beta=1)

Acronyms

ABS	Asset-Backed Security
APP	Active Payment Periods
CAD	Canadian Dollar
CAPM	Capital Asset Pricing Model
CHF	Swiss Franc
CMV	Current Market Value
CNY	Chinese Yuan
CPI	Consumer Price Index
ESG	Economic Scenario Generator
EUR	Euro
FRED	Federal Reserve Economic Data
FX	Foreign Exchange
GBP	Pound sterling
HPI	Housing Price Index
ILS	Insurance-Linked Securities
IR Risk	Interest Rate Risk
JPY	Japanese Yen
MBS	Mortgage-Backed Security
PRE	Partner Re
PSA	Public Security Associations
S&P	Standard & Poor's
SGD	Singapore Dollar
TIPS	Treasury Inflation-Protected Securities
TVaR	Tail Value-at-Risk
USD	US Dollar
VaR	Value at Risk
WTW	Willis Towers Watson
ZCB	Zero-Coupon Bond

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Cheatsheet: IGLOO Asset Model

Box A: Asset Classes: Risks & Return

This box summarizes the sensitivity of asset risks and mean returns to changes in model parameters.

Government Bonds — fig. 1

↑ **Maturity**	↑ IR Risk ↑ Return
↑ **Coupon Rate**	↓ IR Risk ↑ Return
Hold & Reset / Hold	No influence
Nominal value	No influence

Corporate Bonds — fig. 2, 3

↑ **Maturity**	↑ IR Risk, ↑ Spread Risk ↑ Return
↑ **Coupon Rate**	↓ IR Risk, ↓ Spread Risk ↑ Return
↑ **Rating**	↓ Spread Risk ↓ Return

Equity, Property — fig. 6, 7

↑ **Beta**	↑ Equity / Property Risk ↑ Return

MBS — fig. 4, 5

↑ **APP**	↓ IR Risk, ↓ Spread Risk ↓ Return
↕ **Coupon Rate**	↓ IR Risk ↑ Return
Underlying Curve	Risk: ↑ Spread Risk ↑ Return Risk-free: ↓ Spread Risk ↓ Return
Current Market Value	↑ IR Risk, ↑ Spread Risk ↓ Return
↑ **Maturity**	↑ IR Risk, ↑ Spread Risk ↑ Return
↑ **PSA Factor**	↓ IR Risk, ↓ Spread Risk *
↑ **Rating**	↓ Spread Risk ↑ Return

Extra Indices — fig. 8

↑ **Beta**	↑ Equity Risk ↑ Return

* PSA_f could lead to higher or lower return depending on if the bond was bought at discount or premium

Box B: Tail Risk Summary

VaR 1/100 and VaR 1/250 for all modeled asset classes can be found in the tables below.

Risk Summary Tables — section A

Government Bonds	⟶	Table A.1
Corporate Bonds	⟶	Table A.2
MBS	⟶	Table A.3
Equity	⟶	Table A.4
Real Estate	⟶	Table A.5
Extra Indices	⟶	Table A.6

Box C: Empirical Validation

Figures for the empirical validation of the model can be found below.

Empirical Validation — section 4.2

Government Bonds	⟶	Fig. 9, 10, 11, 12
Corporate Bonds	⟶	Fig. 13, 14
MBS	⟶	Fig. 15, 16
Equity	⟶	Fig. 17, 18
Real Estate	⟶	Fig. 19, 20, 21
FX	⟶	Fig. 22

Box D: Sensitivities: subclasses & currencies

Sensitivities for different asset subclasses and for different currencies are shown in the figures below.

Currencies — section 4.3.2

GBP, EUR Equity	→	Fig. 26
GBP, EUR Property	→	Fig. 28
EUR Private Equity	→	Fig. 27

Asset Subclasses — section 4.3.2

Extra Indices	→	Fig. 24

Box E: Extra Indices: Fixed Income

Properties from Bloomberg for fixed-income like Extra Indices are shown below.

EI Matching: Fixed Income — fig. 25

Extra Index	Bloomberg Data		
	Rating	Maturity	Coupon
High Yield	B	9.33	6.45
US HY	BB	5.68	5.87

Box F: Extra Indices: Equity

Theoretical betas from Bloomberg for equity-like Extra Indices and the betas of the asset model are shown below.

EI Matching: Equity — fig. D.1

Extra Index	Bloomberg Data	Apparent Matching Beta
Emerging Equity	1.13	1.06
Global Equity	0.99	1.05
Hedge Fund	0.22	0.70
Private Equity	1.17	1.25

Box G: Asset Classes: Currencies

The table below lists a recommended mapping to model non-modeled currencies as the closest currencies in terms of downside tail risk.

Government Bonds — fig. E.1, E.2, E.3

CNY	⟶	SGD
JPY	⟶	SGD
CHF	⟶	EUR

Corporate Bonds — fig. E.4, E.5, E.6, E.7

CNY	⟶	CAD
JPY	⟶	(CAD)*

Equity — fig. E.8, E.9

CNY	⟶	(EUR)*
JPY	⟶	(CAD)*

* Based on numerical comparisons between distributions, requiring additional expert judgment