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Common Factors in International Bond Returns

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Common Factors in International Bond Returns

Abstract

In this paper we estimate and interpret the factors that jointly determine bond returns of different maturities in the US, Germany and Japan. We analyze both currency-hedged and unhedged bond returns. For currency-hedged bond returns, we find that five factors explain 96.5% of the variation of bond returns. These factors can be associated with changes in the level and steepness of the term structures in (some of) these countries. In particular, it turns out that changes in the level of the term structures are correlated across countries, while changes in the steepness of the term structures are country-specific. The five-factor model also provides a good fit of the expected returns of bond returns in all countries. We find similar results for bond returns that are not hedged for currency risk. Finally, we show how the model can be used to calculate the Value at Risk for international bond portfolios and to price cross-currency interest rate derivatives, and compare the results with simpler models.

JEL Codes: F21, G12, G15, E43.

Keywords: Bond Returns; Multi-Country model; Common Factors; Term Structure of Interest Rates.

1 Introduction

Most large investors do not invest the fixed income part of their portfolio solely in government bonds that are issued by their home country, but usually they diversify risk by investing in bonds issued by different countries. For risk management of such international bond portfolios, it is essential to have a joint model for the bond returns of the relevant maturities and in the relevant countries. Also, for the pricing of cross-currency interest rate derivatives, such as differential swaps, a joint model for term structure movements in different countries is required. In this paper, we empirically analyze a multi-country factor model that can be used for risk management purposes as well as for the pricing of cross-currency interest rate derivatives. We estimate and interpret the common factors that determine international bond returns of different maturities. The multi-country model is compared with a model that specifies the behaviour of bond returns in each country separately, by comparing the size of risk measures and derivative prices that are generated by these two models.

Our work is related to Knez, Litterman and Scheinkman (1994) and Litterman and Scheinkman (1991). In these papers, a linear factor model is estimated for short-term US money market returns and long-term US government bond returns, respectively. In Knez, Litterman and Scheinkman (1994), a four-factor model is proposed. The first two factors correspond to movements in the level and the steepness of the term structure of money market rates, while the other two factors account for differences in credit risk of the different money market instruments. Litterman and Scheinkman (1991) find, on the basis of a principal component analysis, that US bond returns are mainly determined by three factors, which correspond to level, steepness, and curvature movements in the term structure.

We extend these papers by jointly analyzing bond returns of different maturities in three countries, namely the US, Germany and Japan. In the spirit of the Arbitrage Pricing Theory developed by Ross (1976), we assume a linear factor model for these bond returns, and assess how many factors are required to explain most of the variation in bond returns of all countries. Similar to Litterman and Scheinkman (1991), we use principal components analysis on the unconditional covariance matrix of bond returns of the different maturities in all countries to estimate the factors that determine these bond returns. The estimated principal components or *factor loadings* indicate per factor how this factor influences bond returns of the different maturities in each country. We also estimate the prices of the risk associated with each factor. Confidence intervals for the estimated factor loadings and factor risk prices are constructed using bootstrap techniques.

In our empirical analysis, we analyze bond returns that are hedged for currency risk as well as unhedged bond returns. In case of hedged bond returns, the returns are driven only by changes in the underlying term structure. We use weekly data from 1990 to 1999 on Merrill Lynch bond indices for the US, Germany, and Japan. For each country, bond index returns for five maturity classes are used, from

1-3 years to larger than 10 years. In line with results presented by Ilmanen (1995), bond returns are positively correlated across countries.

For the hedged bond returns, we find that a five-factor model explains 96.5% of the total variation of international bond returns. Adding more factors to this model only slightly increases the explained variation, and the factor loadings for the extra factors are small and statistically insignificant. The first factor of the five-factor model can be interpreted as a world level factor, because this factor represents movements in the level of the term structures in all countries in the same direction. This factor explains 46.6% of the variation in bond returns. It is closely related to the one-dimensional Macaulay (1938) duration measure and the duration measure for international bond portfolios proposed by Thomas and Willner (1997), but similar to this measure, it captures only some part of all movements in international bond prices. The second factor represents parallel shifts in the term structures of Japan and the US in opposite directions, and explains 27.5% of bond return variation. Similarly, the third factor represents parallel shifts in opposite directions in the term structures of Germany and the US, explaining 17% of bond return variation. The fourth and fifth factor represent changes in the steepness of the term structure of Germany and Japan, respectively, explaining 3.1% and 2.3% of the bond return variation. Thus, we conclude that the positive correlation between bond returns across countries is only driven by correlation between the level of the term structures in the several countries. Changes in the slope of the term structure are not correlated across countries.

We also estimate the risk price of each factor, and analyze whether the model can explain the expected returns on bonds of different maturities and different countries. It turns out that the five-factor model provides a good fit of these expected returns. In fact, only the first two factors have statistically significant risk prices.

Next, we compare the multi-country model with a model that separately specifies term structure movements in each country, assuming zero correlation between term structure movements across countries. This comparison consists of two parts. First, we calculate the Value at Risk for several international bond portfolios for both models, thereby extending the Value at Risk methodology of Singh (1997) to a multi-country setting. Second, using results from Frachot (1995), we show how the linear factor model can be linked to multi-currency extensions of the framework of Heath, Jarrow and Morton (HJM, 1992). As noted by Heath, Jarrow and Morton (1990), principal component analysis can be used to estimate models in the HJM-framework, and this result translates directly to the multi-country framework. Then, we calculate prices for cross-country interest rate derivatives for both models. The two applications show that ignoring the cross-country bond return correlation can have a significant effect on risk measures and derivative prices.

Finally, we also analyze bond returns that are not hedged for currency risk, by including currency returns for the DM/\$ and Yen/\$ exchange rates in the principal component analysis. We find that two additional factors are needed to explain the same amount of variation as the five-factor model for

hedged bond returns. The interpretation of the first five factors in this seven-factor model is similar to the five-factor model, but, because currency returns are correlated with hedged bond returns, the two extra factors are not simply a DM/\$ and Yen/\$ factor.

The remainder of this paper is organized as follows. The next section describes in detail the linear factor model and the estimation methodology that is used. In section 3 we describe the data and replicate the analysis of Litterman and Scheinkman (1991) for each country in our data. In section 4 we estimate and interpret the multi-country factor model for hedged bond returns. Section 5 contains two applications of the multi-country model, namely calculating the Value at Risk of international bond portfolios and the pricing of cross-currency interest rate derivatives. In section 6 we extend the multi-country model by also including currency returns. Section 7 concludes.

2 Model Setup

2.1 Model Specification

The starting point of our analysis is the following factor model for bond returns

$$R_t - \mathbf{1}r_t^{US} = \Gamma\lambda + \Gamma F_t + \epsilon_t \quad (1)$$

where R_t is an N -dimensional vector containing (weekly) returns on bonds of different maturities and different countries, $\mathbf{1}$ is an N -dimensional vector of ones, and r_t^{US} is the one-week US risk-free short rate. The model states that excess returns $R_t - \mathbf{1}r_t^{US}$ are determined by K common factors F_t through the $N \times K$ matrix Γ (the factor loadings), and an N -dimensional vector ϵ_t containing bond-specific residuals, which can either be interpreted as measurement error in the bond returns or as idiosyncratic risk components. This model fits into the framework of the Arbitrage Pricing Theory (APT, Ross (1976)), and thus the elements of the K -dimensional vector λ can be interpreted as the market prices of factor risk.

The unobservable variables F_t and ϵ_t are assumed to be i.i.d. distributed¹ with

¹An extension to this model would be to include time-varying expected bond returns and time-varying variances and covariances of bond returns.

$$\begin{aligned}
E[\epsilon_t] &= 0, & \text{Var}[\epsilon_t] &= \sigma^2 I_N, \\
E[F_t] &= 0, & \text{Var}[F_t] &= I_K, \\
\text{Cov}[F_t, \epsilon_t] &= 0
\end{aligned} \tag{2}$$

where I_n is an $n \times n$ identity matrix. The last three assumptions in equation (2) are just one choice for the normalizations that are required to properly define the factor loadings. The assumption that the residual variances are all equal to each other is restrictive, but it allows us to estimate the model (1) with principal components analysis, which is a simple and frequently used technique in interest rate modeling (see, for example, Buhler et al. (1999), Golub and Tilman (1997), Rebonato (1996), and Singh (1997)). Knez, Litterman and Scheinkman (1994) allow these residual variances to be different from each other, at the cost of having to use a more complicated estimation technique, i.e., maximum likelihood, and the possibly restrictive assumption that the returns follow a multivariate normal distribution.

For each factor, one can easily calculate how much of the average variation in excess bond returns is explained by this factor, namely

$$\frac{\sum_{i=1}^N (\Gamma_j \Gamma_j')_{ii}}{\sum_{i=1}^N \Sigma_{ii}} \quad j=1, \dots, K \tag{3}$$

where Γ_j is the j th column of Γ and Σ_{ii} is the i^{th} diagonal element of Σ , the covariance matrix of $R_t - r_t^{US}$.

Because the factors F_t are unobserved, one would like to construct a portfolio that is sensitive to movements of a given factor, while it is insensitive to movements in all other factors. These factor mimicking portfolios are not uniquely determined, see Knez, Litterman and Scheinkman (1994). A convenient choice is as follows. For factor j , the weights of this factor mimicking portfolio w_j are equal to the factor loadings Γ_j normalized to sum up to one. As outlined below, we will normalize the sum of the factor loadings to be positive, so that a positive factor loading directly corresponds to a long position in the corresponding bond. One can easily check that this portfolio is only sensitive to factor j and not to the other factors. These factor mimicking portfolios can be used to analyze the properties of the factors.

We consider bond returns of $M=5$ different maturities, τ_1, \dots, τ_M , in three countries, US, Germany, and Japan. The τ_i -maturity log-return in terms of the country specific currency from time t to time $t+1$ is denoted by R_{t, τ_x}^{US} for US bond returns, and, similarly, by R_{t, τ_x}^{GER} for Germany, and by R_{t, τ_x}^{JAP} for Japan. In this paper, we take the viewpoint of a US investor, so that the German and Japanese bond returns have

to be converted to \$-returns. We will consider both bond positions that are hedged for currency risk as well as unhedged bond positions.

We start with the case of hedged bond returns. The time t values of the DM/\$ and Yen/\$ exchange rates are denoted by S_t^{DM} and S_t^{Yen} , and the one-period forward rates at time t are defined as F_t^{DM} and F_t^{Yen} . Then, the currency-hedged \$ returns on German bonds $R_{t,\tau_x}^{GER}(\$, Hedged)$ are given by^{2 3}

$$R_{t,\tau_x}^{GER}(\$, Hedged) = R_{t,\tau_x}^{GER} + \ln(F_t^{DM}) - \ln(S_t^{DM}), \quad i=1,\dots,M \quad (4)$$

For Japanese returns an analogous relation holds. Since weekly forward currency rates are typically close to current spot exchange rates, the difference between the hedged bond returns and the local bond returns will be small relative to the total return. Therefore, hedged bond returns are primarily driven by changes in the underlying local term structure of interest rates. We let the vector R_t contain all US bond returns and the hedged bond returns for both Germany and Japan. Thus, the dimension of this return vector is equal to $3M$, so that N is equal to $3M$ in equation (1).

The model can easily be extended to include unhedged bond positions. If we define the currency return from week t to week $t+1$ as

$$\ln(S_{t+1}^{DM}) - \ln(F_t^{DM}) \quad (5)$$

for the DM/\$ currency, and, analogously, for the Yen/\$, then it follows directly that an unhedged (excess) bond return is equal to the hedged (excess) bond return plus the currency return. Thus, we add the two currency returns (DM/\$ and Yen/\$) to the vector of hedged bond returns R_t , to obtain the $(3M+2)$ -dimensional vector of bond and currency returns \tilde{R}_t , and again assume a linear factor model for these returns as in (1) and (2).

2.2 Model Estimation

Using data on the excess bond returns, we will perform a principal component analysis on the sample covariance matrix of $R_t - \nu r_t^{US}$, to estimate the factor loadings Γ . The principal components are

²Because the time $t+1$ bond price is not known with certainty at time t , it is not possible to completely eliminate currency risk using forward currency contracts. Because we consider a short return period, namely one week, we can safely neglect this quantity risk.

³We define returns in logarithms, to separate the currency return from the bond return in a convenient way.

given by the eigenvectors of this covariance matrix. Then, the first K principal components of the sample covariance matrix are consistent estimates⁴ of the factor loadings Γ in equation (1).

Given the assumptions in (1) and (2), the return covariance matrix Σ is equal to

$$\Sigma = \Gamma\Gamma' + \sigma^2 I_{3M} \quad (6)$$

Note that the factor loadings matrix Γ can be postmultiplied with an orthonormal matrix Λ without changing the common covariance matrix part $\Gamma\Gamma'$. Hence, given the covariance matrix Σ , the factor loadings Γ cannot be distinguished from the loadings $\Gamma\Lambda$. Principal component analysis imposes that each subsequent factor explains an as large as possible part of the variation and co-variation of bond returns, by imposing that the factor loading is orthogonal to all the previous ones. Then, the factor loadings are uniquely determined, except for a sign change. We therefore impose that the sum of the factor loadings of a given factor is positive. As mentioned above, this sign restriction facilitates the interpretation of factor mimicking portfolios.

If all returns follow a multivariate normal distribution, the normal limit distribution of these estimators for the eigenvectors and eigenvalues is known explicitly, see Basilevsky (1995). For other bond return distributions, the asymptotic distribution will, in general, still be the normal distribution, but the expression for the asymptotic covariance matrix is complicated. Therefore, to obtain confidence intervals for the estimates of the principal components or factor loadings, we use a bootstrap technique, which is described shortly in the appendix. As noted by Shao and Tun (1996), the bootstrap distribution converges to the asymptotic distribution under weak assumptions on the return distribution. Hence, by using the bootstrap technique, we are able to construct confidence intervals and standard errors for the factor loadings estimates without having to make the normality assumption.

We also calculate the bootstrap distribution of the eigenvalues that correspond to the eigenvectors. In the appendix it is shown that the model in equation (1) implies that the last $3M-K$ eigenvalues of Σ are equal to each other. Given the iid assumption on bond returns and weak assumptions on the bond return distribution (see Shao and Tun (1996)), the eigenvalues are asymptotically normally distributed, and the restriction on the eigenvalues can be tested using a standard chi-square test statistic. We use the bootstrap distribution of the eigenvalues to estimate the covariance matrix of the eigenvalues and to

⁴The ordinary principal component estimates are biased upward given the model in (1), due to the residual variance terms. To correct for this bias, each principal component has to be multiplied with a scale factor, see Basilevsky (1995) and the appendix. For our models, the residual variances turn out to be small, so that these scale factors are only slightly smaller than one. Litterman and Scheinkman (1991) make the assumption that the idiosyncratic shocks are negligible.

calculate the test statistic. By performing this test for different numbers of factors K , one can test for the number of factors.

In a second step, we estimate the prices of factor risk, λ , given the estimated factor loadings. Notice that the model implies that the expected excess bond returns satisfy

$$E[R_t - r_t^{US}] = \Gamma\lambda \quad (7)$$

We use the Generalized Methods of Moments (Hansen (1982)) on the moment restrictions in (7) to estimate λ , using the estimated factor loadings for Γ . This is equivalent to a GLS regression of the average bond returns on the factor loadings matrix Γ . The covariance matrix of the estimated moment restrictions and standard errors of the estimates for λ are again calculated using bootstrap techniques, and we correct these standard errors for the estimation error in the factor loadings estimates. The factor price of risk of each factor can be interpreted as the expected excess return on the factor mimicking portfolio, divided by its standard deviation

$$\lambda_j = \frac{E[w_j'R_t - r_t^{US}]}{\sqrt{Var[w_j'R_t]}} \quad j=1,\dots,K \quad (8)$$

where w_j contains the weights of the factor mimicking portfolio of factor j .

2.3 Duration Measures

The linear factor model, defined in equations (1) and (2), is an extension of linear one-factor models that correspond to Macaulay's duration measure (Macaulay (1938)) and the international duration measure proposed by Thomas and Willner (1997). Macaulay's duration measure is based on a linear one-factor model, where the factor loading of a bond is equal to the duration of this bond. In this case, the factor represents a parallel shift in the entire term structure. If applied to international bond portfolios, this model implies that bonds from different countries, but with the same duration, have exactly the same factor loading. One problem of applying Macaulay's duration measure to international bond portfolios is that parallel shifts in term structures of different countries do not have the same variance and are not perfectly correlated. Therefore, to measure the sensitivity of international bond portfolios to parallel shifts in the local term structure (in our case the US term structure), Thomas and Willner (1997) propose a modification of Macaulay's duration measure, that is again based on a linear one-factor model. In this case, each bond has a factor loading that is equal to its duration times a so-called

country-beta. Analogous to the Capital Asset Pricing Model, this country-beta is defined as the covariance of the US (all-maturity) bond index return and the foreign country's all-maturity bond index return, divided by the variance of the US bond index return⁵. As we have taken the viewpoint of a US investor, the country-beta for the US is equal to one.

The factor model in (1) can also be used to calculate duration-type risk measures for a given bond portfolio, as shown by Golub and Tilman (1997). If the bond portfolio has a weight vector w and corresponding return $w'R_t$, the 'PCA-duration' for factor j is given by $w'T_j$. Recalling that the variance of the factors F_t is equal to one, this PCA-duration measures the percentage price change of the portfolio when there is a positive shock of one (i.e., one standard deviation) to the underlying factor in the next period. As argued by Willner (1996), and Golub and Tilman (1997), using multiple PCA-durations to assess the risk of a bond portfolio typically gives a more accurate description of interest rate risk than using Macaulay's one-dimensional duration measure. We will make a similar argument for international bond portfolios, by comparing the models corresponding to Macaulay's duration measure and the duration measure of Thomas and Willner (1997), with the multi-factor multi-country model in equation (1).

3 Data Description and Results for Single-Country Models

The data we use are total returns on Merrill Lynch Government Bond Indices for the US, Germany, and Japan, which are available through Datastream. We have chosen these bond indices because they are available at a relatively high frequency, namely weekly. These weekly data start at January 8, 1990; we use data until October 11, 1999, which renders 510 time-series observations on weekly bond index returns. For each country, five maturity classes are available: 1-3 years, 3-5 years, 5-7 years, 7-10 years, and more than 10 years. We construct excess bond returns, using Datastream data on the 1-week Eurodollar interest rate.

The bond indices are all denominated in US \$, and are not hedged for currency risk. To construct returns on bond positions that are hedged for currency risk, we use data on spot and forward exchange rates for the DM/\$ and Yen/\$ exchange rates⁶. These data are also from Datastream. Thus, we have data on 15 returns on (currency-hedged) bond indices, as defined in equation (4), for US, Germany and

⁵Thomas and Willner (1997) define the country-beta in terms of yield changes instead of bond returns.

⁶Because 1-week forward exchange rates are not available for the entire data period, we transform 1-month forward rates to 1-week forward rates, assuming that 1-week and 1-month interest rates are equal. Because of the short forward maturity, the error caused by this assumption will be small.

Japan, and we have data on two currency returns, as defined in equation (5), for the DM/\$ and the Yen/\$ exchange rates.

In table 1 we provide statistics on the bond and currency returns. In almost all cases, both the average returns and the standard deviations increase with the maturity of the bond index, as expected. Average bond returns are highest for Japan, which corresponds to the decrease of Japanese interest rates over the last 10 years. We also calculate the skewness and kurtosis of the bond returns. It turns out that the return distributions are not very asymmetric. But, especially for Japanese bond returns, the tails of the return distribution are fatter than the normal distribution. Given this evidence against normally distributed bond returns, we will in the sequel calculate confidence intervals and standard errors using bootstrap techniques rather than the explicit expressions for these, which only hold under the normality assumption (see section 2).

Recall that we assume that returns are iid distributed. To investigate whether this assumption makes sense, we report the autocorrelations of bond returns. There seems to be some negative autocorrelation in the (short-maturity) bond returns, which is consistent with mean-reverting behaviour of interest rates. From the statistics on currency returns, it follows that hedging currency risk would have led to slightly higher average total returns, namely 0.34% per year for German bonds, and 0.19% for Japanese bonds. Currency returns are more volatile than hedged bond returns. The correlation between the Yen/\$ and DM/\$ currency returns is quite high, namely 0.44, which implies that unhedged German and Japanese bond returns are more strongly correlated than hedged returns.

In table 2, we present the average correlations between hedged bond returns and currency returns, and in figure 1, we plot the correlations between hedged bond returns of different maturities and different countries. In general, the cross-country bond return correlations lie between 0 and 0.5, indicating that interest rates movements across countries are positively correlated. The graph also shows that, within each country, bond returns are highly correlated, and that there is no clear maturity pattern in the cross-country correlations of bond returns. Table 2 shows that the average cross-country correlations are between 0.11 and 0.29. These numbers are smaller than reported by Ilmanen (1995), who reports correlations between 0.40 and 0.55, for the period 1978-1993 using monthly data. The correlation between hedged bond returns and currency returns is close to zero in almost all cases. Only for the DM/\$ currency return and US bond returns there seems to be some small positive correlation.

To provide further insight in the bond return data, a linear factor model for hedged excess bond returns, as in equation (1), is estimated for each country separately. In line with Litterman and Scheinkman (1991), and Singh (1997), we estimate a three-factor model for the hedged excess bond returns. Estimation is performed using principal component analysis. The results for these single-country models will be used as a benchmark for the multi-country model.

In figure 2, the factor loadings of the single-country three-factor models are graphed. For all three countries, the estimates for the three factors are in line with the existing literature on linear factor

models for bond returns and principal component analysis (see Litterman and Scheinkman (1991), Rebonato (1996), and Singh (1997)). For the first factor, the factor loadings for bond returns all have the same sign and increase with the maturity of the bond. Note that a change in the level of the term structure will more strongly influence long-maturity bond returns. Thus, this factor can be interpreted as a factor that influences the *level* of the term structure of interest rates. The second factor can be called a *steepness* factor, as movements in this factor imply a steepening or flattening of the yield curve. The third factor changes the *curvature* of the yield curve, because it influences bond returns of intermediate maturities in the opposite direction of short-maturity and long-maturity bond returns. The confidence intervals indicate that the factor loadings are estimated quite accurately⁷.

Although the shape of the factor loadings is the same for all three countries, the explained variance per factor is quite different across countries, as shown in table 3. Using equation (3), it follows that, for US bonds, the first factor explains on average 96.9% of the variance of excess bond returns, and the explained variance for the second and third factor is quite low. In Litterman and Scheinkman (1991), the explained variance is lower for the first factor, and higher for the second and third factor. The differences with their study are due to the use of a different data period, but also due to the fact that we use returns on portfolios of bonds within a certain maturity class, whereas Litterman and Scheinkman (1991) use individual bond price data, which might contain more idiosyncratic risk. For German and Japanese bonds, the explained variance is lower compared to the US for the first factor, and higher for the second and third factors. This indicates that, over the last 10 years, large steepness and curvature movements of the yield curve have occurred more often in Germany and Japan than in the US. As shown in table 3, for each country three factors explain on average at least 98.5% of the variation in excess bond returns.

Finally, for every country, we test the appropriateness of one-, two-, and three-factor models. For the US, the hypothesis that the remaining eigenvalues are equal to each other is rejected for all numbers of factors. For Germany and Japan, this restriction is rejected for the one- and two-factor models, but it is not rejected in case of the three-factor model. We will return to the issue of the number of factors when we analyze the multi-country models.

4 Empirical Results Multi-Country Model

In this section, we will restrict attention to the 15 currency-hedged excess bond returns, and present results for the multi-country linear factor model for these bond returns. We find that a five-factor model explains on average 96.4% of the bond return variation, and 98.5% of the cross-sectional variation in

⁷In all cases, we use 1000 bootstrap simulations to calculate confidence intervals and standard errors.

average bond returns. Furthermore, the factor loadings of additional factors are always individually insignificant, as well as the risk prices of these additional factors. Therefore, we choose to restrict attention to a five-factor model. Note also that the factor loadings of these first five factors remain exactly the same if we would estimate a model with a larger number of factors, because we do not rotate the estimated factor loadings.

4.1 Interpretation of Factor Loadings

In figures 3a-e we graph the estimated factor loadings together with 95%-confidence intervals for the factor loadings, and in table 4 we give for each factor the explained variance, relative to the total variance of bond returns. We interpret the first factor as a *world level factor*. This factor shifts the entire term structure in all countries in the same direction, and, as shown in table 4, this factor accounts for 46.6% of all variation in the international excess bond returns. In figure 4, we give the explained variance per country. This graph shows that the first factor explains around 60% of the variation in US bond returns, around 50% of the variation of hedged German bond returns, and 25% of the variation of hedged Japanese bond returns. As described in section 2, the factor loadings in figure 3a directly describe the weights of a factor mimicking portfolio, which has a weight of 41% in US bonds, 32% in German bonds, and 27% in Japanese bonds.

As described in section 2, this first factor is also related to Macaulay's duration and the multi-country duration of Thomas and Willner (1997). In figure 5, we graph the factor loadings of the one-factor models that correspond to these two duration measures^{8 9}. This graph shows that the first factor of our multi-country model is closely related to the Macaulay-duration factor, which confirms our interpretation of this factor as a world level factor. This also implies that the factor mimicking portfolios that correspond to the factors 2 to 5, that will be analyzed below, have a Macaulay duration that is close to zero. The graph also shows that, since the duration measure of Thomas and Willner (1997) aims at measuring the international bond portfolio sensitivity to shifts in the US term structure, and because the country-beta's are equal to 0.32 for Germany and 0.13 for Japan, the factor loadings that correspond to this duration measure are low for German and Japanese bonds. Given that the linear

⁸For the Macaulay-duration one-factor model, the variance of the factor is chosen such that the factor loadings are close, in a least-squares sense, to the factor loadings for the first factor of the multi-country model. As the one-factor model of Thomas and Willner (1997) aims at measuring the sensitivity to US term structure movements, we choose the factor variance such that, for US bonds, the factor loadings are close to the factor loadings of the first factor of the multi-country model.

⁹To calculate these factor loadings, we assume that the durations of the bond indices are equal to 2, 4, 6.5, 8.5 and 12.5 years, respectively. The country-beta's of Thomas and Willner (1997) are estimated using US, German and Japanese all-maturity bond index returns, that are constructed by equally weighting the five maturity classes that are available for each country.

one-factor models that correspond to Macaulay's duration and the duration of Thomas and Willner (1997) are restricted versions of the general linear one-factor model, the fact that this general first factor captures around 47% of total bond return variation, indicates that these two duration measures only capture some part of all movements in the term structures of several countries. On the other hand, as long as one invests in internationally diversified portfolios, with country weights close to the weights of the factor mimicking portfolio, the one-factor model can be used to calculate accurate risk measures. In the next section we will see that such a one-factor model can severely misprice cross-country interest rate derivatives.

We interpret the second factor, whose factor loadings are plotted in figure 3b, as a *Japan minus US level factor*. Again, this factor primarily influences the level of the term structure of interest rates, as the factor loadings have the same sign within each country and because the factor loadings are increasing with maturity. This factor influences Japanese bond returns in the opposite direction of US bond returns, while German bond returns are hardly influenced by this factor. The factor mimicking portfolio thus consists of long positions in Japanese bonds, and short positions in US bonds. Thus, for a given bond portfolio, the PCA-duration associated with this factor measures how sensitive the portfolio is to a change in the difference between the US and Japanese term structures. This factor explains 27.5% of the average bond return variation. In particular, it explains around 60% of Japanese bond return variation and 20% of US bond return variation.

Similarly, we interpret the third factor as a *Germany minus US level factor*; this factor explains 16.9% of the international bond return variation. We interpret the fourth and fifth factor as a Germany steepness factor and a Japan steepness factor; these factors explain 3.1% and 2.3% of the bond return variation, respectively. Each of these two factors changes the steepness of the yield curves in Germany and Japan, respectively, while they do not significantly influence the bond returns in the other two countries. In fact, these steepness factors are almost the same as the steepness factors in the single-country models for Germany and Japan. The fact that the steepness factors are almost completely country-specific, whereas the level movements in international yield curves are correlated, implies that the positive correlation between international bond returns seems to be caused by correlation between the levels of the international yield curves.

As mentioned above, for additional factors, the factor loadings are always individually insignificant. In particular, this implies that steepness movements in the US yield curve are not included in the five-factor model. In the loadings of additional factors, we do find steepness shapes for the US, but the explained variance of these factors is very low, which is in line with the results for the single-country model for the US. We also test for the number of factors, by testing for each K -factor model whether the remaining $(15-K)$ eigenvalues are equal to each other, as described in section 2 and the appendix. It turns out that even the model with thirteen factors is rejected, as the hypothesis that the 14th and 15th eigenvalues are equal to each other is rejected. As noted by Basilevsky (1995), these formal statistical

tests typically tend to overestimate the number of factors in small samples, so that other considerations, such as the explained variance relative to the total variance and the interpretation of the factor loadings are also important when choosing the number of factors. Therefore, we do not attempt to extend the five-factor model with more factors.

4.2 Estimation of Factor Risk Prices

As described in section 2, in a second step the prices of factor risk for this multi-country model can be estimated using GMM or, equivalently, a GLS regression of average bond returns on the factor loadings matrix Γ . As shown in equation (8), each factor price of risk equals the Sharpe-ratio of the factor mimicking portfolio. The estimates and corresponding standard errors are given in table 5. This table shows that only the first two factors, the *world level factor* and the *Japan minus US level factor*, have a risk price that is significant at a 10% significance level, and the size of the factor risk prices is also largest for the first two factors. Setting all insignificant risk prices to zero, the results on the risk price estimation imply that the mean-variance efficient frontier is spanned by the two factor mimicking portfolios that correspond to the first two factors.

Table 5 also contains the GMM J-statistic, a test-statistic for testing the overidentifying restrictions in equation (7), and the corresponding p-value. The hypothesis that the five-factor model correctly describes expected returns of all bonds is statistically rejected. However, as discussed above, the individual factor risk prices are all insignificant except for the first two factors. Furthermore, the five-factor model provides a good fit of the average bond returns, as measured by the R^2 of the GLS regression, which is equal to 98.5%. This is confirmed by figure 6, where we graph the expected excess hedged bond returns implied by several models, and unrestricted estimates, the sample averages, of these expected returns. The figure shows that the two-factor model already gives a reasonable fit of the average bond returns, which is in line with the fact that only the first two factors have a statistically and economically significant risk price. The fact that the GMM J-test still leads to a rejection of the five-factor model, is due to the fact that bond returns are highly correlated within countries. This implies that even small expected return errors of two near-maturity bonds are enough to statistically reject the model.

5 Value at Risk and Cross-Country Derivatives

In this section we will illustrate two applications of the multi-country model, calculating the Value at Risk of international bond portfolios and pricing cross-country derivatives. Also, we will compare the implications of the multi-country model with those of the single-country models that were analyzed in

section 3. As a counterpart to the five-factor multi-country model for hedged bond returns, we construct a five-factor model based on the single-country models for the US, Germany and Japan. Of course, there are several ways to combine these single-country models. We will choose a very simple combination of the single-country models: three of the five factors are the level factors for the US, Germany, and Japan, as given in figures 2a-c, and the other two factors are given by the (single-country) steepness factors for Germany and Japan. In this way both the multi-country model and the combined single-country model describe level and steepness movements of term structures in the US, Germany, and Japan. In this combined single-country model, each factor only influences (hedged) bond returns in one country. As it is assumed that the factors are uncorrelated, this model implies zero correlations between (hedged) bond returns in different countries. By comparing the combined single-country model and the multi-country model, we can assess the importance of a joint analysis of international bond returns.

For simplicity and analytical tractability, we assume for both the Value at Risk analysis and the derivative price analysis that the bond returns follow a multivariate normal distribution.

5.1 Value at Risk Analysis

Under the normality assumption, the Value at Risk (for a one week horizon) with confidence level $(1-\alpha)$ of a bond portfolio with weights w can be calculated as

$$VaR_t(\alpha) = r_t^{US} + w'\Gamma\lambda + \Phi^{-1}(\alpha)\sqrt{w'\Gamma\Gamma'w} \quad (9)$$

The portfolios that we analyze are the factor mimicking portfolios that correspond to the five factors of the combined single-country model and the multi-country model, respectively. In this way, we analyze both whether the multi-country model correctly describes the country-specific term structure factors, and how well the combined single-country model describes the global term structure factors. Note that the factor mimicking portfolios represent almost all variation in national and international bond returns. By construction, the combined single-country model yields the appropriate estimate for the Value at Risk of the factor mimicking portfolios corresponding to the factors of this model. The same holds for the multi-country model and its factor mimicking portfolios.

In table 6, we give the Value at Risk estimates. According to the results in the upper panel, the multi-country model provides very accurate estimates of the Value at Risk of the country-specific factor mimicking portfolios: the differences with the VaRs of the combined single-country model are small and statistically insignificant. Hence, the movements in the country-specific term structures can be described satisfactorily by the multi-country model. As shown in the lower panel, the combined single-country

model yields estimates of the Value at Risk of the international factor mimicking portfolios that are significantly different from the (correct) VaRs of the multi-country model. This is a direct result of the zero correlation between bond returns across countries in this model. Consequently, in terms of VaRs, the multi-country model outperforms the combined single-country model.

5.2 Pricing of Cross-Country Derivatives

As a second application, we show how to calculate prices of cross-country interest rate derivatives. To be able to do so, we interpret the residual terms in equation (1) as measurement error in the bond index data. Then the model in (1) can be seen as a discretization of the multi-currency extension of the Heath, Jarrow and Morton (1992) framework, as described in Frachot (1995)¹⁰, with normally distributed interest rates. Because the US bonds as well as the hedged German and Japanese bonds pay out in US \$, all these assets should have a drift that is equal to the US short rate under the risk-neutral equivalent martingale measure. Hence, if we choose the US money market account as numeraire, and set the market prices of factor risk all equal to zero, we obtain the discretized process of bond returns under the unique equivalent martingale measure. This process can directly be used to obtain prices for derivatives whose payoffs depend on these bond returns. For simplicity, we ignore possible variation in the US short rate r_t^{US} when valuing the derivatives¹¹.

The derivatives that we analyze are basket options. These basket options pay out a notional amount times the maximum of the returns on bond indices of a given maturity in the US, Germany and Japan. If all three returns are negative, the option payoff is equal to zero. We choose the option maturity period equal to one year. This contract clearly depends on the correlation between bond returns in different countries, so that we can measure the influence of the assumption of zero cross-country correlations via this instrument.

For comparison, we not only calculate option prices on the basis of the combined single-country model and the multi-country model, but also on the basis of models with one factor and fifteen factors. In case of the 1-factor model, the factor is given by the first factor of the multi-country model. This model implies that bond returns of different maturities and different countries are all perfectly correlated. The 15-factor model exactly fits the covariance matrix of the 15 bond returns that are modeled. We shall measure the performance of the other models by comparing their implied derivative prices with the derivative prices that are implied by the 15-factor model.

¹⁰In equation (1), bond returns with a fixed maturity are modeled, instead of a fixed maturity date, as is done by HJM (1992). Brace and Musiela (1995) provide a modeling framework, similar to the HJM (1992) framework, on the basis of fixed maturity bond returns.

¹¹Given the underlying continuous-time framework of Frachot (1995), it is, in principle, possible to derive the process of the short rate from the processes of bond prices of all maturities.

In table 7, we report the prices of the basket options as a percentage of the notional amount. Except for the 1-3 year maturity index, the prices on the basis of the multi-country model are closer to the prices from the 15-factor model than the prices from the combined single-country model. Because the combined single-country model neglects the positive bond return correlations across countries, it overestimates the prices of the options (compared to the 15-factor model). The multi-country model slightly underestimates the value of the options, because it contains a subset of the factors in the 15-factor model. In all cases, the one-factor model clearly underestimates the value of the derivative prices, because this model largely underestimates the variance of bond returns.

6 An Extension to Unhedged Bond Returns

In this section, we analyze a multi-country model for both hedged bond returns and DM/\$ and Yen/\$ currency returns. In this way, the risk of international bond portfolios that are not hedged for currency risk can also be analyzed with a multi-country model. Therefore, we re-estimate the linear factor model in equation (1), but now for the 17-dimensional return vector \tilde{R}_t . Again, we choose to estimate a low-dimensional factor model, because almost all variation in the bond returns can be explained by a low number of factors. More specifically, we estimate a seven-factor model. As shown in table 4, this model explains 97.4% of the bond and currency return variation.

To facilitate the interpretation of the factors, we perform an orthonormal rotation of the estimated factor loadings. We rotate the seven factors, by choosing the orthonormal rotation matrix that minimizes the sum of squared differences between the rotated factor loadings for hedged bond returns and the factor loadings of the five factors of the multi-country model of section 4. It turns out that it is possible to obtain almost exactly the same factor loadings for hedged bond returns for the first five factors as for the multi-country model of section 4. Therefore, we only report the loadings on the hedged bond returns for the factors 6 and 7, as well as the loadings on the currency returns for all seven factors; see figures 7a-c. In figure 7a we see that, of the first five factors, the German and Japan steepness factors are correlated with movements in the Yen/\$ and DM/\$ exchange rates, respectively. The 6th and 7th factor are essentially currency factors. The 6th factor mostly influences the Yen/\$ exchange rate, and hardly influences hedged bond returns. The 7th factor primarily influences the DM/\$ exchange rate. This factor also causes some movements in the term structures of the US and Japan. We again test for the number of factors, and find that, even for the fifteen-factor model, the hypothesis of equality of the 16th and 17th eigenvalues is rejected. However, the explained variation of these additional factors is low, and the factor loadings are always individually significant.

Summarizing, including the currency returns requires two extra factors to explain the same amount of variation in hedged bond returns, but these two additional factors are not simply a DM/\$ factor and a

Yen/\$ factor. Instead, to account for the correlation between the two currencies and the correlation between bond and currency returns, all factors influence both bond and currency returns.

Note that the confidence intervals of the factor loadings for the currency returns are much larger than for the hedged bond returns. Apparently, the correlations between hedged bond returns and currency returns are less accurately estimated than the correlations between hedged bond returns in different countries.

Finally, we again estimate the market prices of factor risk for the seven factors of this model. The results, not reported here, are very similar to the case of hedged bond returns: the first two factors have the largest prices of risk, and these two factor risk prices are significantly different from zero at the 10% significance level. For all other factors the prices of risk are insignificant. In particular, the 6th and 7th factors, that represent primarily currency movements, have insignificant prices of risk.

7 Conclusions

In this paper we jointly analyze bond returns of different maturities in the US, Germany and Japan. In particular, by specifying and estimating a linear factor model for these bond returns, we attempt to identify the common factors that determine these international bond returns.

We find that a five-factor model explains almost all variation in international bond returns that are hedged for currency risk. All these factors either influence the level or the steepness of the term structure of interest rates in different countries. Changes in the level of the term structure turn out to be positively correlated across countries, while changes in the steepness of the term structures are country specific.

The five-factor model also provides a good fit of the expected returns on the bonds of different maturities and different countries. Estimation of the factor risk prices reveals that only the first two factors have significant risk prices.

We compare this multi-country model with a simpler model, that is a combination of single-country linear factor models and implies zero cross-country bond return correlations. This comparison is twofold. First, we calculate the Value at Risk for several international bond portfolios, and second, we calculate prices of cross-country interest rate derivatives. In both cases the multi-country model has a better performance, indicating that neglecting the correlation between bond returns in different countries can lead to incorrect estimates for the Value at Risk and derivative prices.

Finally, we extend the model by adding currency returns, so that the model describes returns on bond positions that are not hedged for currency risk as well. In this case, a seven-factor model explains almost all variation in bond and currency returns. The first five factors of this model are very similar to the five factors of the model for hedged bond returns only, and the additional two factors mainly describe currency returns.

Appendix: Bootstrapping of Principal Components Analysis

In this appendix we show how the bootstrap technique can be used to calculate standard errors and confidence intervals for the PCA estimates.

Given the linear factor model defined in equations (1) and (2), the covariance matrix of bond returns can be decomposed as in equation (6). The first K principal components x_1, \dots, x_K of the covariance matrix Σ are defined by

$$\begin{aligned}\Sigma x_i &= \delta_i x_i \\ x_i' x_i &= \delta_i, \quad i=1, \dots, K \\ \delta_1 &\geq \delta_2 \geq \dots \geq \delta_K > \sigma^2\end{aligned}\tag{A.1}$$

As shown by Basilevsky (1995), for the linear factor model in equation (1), the solution to (A.1) is given by

$$\begin{aligned}x_i &= \Gamma_i \sqrt{\frac{\Gamma_i' \Gamma_i + \sigma^2}{\Gamma_i' \Gamma_i}} \\ \delta_i &= \Gamma_i' \Gamma_i + \sigma^2, \quad i=1, \dots, K \\ \text{with } \Gamma_1' \Gamma_1 &\geq \Gamma_2' \Gamma_2 \geq \dots \geq \Gamma_K' \Gamma_K\end{aligned}\tag{A.2}$$

Furthermore, the remaining $3M-K$ eigenvalues are all equal to σ^2 .

Hence, given a sample estimate $\hat{\Sigma}$ of the covariance matrix Σ and corresponding eigenvectors or principal components $\hat{x}_1, \dots, \hat{x}_K$ and eigenvalues $\hat{\delta}_1, \dots, \hat{\delta}_K$ of $\hat{\Sigma}$, estimates of the factor loadings Γ and the residual variance σ^2 can be obtained as follows

$$\begin{aligned}\hat{\Gamma}_i &= \hat{x}_i \sqrt{\frac{\hat{\delta}_i - \hat{\sigma}^2}{\hat{\delta}_i}}, \quad i=1, \dots, K \\ \hat{\sigma}^2 &= \frac{1}{3M-K} \sum_{i=K+1}^{3M} \hat{\delta}_i\end{aligned}\tag{A.3}$$

To approximate the bootstrap distribution of these estimates, suppose one has T time-series observations on the $3M$ bond returns. We assume that these bond returns are iid distributed over time. Then, draw T times with replacement from these T time-series observations, and calculate eigenvectors, eigenvalues, and the factor loadings from equation (A.3). By repeating this procedure sufficiently many times, the bootstrap distribution of the eigenvectors, eigenvalues and factor loadings can be approximated, which can be used to construct confidence intervals and test statistics as described in the text. For example, if we define \hat{v} as the vector that contains the pairwise differences between the smallest $3M-K$ eigenvalue estimates, $(\hat{\delta}_{K+2} - \hat{\delta}_{K+1}), \dots, (\hat{\delta}_{3M} - \hat{\delta}_{3M-1})$, and if we define \hat{V} as the bootstrap covariance matrix of this vector, the test statistic for testing whether the smallest $3M-K$ eigenvalues are equal to each other, is given by

$$\hat{v}' \hat{V}^{-1} \hat{v} \tag{A.4}$$

Under the assumption that bond returns are iid distributed, the vector \hat{v} is, under the null hypothesis, asymptotically normally distributed, with mean zero and covariance matrix V , so that the test statistic is asymptotically χ_{3M-K-1}^2 distributed.

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Table 1. Descriptive Statistics Hedged Bond and Currency Returns.

Summary statistics are calculated from 510 weekly observations from January 1990 until October 1999, for hedged bond returns and DM/\$ and Yen/\$ currency returns. All returns are in US dollars, and defined as in equations (4) and (5). The results are presented on a weekly basis, except for the average and standard deviation, which have been annualized assuming zero autocorrelation of weekly returns.

	Average Return	Standard Deviation	Skewness	Kurtosis	Auto- correlation
US 1-3 Years	6.43%	1.70%	-0.12	3.71	-0.03
US 3-5 Years	7.26%	3.62%	-0.17	3.52	-0.09
US 5-7 Years	7.65%	4.87%	-0.30	3.92	-0.12
US 7-10 Years	7.82%	6.24%	-0.37	4.21	-0.14
US >10 Years	8.49%	8.84%	-0.32	4.19	-0.14
Germany 1-3 Years	6.12%	2.84%	0.06	5.98	-0.34
Germany 3-5 Years	6.95%	3.56%	0.12	4.10	-0.18
Germany 5-7 Years	7.45%	4.29%	-0.17	6.14	-0.14
Germany 7-10 Years	7.34%	5.44%	-0.70	5.80	-0.05
Germany >10 Years	8.26%	8.31%	-0.43	5.13	-0.07
Japan 1-3 Years	7.50%	3.06%	0.73	9.23	-0.36
Japan 3-5 Years	9.80%	4.34%	0.62	7.01	-0.16
Japan 5-7 Years	10.07%	5.05%	0.25	5.88	-0.12
Japan 7-10 Years	10.36%	6.19%	0.16	5.74	-0.06
Japan >10 Years	10.96%	7.79%	-0.11	5.50	0.08
DM/\$ Currency Return	-0.34%	11.18%	-0.08	4.11	-0.08
Yen/\$ Currency Return	-0.19%	12.81%	0.98	9.19	-0.03

Table 2. Average Correlations Hedged Bond Returns and Currency Returns.

Correlations are calculated from 510 weekly observations from January 1990 until October 1999, for hedged bond returns and DM/\$ and Yen/\$ currency returns, and averaged over the five bond maturity classes for each country.

	US	Germany	Japan	DM/\$	Yen/\$
US Bond Returns	1				
German Hedged Bond Returns	0.29	1			
Japanese Hedged Bond Returns	0.11	0.28	1		
DM/\$ Currency Return	0.14	-0.08	-0.08	1	
Yen/\$ Currency Return	-0.01	0.06	-0.05	0.44	1

Table 3. Explained Variance Single-Country Three-Factor Models.

For hedged bond returns in each country, a separate three-factor model is estimated using principal component analysis. The table reports the average explained variance for each factor as a fraction of the total variance of bond returns, calculated using equation (3), as well as the standard error of this ratio in brackets. This standard error is calculated applying the bootstrap technique.

	Factor 1	Factor 2	Factor 3	Total
US Bond Returns	96.91% (0.27%)	2.68% (0.25%)	0.24% (0.03%)	99.83% (0.17%)
German Hedged Bond Returns	84.91% (2.01%)	10.73% (1.71%)	2.98% (0.32%)	98.62% (1.24%)
Japanese Hedged Bond Returns	89.64% (1.03%)	7.22% (0.81%)	1.83% (0.19%)	98.69% (0.75%)

Table 4. Explained Variance Multi-Country Models.

For hedged bond returns in all countries, a five-factor model is estimated using principal component analysis. For hedged bond returns and currency returns, a seven-factor model is estimated. The table reports the average explained variance for each factor as a fraction of the total variance, as well as the standard error of this ratio in brackets. This standard error is calculated applying the bootstrap technique.

	Multi-Country Model: Hedged Bond Returns	Multi-Country Model: Hedged Bond Returns and Currency Returns
Factor 1	46.62% (2.32%)	27.48% (0.79%)
Factor 2	27.49% (1.97%)	16.77% (1.36%)
Factor 3	16.94% (1.28%)	10.21% (0.49%)
Factor 4	3.13% (0.23%)	8.10% (0.17%)
Factor 5	2.31% (0.24%)	6.21% (0.11%)
Factor 6	-	14.94% (0.42%)
Factor 7	-	13.72% (0.34%)
Total	96.49% (1.25%)	97.41% (1.12%)

Table 5. Factor Risk Prices Multi-Country Model for Hedged Bond Returns.

For each factor of the multi-country model, the market price of factor risk is estimated using GMM as described in the text. The table reports annualized market prices of risk, which can thus be interpreted as the expected excess return on the factor mimicking portfolio, divided by the standard deviation of this excess return. Standard errors are in brackets, and calculated applying the bootstrap technique. As a test of the overidentifying restrictions in equation (7), we also present the GMM J-statistic and the associated p-value, for one-factor to five-factor models. The number of overidentifying restrictions is equal to 15 minus the number of factors. The last column contains the R^2 , which measures the fit on expected returns for one-factor to five-factor models.

	Factor Price of Risk (Standard Error)	J-statistic (p-value)	Cross-sectional R^2
Factor 1	0.81 (0.33)	28.32 (0.013)	75.5%
Factor 2	0.56 (0.34)	25.27 (0.021)	96.5%
Factor 3	-0.13 (0.34)	25.12 (0.014)	97.2%
Factor 4	0.23 (0.32)	24.57 (0.010)	97.6%
Factor 5	0.43 (0.33)	22.88 (0.011)	98.5%

Table 6. Value at Risk of Factor Mimicking Portfolios.

For the combined single-country model and the multi-country model for hedged bond returns, the 95%-Value at Risk is calculated for a one-week horizon. The portfolios that are analyzed are the factor mimicking portfolios (FMP) of the combined single-country model and multi-country model, respectively. The last column contains t-ratios of the difference between the VaRs, which are calculated applying the bootstrap technique.

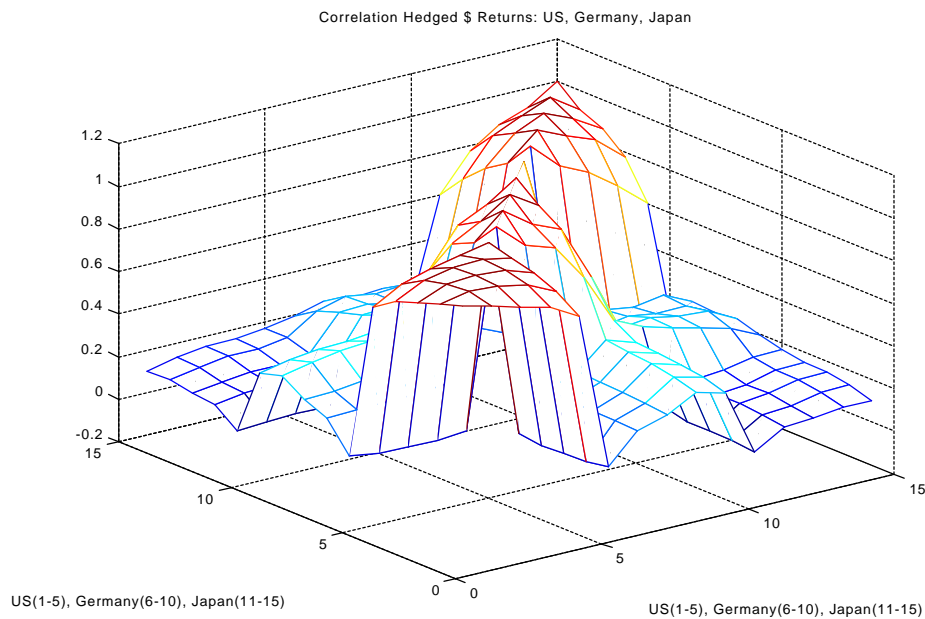
	Combined Single-Country Model	Multi-Country Model	t-Ratio of Difference
<i>Factor Mimicking Portfolios (FMP)</i>			
<i>Combined Single-Country Model</i>			
US Level Factor	-1.25%	-1.25%	-1.60
Germany Level Factor	-1.07%	-1.07%	-0.61
Japan Level Factor	-0.86%	-0.89%	0.75
Germany Steepness Factor	-1.07%	-1.07%	-0.73
Japan Steepness Factor	-0.97%	-0.96%	-0.95
<i>Factor Mimicking Portfolios (FMP)</i>			
<i>Multi-Country Model</i>			
World Level Factor	-0.62%	-0.80%	7.73
Japan minus US Level Factor	-3.18%	-2.98%	-2.56
Germany minus US Level Factor	-9.65%	-7.62%	-5.49
Germany Steepness Factor	-0.79%	-0.73%	-4.07
Japan Steepness Factor	-1.73%	-1.61%	-3.32

Table 7. Prices of Basket Options.

For the combined single-country model and the multi-country model for hedged bond returns, prices of 1-year basket options are calculated. Each basket option pays out a notional amount times the maximum of the returns on the bond-indices in US, Germany, and Japan, for a certain maturity class. The table contains the model option prices as percentage of the notional amount. For comparison, the option prices from models with 1 factor and 15 factors, respectively, are also presented.

	1-Factor Model	Combined Single-Country Model	Multi-Country Model	15-Factor Model
1-3 Year Bond Index	0.46%	1.98%	1.93%	2.11%
3-5 Year Bond Index	1.12%	3.22%	2.93%	3.01%
5-7 Year Bond Index	1.48%	3.99%	3.71%	3.73%
7-10 Year Bond Index	1.94%	5.03%	4.53%	4.58%
>10 Year Bond Index	2.80%	7.10%	6.49%	6.53%

Figure 1. Correlation Matrix Hedged Bond Returns. The graph contains correlations between (currency-hedged) bond returns for weekly data from 1990 to 1999. On the x- and y-axis, the numbers 1-5 correspond to US returns, with maturities from 1-3 years to >10 years, the numbers 6-10 correspond to German bond returns (in US \$), and the numbers 11-15 correspond to Japanese bond returns (in US \$).



Figures 2a-c. Results Single-Country Models. For each country, a three-factor model is estimated for (hedged) bond returns. The graphs contain estimates and 95%-confidence intervals for the factor loadings of the three factors. The factor loadings represent the weekly return that would be caused by a one standard deviation shock to the factor. The confidence intervals are obtained applying the bootstrap technique.

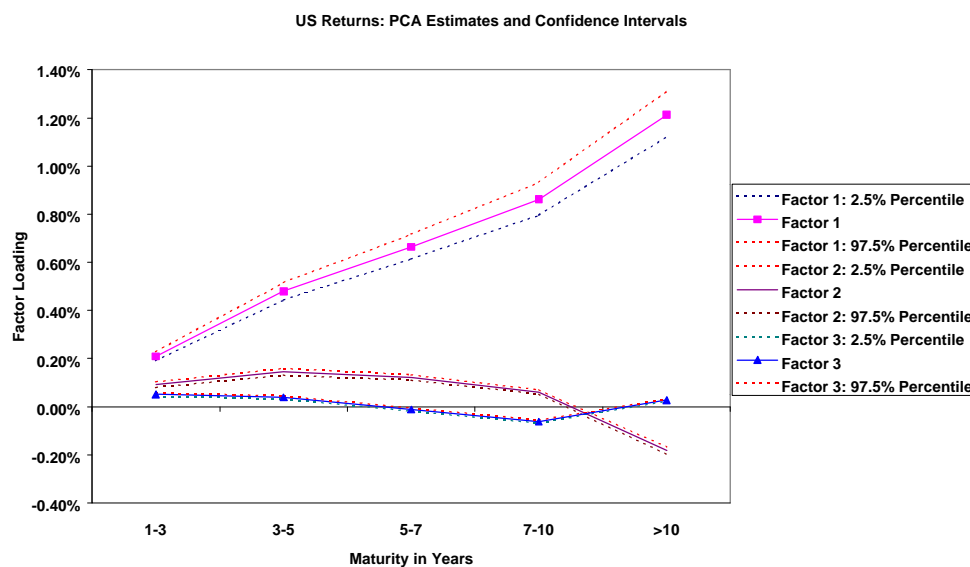


Figure 2a

Figure 2b

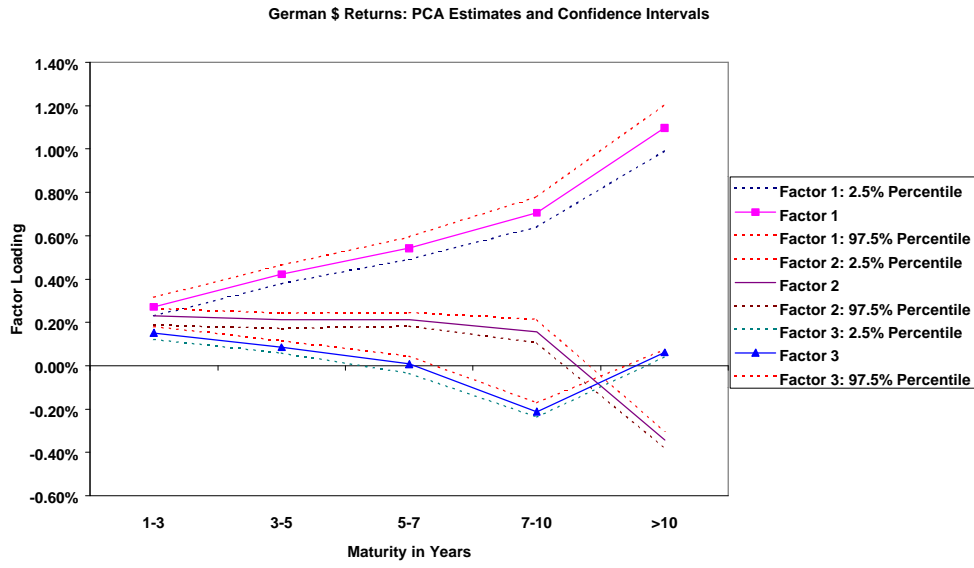
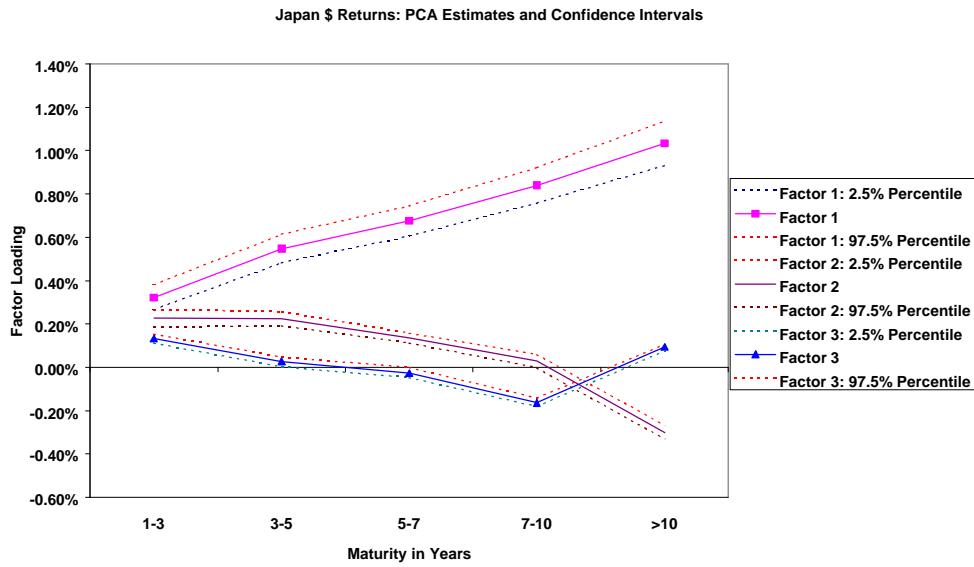


Figure 2c



Figures 3a-e. Results Multi-Country Model for Hedged Bond Returns. A five-factor model is estimated for (hedged) bond returns in US, Germany, and Japan. The graphs contain estimates and confidence intervals for the factor loadings of the five factors. The factor loadings represent the weekly return that would be caused by a one standard deviation shock to the factor. The confidence intervals are obtained applying the bootstrap technique.

Figure 3a

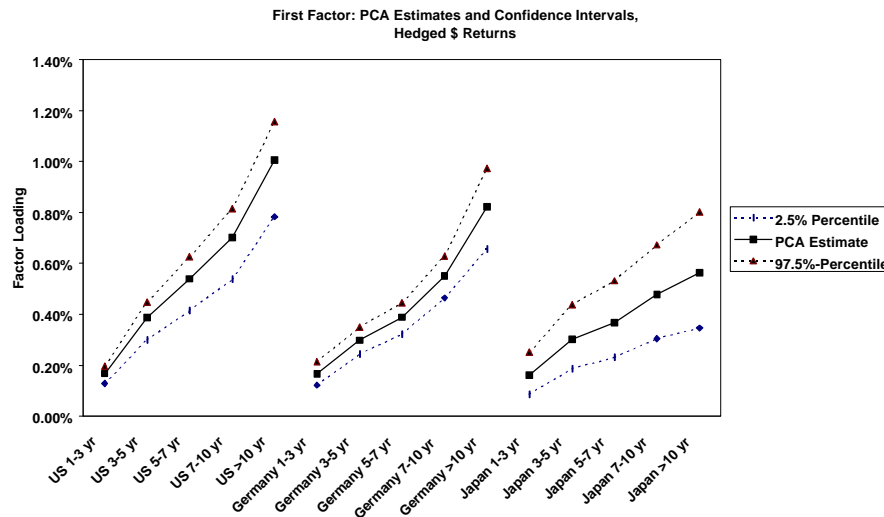


Figure 3b

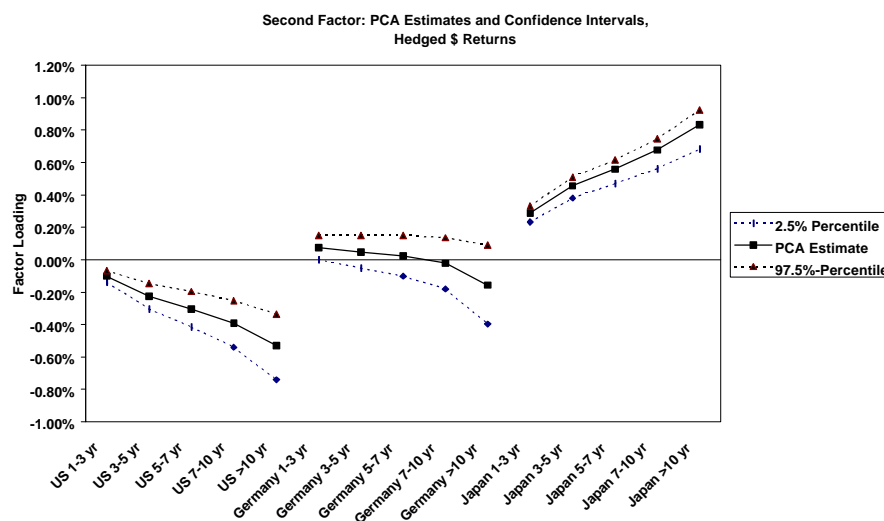


Figure 3c

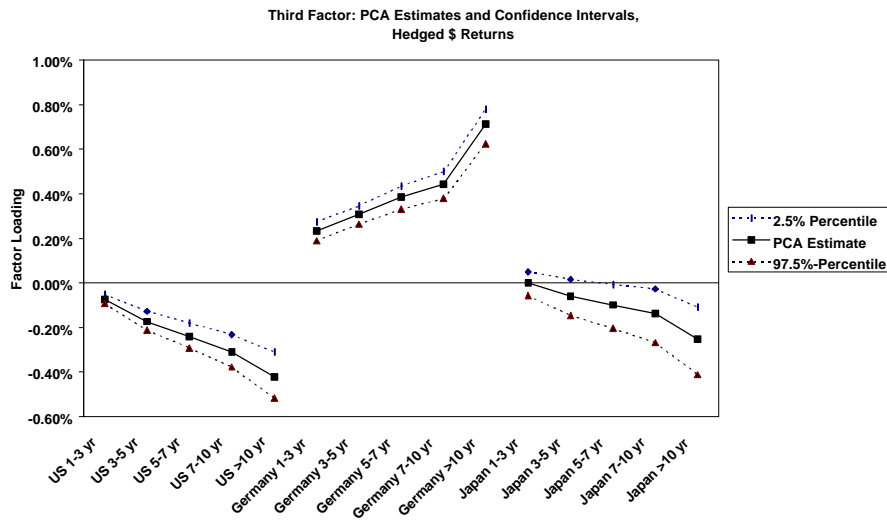


Figure 3d

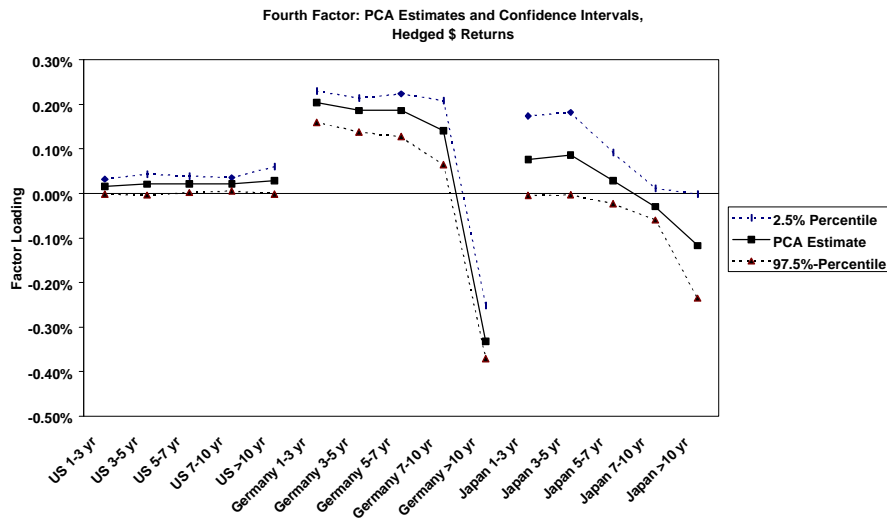


Figure 3e

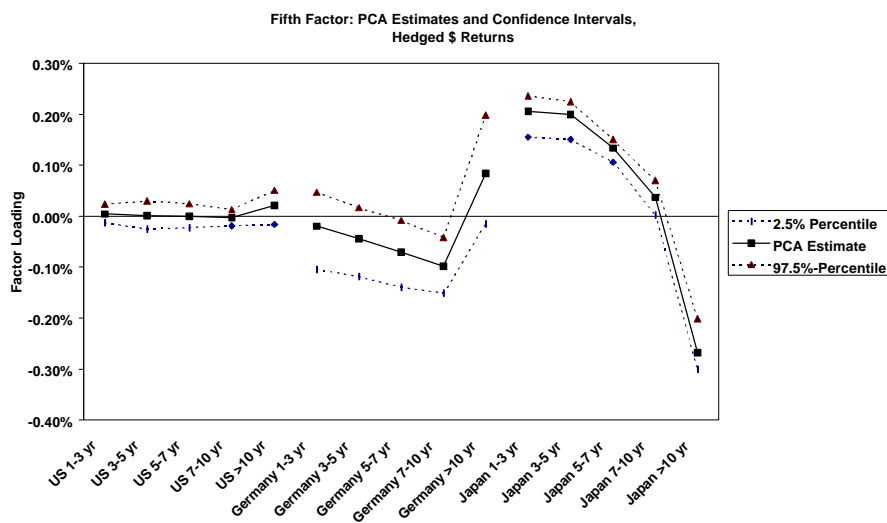


Figure 4. Explained Variance Multi-Country Model for Hedged Bond Returns. The graph shows the explained variance relative to the total variance in bond returns for each country, as a function of the number of factors.

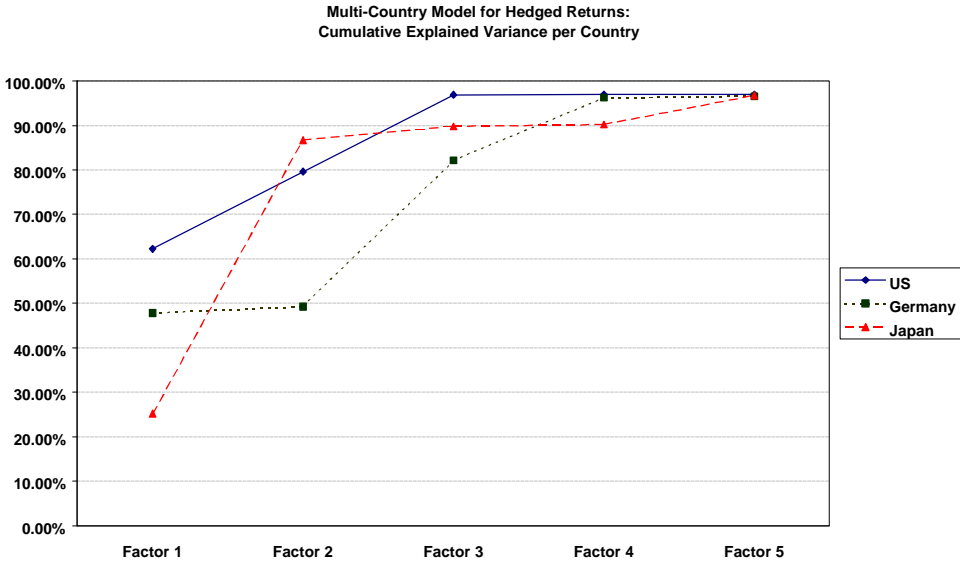


Figure 5. Duration Factors. The graph shows the factor loadings associated with Macaulay’s duration and the duration of Thomas and Willner (1997). The graph also contains the factor loadings of the first factor of the multi-country model. The factor loadings represent the weekly return that would be caused by a one standard deviation shock to the factor.

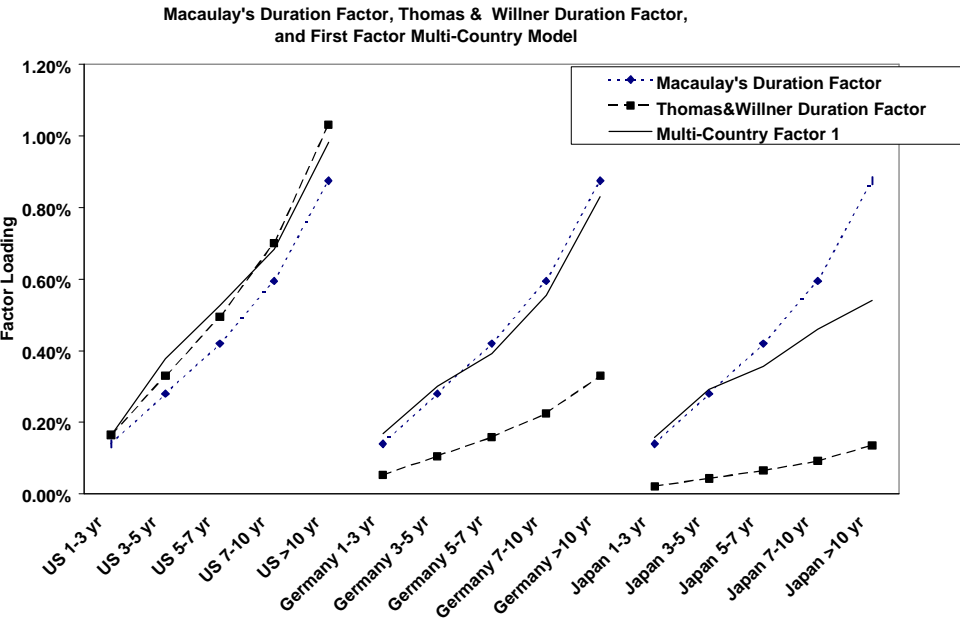
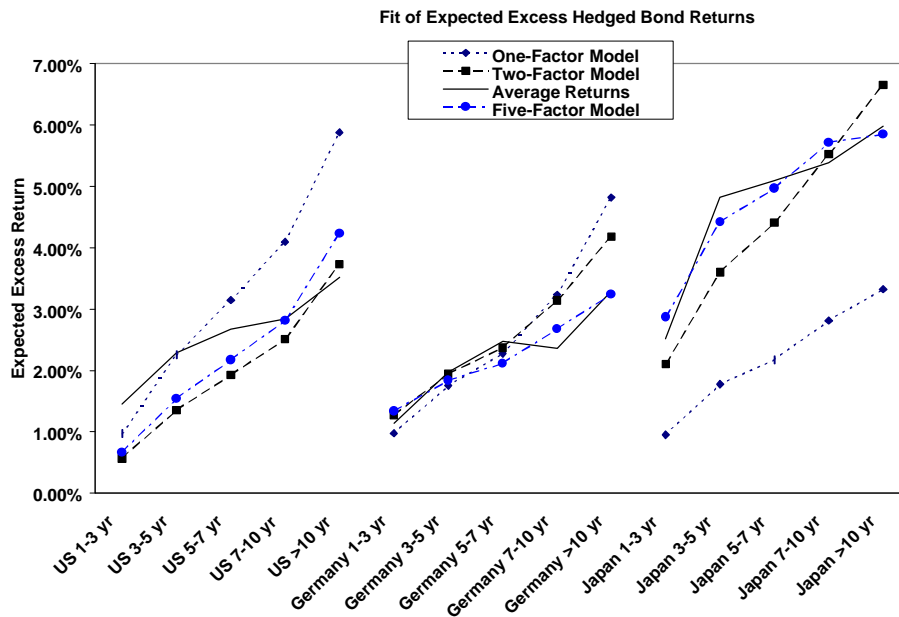


Figure 6. Expected Excess Hedged Bond Returns Implied by One-factor, Two-factor, and Five-factor Models, and Average Returns. The figure contains the expected excess hedged bond returns, as implied by one-, two-, and five-factor models (equation (7)). The sample averages for the excess hedged bond returns are also graphed.



Figures 7a-c. Results Multi-Country Model for Hedged Bond Returns and Currency Returns. A seven-factor model is estimated for (hedged) bond returns in US, Germany, and Japan, and DM/\$ and Yen/\$ currency returns. The factor loadings are rotated as described in the text. Figure 5a contains estimates and confidence intervals for the factor loadings of currency returns for the seven factors. The factor loadings represent the weekly return that would be caused by a one standard deviation shock to the factor. The confidence intervals are obtained applying the bootstrap technique. Figures 5b and 5c contain the factor loadings of hedged bond returns for the factors 6 and 7.

Figure 7a

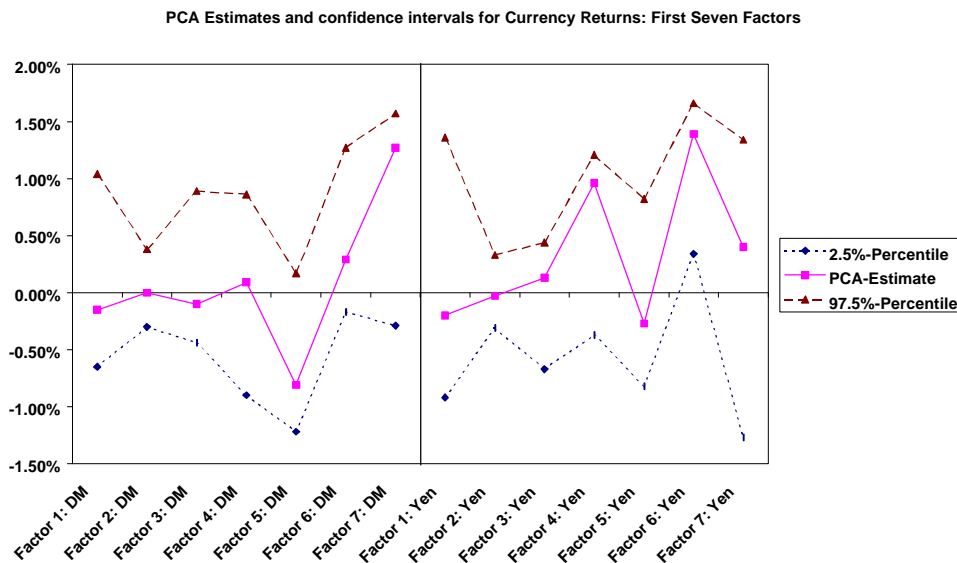


Figure 7b

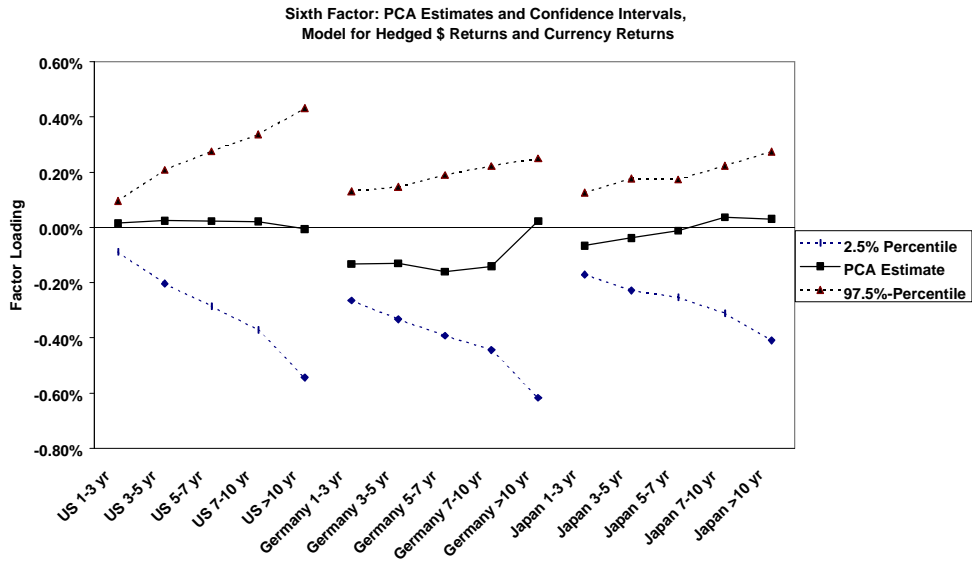


Figure 7c

