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An economic capital model integrating credit and interest rate risk in the banking book

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Abstract

Banks often measure credit and interest rate risk separately and then add the two risk measures to determine their overall economic capital. This approach misses complex interactions between the two risks. We develop a framework where credit and interest rate risks are analysed jointly. We focus on a traditional banking book where all positions are held to maturity and subject to book value accounting. Our simulations show that interactions between risks matter, and that their implications depend on the structure of the balance sheet and on the repricing characteristics of assets and liabilities. The analysis suggests that a joint analysis of risks can deliver substantially different results relative to a piece-wise approach: risk integration is challenging but feasible and worthwhile.

Key words: Economic capital, risk management, credit risk, interest rate risk, asset and liability management.

JEL classification: G21, E47, C13.

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Summary

Banking activities are subject to various types of risk, including credit, market and liquidity risk. As part of their risk management, banks need to monitor and quantify these risks on a continuous basis, maintaining capital and liquidity buffers that are sufficient to protect them against large, negative shocks. Various analytical tools have been developed to look at these risks in isolation, especially for credit and market risk. However, no unified economic capital model exists which integrates risks in a consistent fashion. Therefore, banks generally analyse risks in isolation, deriving total economic capital by some rule of thumb. Indeed, a common rule consists of calculating risk-specific buffers and then simply adding them up (possibly subject to a correlation adjustment) to calculate a bank's total capital. The conventional wisdom is that, since risks are only imperfectly correlated, adding up always delivers a conservative capital buffer. However, recent research and experience in the financial sector has shown that this is a fallacy; under some circumstances, risks actually amplify one another and additive rules of thumb do become dangerous. This is an important result for both practitioners and regulators, and it represents a crucial motivation for this work: the main aim of the paper is to investigate to what extent standard, traditional banking (in a sense to be defined below) is subject to this risk amplification problem.

The conceptual contribution of this paper is the derivation of an economic capital model which consistently integrates credit and interest rate risk in the banking book. The paper does not address the issue of what the appropriate level of capital for a bank is; we focus instead on the narrower question of how this level of economic capital is influenced by interactions between risks. According to industry reports, credit and interest rate risk represent the most important sources of risk for a standard 'banking book'. Furthermore, there are good reasons to believe that these risks interact in a non-trivial way. Interest rates and default frequencies are linked to the state of the business cycle; hence, they are implicitly driven by a common set of macroeconomic factors. Interest rates are themselves an important determinant of credit risk: borrowers are more likely to default when interest rates are high. Finally, a bank's interest income depends on its credit risk profile in that credit losses reduce the stock of assets that generate interest payments.

Credit and interest rate risk are modelled in line with standard practices. The credit risk component is based on the same conceptual framework as Basel II and the main commercially available credit risk models. Interest rate risk, on the other hand, is captured by earnings at risk, a well-established metric among practitioners. The key innovation of the paper is in the way risks are integrated. The model explicitly links the systematic component of these risks to a common set of macroeconomic factors. Furthermore, net interest income is modelled dynamically, taking into account the fact that interest rates adjust in response to shifts in the risk-free yield curve and/or changes in the riskiness of the underlying credit exposures. This makes it possible to capture any income compression due to the repricing mismatch between long-term assets and short-term liabilities.

The model is applied to a stylised bank whose portfolio is designed to broadly replicate a standard UK banking book in terms of types of exposures (including corporate, mortgage and credit cards loans), size of the loans and pricing maturities. All loans are assumed to be held to

maturity and subject to book value accounting. By running numerical simulations, we derive distributions of profits and losses under a range of possible macroeconomic scenarios. We then compare ‘simple’ (ie additive) economic capital to an ‘integrated’ capital that takes into account interactions across risks.

The main result of the analysis is that in the narrow set of circumstances tested here the conventional wisdom holds up: simple capital exceeds integrated capital. In other words, in this particular exercise, a simple approach to aggregating credit risk and interest risk in the retail loan book does not lead to an underestimation of risk, compared to an approach that takes into account the interactions between the two sources of risk. The difference between the two depends on various features of the bank, such as granularity of the portfolio, funding structure and pricing behaviour, but it is positive under a broad range of circumstances. Various factors contribute to generating this result. A relatively large portion of credit risk is idiosyncratic, and thus independent of the macroeconomic environment, and the correlation between systematic credit risk factors and interest rates is itself not perfect. Furthermore, as long as the bank’s portfolio can be repriced relatively frequently, any increase in credit risk can be partly passed on to borrowers.

Some caution is warranted on the generality of the exercise. The results cannot be used to argue that *in general* an economic capital model that fully integrates all risks would result in lower capital than that implied by simple aggregation rules. Neither does the paper address the issue of what is the appropriate level of capital for a bank. Since the paper focuses only on traditional banking book risks, it does not deal with insights relating to the recent crisis. Securitisation, derivatives and liquidity management, which were at the core of the turmoil, remain outside the scope of this work, and mark-to-market accounting is not taken into consideration. We also assume that banks recover a fixed fraction of any defaulted loan, thus abstracting from the impact of asset prices on recovery rates. Finally, we demonstrate that ‘traditional’ banking book risks do not generate perverse interactions. However, many banks manage large, complex portfolios that expose them to a wider range of risks than the ones we analyse here: our conclusions cannot be generalised to those cases. Furthermore, complexity might imply a stronger non-linearity in banks’ returns than the ones we examine here. As a consequence, banks should generally work on the assumption that additive rules are not reliable and could in some circumstances lead to underestimating economic capital. Developing integrated economic capital models is arguably a key priority for the industry going forward.

1 Introduction

'The Committee remains convinced that interest rate risk in the banking book is a potentially significant risk which merits support from capital' (Basel II, Section 762, Basel Committee (2006)).

The view expressed by the Basel Committee in the Basel II capital accord receives strong support from the data. According to industry reports, interest rate risk is, after credit risk, the second most important risk when determining economic capital for the banking book (see IFRI-CRO Forum (2007)). However, no unified economic capital model exists which integrates both risks in a consistent fashion for the banking book. Therefore, regulators and banks generally analyse these risks independently from each other and derive total economic capital by some rule of thumb. Indeed, a common rule consists of simply 'adding up'. A serious shortcoming of this procedure is that it obviously fails to capture the interdependencies between both risks. For example, the literature has shown consistently that interest rates are a key driver of default frequencies, ie interest rate risk drives credit risk. And as we will show, credit risk also drives interest rate risk in the banking book. This raises several questions: what is the optimal allocation of economic capital if the interdependencies are captured? Do additive rules provide a good approximation of the true integrated capital? More importantly, is the former approach always conservative or can both risks compound each in some circumstances? In order to answer these questions, we derive integrated economic capital for a traditional banking book and we compare it to economic capital set against credit as well as interest rate risk when interdependencies are ignored. We show that this is only possible by using an economic capital model, such as that developed in this paper, which consistently integrates credit and interest rate risk taking account of the complex repricing characteristics of asset and liabilities.

Traditionally it would be argued that if a portfolio is exposed to two imperfectly correlated risks, the sum of capital buffers set against the two ought to be larger than the (true) underlying economic capital level. Unfortunately, this is not generally the case. Breuer *et al* (2008) discuss this problem in the context of market and credit risk assessment for the banking and trading book. They show theoretically as well as empirically that under some circumstances the risk measure of the total portfolio (ie the bank) can be higher than the sum of the risk measures set for the two books independently. This possibility can arise whenever market and credit risk are not 'separable', in the sense that some exposures depend on both credit and market risk factors.

This result has strong implications for risk management as banks typically set capital against credit and interest rate risk independently, and then obtain a measure of total capital by simply adding these up (we label this 'simple economic capital' for convenience). If risks were separable and a sub-additive measure of risk is used, this procedure would always deliver an upper bound in comparison with the correct underlying capital. However, as we argue below, credit and interest rate risk interact in a complex, non-linear way. Depending on how strong these interactions are, it is possible in principle that simple economic capital will actually be lower than 'integrated economic capital', ie the desired capital level implied by a consistent, joint analysis of credit and interest rate risk.

The conceptual contribution of the paper is to derive an economic capital model which takes account of credit and interest rate risk in the banking book. Although new accounting standards allow banks to use the fair value option for some securities, most assets and liabilities in the banking book are valued at book value as banks hold them to maturity. Under book value accounting, profits and losses are accounted for only when they materialise, ie what matters are realised net cash flows and not changes in the economic value. The way we set capital against credit and interest rate risk individually is fully in line with standard practices. The credit risk component is based on the same conceptual framework as Basel II and the main commercially available credit risk models. Interest rate risk, on the other hand, is captured by earnings at risk, the approach banks commonly use to measure this risk type (see Basel Committee (2008)). In contrast to standard models, however, we integrate credit and interest rate risk using the framework proposed by Drehmann, Sorensen and Stringa (2008) (henceforth DSS) taking into account all relevant interactions between both risks. These are threefold: (a) both risks are driven by a common set of risk factors; (b) interest rates are an important determinant of credit risk; and (c) credit risk impacts significantly on net interest income. These interactions can be illustrated with a simple example. Consider a macroeconomic shock that shifts the yield curve upwards and depresses asset prices, thereby increasing credit losses. Since banks tend to borrow at shorter maturities that are more frequently repriced than their lending, interest margins are compressed and net interest income falls, which generates a further fall in net profits. Over time the bank can progressively reprice its exposures taking into account higher interest rates and credit risk. The repricing process boosts net interest income, offsetting the effects of higher funding costs and higher default rates. DSS analyse a similar stress scenario, showing that profits drop substantially at the beginning but start to recover after about one year, even before defaults reach their peak.

In this paper we show that changes in net interest income can be decomposed into two components: the first one captures the impact of changes in the yield curve, while the second accounts for realised credit losses, which implies a loss of interest payments on defaulted loans. As coupons only default in conjunction with the underlying loans, the latter component can be integrated easily into a standard credit risk model. Conditionally on the state of the macroeconomy, these two sources of income risk are independent. This important insight significantly simplifies their aggregation. It also underlines that conditioning on the macroeconomic environment is crucial for an economic capital model aiming to integrate credit and interest rate risk.

Assuming a one-year horizon, we apply our model to a stylised bank and compare the (true) integrated economic capital to simple economic capital, ie the sum of capital set separately against credit and interest rate risk. Economic capital is set in line with current market and regulatory practices as ‘the amount of capital a bank needs to absorb unexpected losses’ (page 9 Basel Committee (2008)). Our main finding is that, in the narrow case analysed here, simple economic capital adequately reflects these underlying risks. Obviously, this conclusion does not extend to the appropriate level of capital an institution needs to withstand a wider range of risks, as evidenced by the recent crisis. But in the context of our model – and subject to the caveats above – additive rules do not underestimate banking book risks.

The remainder of the paper is structured as follows. Section 2 provides a short overview of the literature. In Section 3 we derive the integrated economic capital model. Section 4 discusses our implementation and Section 5 presents the results. Section 6 undertakes some sensitivity tests. Section 7 concludes.

2 Literature

There is by now a large and well known literature on economic capital models for credit risk (for an overview see eg Gordy (2000) or McNeil *et al* (2005)). Most models are based on the idea that there is one or a set of common systematic risk factors which drive default rates of all exposures, but that conditional on a draw of systematic risk factors, defaults across exposures are independent. Our approach to credit risk modelling follows this tradition. However, contrary to most models, we condition credit risk and the yield curve on a common set of systematic risk factors. Furthermore, we account for the loss in coupon payments if assets default.

In contrast to credit risk, no unified paradigm has yet emerged on how to best measure interest rate risk in the banking book (eg see Kuritzkes and Schuermann (2007)). The Basel Committee points to this as an important reason why interest rate risk in the banking book is not treated in a standardised fashion in the Basel II capital framework (see Basel Committee (2006), Section 762). Interest rate risk in the banking book can either be measured by earnings at risk or using an economic value approach.[1] The latter measures the impact of interest rate shocks on the value of assets and liabilities (eg see OTS (1999)), whereas the former looks at the impact of the shocks on the cash flow generated by the portfolio (ie a bank's net interest income). Some banks have moved towards an economic value perspective, but this paper follows the traditional earnings at risk approach which is still heavily used in the industry and for regulatory purposes (see Basel Committee (2008)).

From the perspective of an integrated risk management framework, standard interest rate risk analysis has an important drawback: implicitly, these methods assume that shocks to the risk-free yield curve have no impact on the credit quality of assets. But clearly this assumption does not hold: interest rates risk and credit risk are highly interdependent and, therefore, need to be assessed jointly.[2]

Jarrow and Turnbull (2000) are among the first to show theoretically how to integrate interest rate (among other market risks) and credit risk. Their theoretical framework is backed by strong empirical evidence that change in interest rates impact on the credit quality of assets (see Duffie *et al* (2007) or Grundke (2005)). However, if papers integrate both risks, they look at the integrated impact of credit and interest rate risk on assets only, for example by modelling bond portfolios without assessing the impact of interest and credit risk on liabilities or off balance sheet items with different repricing characteristics.[3] Barnhill and Maxwell (2002) and Barnhill *et*

[1] See eg Staikouras (2006) for an overview of different methods. When modelling interest rate risk, hedging strategies are obviously crucial. Hedging is ignored or assumed away in most of the literature, and we do the same in our analysis – see Section 6 for a brief discussion of the implications of this assumption.
[2] The literature on modelling default is by now so large that an overview cannot be given in this paper. For recent examples showing a link between interest rates and credit risk see Carling *et al* (2006), Duffie *et al* (2007) or Drehmann *et al* (2006).
[3] An exception is the operations research literature discussing asset and liability management (for an overview see Zenios and Ziemba (2007)). However, only a few models allow for the possibility of default (eg see Jobst *et al* (2006)). In this case they only consider a

al (2001) measure credit and market risk for the whole portfolio of banks. They take a mark-to-market perspective but ignore one of the most important sources of interest rate risk – repricing mismatches between assets and liabilities.[4] While we do not take a mark-to-market perspective, our work focuses on the latter effect, providing a thorough description of how a bank's maturity structure and pricing behaviour affects its risk profile.

While we use the framework of DSS to derive net interest income, our implementation differs. For their stress test, DSS use a structural macroeconomic model which cannot be easily simulated. Instead, we use a two-country Global Vector Autoregression (Pesaran *et al* (2004)) which allows us to undertake stochastic simulations and therefore enables us to derive the full net profit distribution. Furthermore, in contrast to DSS, we look at both expected and unexpected credit risk losses.

So far there has been a limited discussion of how interdependencies across risks impact on economic capital. Decomposing net income into its components (ie market, credit, interest rate risk in the banking book, operational and other risks) and computing returns on risk weighted assets, Kuritzkes and Schuermann (2007) find that interest rate risk in the banking book is, after credit risk, the second most important source of financial risks. Furthermore, they show that there are diversification benefits between risks.

Significant diversification benefits are also found in studies which use simple correlations between different risks (Kuritzkes *et al* (2003) or Dimakos and Aas (2004)). However, as Breuer *et al* (2008) point out, these papers implicitly assume that risks are separable, which in the case of market (and hence interest rate risk) and credit risk is not necessarily true. As already discussed in the introduction, the authors find that total risk can be under as well as overestimated if market and credit risk are wrongly assumed to be separable.

This is consistent with the findings in Kupiec (2007). The paper extends a single-factor credit risk model to take into account stochastic changes in the credit quality (and hence the market value) of non-defaulting loans. The value of the resulting portfolio is a non-separable function of market and credit risk factors. The author compares an integrated capital measure to additive measures calculated under a range of credit and market risk models, and finds that no general conclusion can be reached on whether additive rules under or overestimate risk.

It is worth stressing that the diversification issue should ideally be examined within a model that integrates all relevant risks, and that such a model is not available to date. For instance, Kupiec (2007) and Breuer *et al* (2008) focus on the asset side, abstracting from any issues related to maturity mismatch and net interest income volatility, whereas in this paper we model these in detail but do not consider changes in the economic value of the portfolio. Therefore, the literature can currently only provide partial answers to the general question of when and why additive rules can underestimate risk.

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corporate bond portfolio funded by a simple cash account thereby ignoring the repricing mismatch between assets and liabilities as the most important source of interest rate risk.

[4] The papers look at a maturity mismatch of +/- one year and conclude that this is important. But +/- one year is clearly too simplistic to capture the full impact of the maturity mismatch on the riskiness of banks.

3 The framework

Throughout the framework discussion, we assume that the bank holds a portfolio of *N* assets with $A=[A^1,...,A^N]$. Each exposure A^i has a specific size, a time to repricing b^i, a default probability $PD_t^i(X)$, loss given default LGD^i, and coupon rate $C_t^i(X)$. For the derivation of the one period set-up in Section 3.1 we assume fixed coupons C^i; this assumption is relaxed in Section 3.2. Interest rates and defaults are driven by a common set of systematic risk factors *X*, that follow a generic probability distribution *F*. Following the literature, we also assume that conditional on *X,* defaults across different assets A^i are independent.

The bank is funded by *M* liabilities $L=[L^1,....,L^M]$. Each liability L^j falls into a repricing bucket b^j and pays a coupon rate $C_t^j(X)$. Coupon rates are again assumed to be fixed in the single-period framework but endogenous in the multi-period set-up. All assets and liabilities are held in the banking book, using book value accounting.

3.1 Single-period framework

In a standard portfolio model (eg see McNeil *et al* (2005)), the total loss *L* of the portfolio is a random variable and can be characterised by

$$L(X) = \sum_i^N \delta^i(X) A^i LGD^i \qquad \textbf{(1)}$$

where δ^i (X) is a default indicator for asset *i* taking the value *1* with probability $PD^i(X)$ and the value *0* with probability $(1-PD^i(X))$. We assume conditional independence.[5] Therefore, conditional on the state of systematic risk factors *X*, the default indicators $\delta^i(X)$ are *i.i.d.* Bernoulli random variables. Hence, our set-up is in the tradition of Bernoulli mixture models. It has been shown that all standard industry models such as CreditRisk+ or CreditPortfolioView but also Basel II, can be formulated in this fashion (eg see Frey and McNeil (2002)). Note that generally these models, and in particular Basel II, do not take changes in the mark-to-market value into account. The models only differ in their assumptions on the distribution of the systematic risk factors, the mapping between risk factors and PDs, and whether they are solved analytically or numerically.

Incorporating interest income in this framework is straightforward. Net interest income is simply interest payments received on assets minus interest payments paid on liabilities. Given our assumption of fixed-coupon rates, the only stochastic component of net interest income in the one period set-up is whether assets default or not. Take an asset A^i. If no default occurs, the cash-flow contribution to interest income is C^iA^i. In case of default, the cash-flow contribution is only $(1-LDG^i)C^iA^i$ as we assume that coupon payments can be partially recovered with the same recovery rate $(1-LGD^i)$ as the principal. Total realised net interest income *RNI* is therefore

[5] This is the standard assumption used in credit risk models implemented for day-to-day risk management, even though recent research has shown that this assumption does not necessarily hold (see Duffie *et al* (2007)).

$$
\begin{aligned}
RNI(X) &= \sum_i \left[C^i A^i - \delta^i(X) LGD^i C^i A^i\right] - \sum_j C^j L^j \\
&= \sum_i C^i A^i - \sum_j C^j L^j - \sum_i \delta^i(X) LGD^i C^i A^i \\
&= NI - \sum_i \delta^i(X) LGD^i C^i A^i
\end{aligned} \qquad \textbf{(2)}
$$

As can be seen from equation **(2),** realised net interest income can be decomposed into a component *NI* which excludes the effect of default ($NI = \sum_i C^i A^i - \sum_j C^j L^j$) and a term which sums over coupon losses due to crystallised credit risk. Given that coupon rates are pre-determined, *NI* is not stochastic. However, since coupons only default when the underlying asset defaults, the second random component can be incorporated into a redefined credit loss distribution L^*:

$$
L^*(X) = \sum_i^N \delta^i(X)(1 + C^i) A^i LGD^i \qquad \textbf{(1')}
$$

The unconditional distributions of both L and L^* is then derived numerically. Ultimately we are interested in net profits *NP(X)* which are the sum of credit risk losses and net interest income:

$$
NP(X)=RNI(X)-L(X)=NI-L^*(X) \qquad \textbf{(3)}
$$

Since *NI* is non-stochastic, only L^* introduces randomness into *NP*. Therefore, the net profit distribution is identical to the distribution of $-L^*$ bar a mean shift of the size of *NI* (see Figure A1 in the annex for a graphical representation).

Standard economic capital models for credit risk assume that the expected loss is covered by income, which implies zero expected profits. As an aside, it is interesting to observe that this condition holds exactly in our model if (a) the bank is fully funded by liabilities, (b) all liabilities pay the risk-free rate, (c) assets and liabilities have a repricing maturity of one period, and (d) assets are priced in a risk neutral fashion.[6] As will become apparent from our simulation results, any departure from this simple case will imply non-zero (typically positive) net profits.

3.2 The multi-period framework

In order to implement the model dynamically, we need to introduce explicit assumptions on the behaviour of banks and customers:

(i) Depositors are passive: once deposits mature, depositors are willing to roll them over maintaining the same repricing characteristics.

(ii) The bank does not actively manage its portfolio composition: if assets mature or default, the bank continues to invest into new projects with the same repricing and risk characteristics as the matured assets. At the end of each period, the bank also replaces defaulted assets with new assets which have the same risk and repricing characteristics.

[6] A proof of this claim can be found in Annex 1. We also implemented this simple example (fully matched bank, risk-neutral pricing, one-quarter horizon) in our simulations, confirming that mean net profits are indeed zero. Results are available on request.

These assumptions are essential to ensure that the bank's balance sheet balances at each point in time. While this is a fundamental accounting identity which must hold, risk management models often ignore it as profits and losses are not assessed at the same time. This is a crucial innovation in the framework of DSS. Assumption *(i)* implies that the volume and source of deposits does not change over time. Assumption (*ii*) is often used in practice by risk managers, who call this 'ever-greening' the portfolio. In case of default, the new asset is funded by reinvesting the recovery value of the defaulted loan and the remainder out of current profits or shareholder funds. We assume that any positive profits are held in cash until the end of the year and are not invested in additional loans.[7] This stock of cash is used as a buffer for negative net profits. Whenever the buffer is insufficient and capital falls below initial levels, we assume that shareholders inject the necessary capital at the end of the quarter. Taken together, our assumptions imply that at the beginning of each period the overall portfolio is the same in terms of risk and repricing characteristics. Clearly, our behavioural assumptions are to a certain degree arbitrary. We restrict ourselves to simple, commonly used behavioural rules rather than re-optimising the bank's portfolio in a mean-variance sense in each period as the latter would be beyond the scope of this paper.[8]

Figure 1 clarifies the timeline of the multi-period framework. The bank starts with an initial portfolio $A_0 = \sum_i A_0^i$ and $L_0 = \sum_j L_0^j$. Initial coupon rates for assets/liabilities ($C_0^i(X_0)/C_0^j(X_0)$) are priced based on macroeconomic conditions X_0 at time 0. At the beginning of $t=1$ a shock hits the economy changing the macro conditions to X_1, which can already be taken into account when the bank reprices all assets and liabilities with a time to repricing of 1. After repricing, credit risk losses are realised; then interest on assets and liabilities is paid, and net profits for the first period are calculated. Finally, the bank replaces the defaulted assets and reinvests matured assets and liabilities. Note that a different fraction of the portfolio is repriced in each period, as individual assets and liabilities have different times to repricing (see DSS for a detailed illustration of the dynamics of the pricing process).

3.2.1 Net income in the multi-period framework

In a dynamic set-up, coupons change over time reflecting movements in the yield curve and changes in the credit quality of the exposures; hence, *NI* is itself stochastic. The modelling approach is in line with DSS and it is discussed in Annex 1. Essentially, each asset (liability) can be repriced at a particular point depending on its time to repricing b_i (b_j). Conditional on a realisation of X, total net interest income $NI_t(X_t)$ in period t can therefore be written as

$$NI_t(X_t) = NI_t^A(X_t) - NI_t^L(X_t) \tag{4}$$

with

$$NI_t^A(X_t) = \sum_{i=1}^{N} \sum_{\tau=0}^{t} I_\tau^i \, C_\tau^i(X_\tau) A^i \tag{5}$$

[7] By holding profits in cash the bank foregoes potential interest payments. However, given the one-year horizon, these are immaterial. As a sensitivity test we replicated our baseline results under the assumption that profits earn the risk-free rate of return: the changes relative to baseline results were negligible (details are available upon request).

[8] DSS make similar behavioural assumptions, and provide an extensive discussion on how changes in these assumptions may affect their results. Their discussion largely applies to our framework as well.

$$NI_t^L(X_t) = \sum_{j=1}^{N} \sum_{\tau=0}^{t} I_\tau^j C_\tau^j (X_\tau) L^j \qquad \textbf{(6)}$$

Equation **(5)** sums across coupon incomes from different assets which have been repriced at different periods. Each exposure A^i has been (re)priced in some period $p^i<t$, and earns a coupon $C_{p^i}^i(X_{p^i})$ which was set based on the macroeconomic conditions that prevailed at time p^i. The indicator function I_τ^i (which is equal to one for $\tau=p^i$ and zero otherwise) identifies the point in time at which the repricing took place. Note that assets which had an initial time to repricing $b_i>t$ have not been repriced, so they still earn coupon rates $C_0^i(X_0)$.[9] Equation **(6)** looks at the liability side; the interpretation is analogous to equation **(5)**.

Equations **(5)** and **(6)** are at the heart of the model. They imply that for every macroeconomic scenario we need to track coupon rates for all asset and liability classes with different repricing maturities. Coupon rates in turn are set in different time periods and depend on the prevailing and expected macro factors at that point in time. In comparison to the standard credit risk model, this increases the computational complexity enormously.

3.3 The multi-period profit and loss distribution

Given our timing assumptions (see Figure 1), at every period t banks observe the latest risk factor realisation X_t before pricing their assets. Conditional on X_t, $NI_t(X_t)$ is non-stochastic; therefore, we can apply the framework developed in Section 3.1 on an iterative basis. This is a crucial insight of our framework as it allows us to disentangle interest income and credit risk losses including defaulted coupons. In each period, NI is determined by equation **(4)**, and losses due to the default of coupons and principals are determined by equation **(1')**. Note that coupon rates between periods may change and need to be incorporated into **(1')** in the dynamic set-up. Therefore credit risk losses including defaulted coupons conditional on X at time t are

$$L_t^*(X_t) = \sum_{i=1}^{N} \sum_{\tau=0}^{t} I_\tau^i \delta^i (X_t)\left(1 + C_\tau^i(X_\tau)\right) A^i LGD^i \qquad \textbf{(7)}$$

where I and δ are again indicator functions. $I_\tau^i=1$ for $\tau = p^i$, when asset A^i has been repriced the last time prior to time t, and $I_\tau^i=0$ otherwise. $\delta^i(X_t)=1$ if asset i defaults at time t, and $\delta^i(X_t)=0$ otherwise. The interpretation is again in line with equations **(5)** and **(6)**. Note however that the default indicator does not depend on the repricing maturity but only on credit conditions at time t. We can again define net profits as $NP_t(X_t) = NI_t(X_t) - L_t^*$, and calculate total profits over the whole horizon T as:

$$NP_T(\overline{X}_T) = \sum_{t=1}^{T} NP_t(X_t) = \sum_{t=1}^{T} \left(NI_t(X_t) - L_t^*(X_t)\right) \qquad \textbf{(8)}$$

[9] For example in period 4, all assets that had initially a time to repricing $b_i>4$ continue to carry the initial coupon rates (ie they have I_0^i = 1). Assets with repricing maturities of less than 4 periods have been repriced prior to or at the beginning of period 4. In particular, assets with $b_i=1,2,4$ have been repriced in period $p^i=4$, so for all these assets I_4^i =1, whereas assets with $b_i=3$ were last repriced in period $p^i=3$ and hence I_3^i =1.

where $\overline{X}_T = [X_0, X_1, \dots X_T]$ denotes a history of risk factor realisations.[10] The specific implementation is discussed in the next section, but the mechanism follows our timeline. In each period, we first draw X_t, then determine NI_t, simulate defaults of individual assets and coupons and finally calculate NP_t. After reinvestment, this process is repeated for the next quarter and so on up to time T. In the end we sum across all quarters and repeat the simulation. Note that our horizon of interest is one year; since $T=4$ throughout the analysis, we drop the time index T in the remainder of the paper.

3.4 Economic capital

As discussed in the introduction, we set the level of capital such that it equals the amount a bank needs to absorb unexpected losses over a certain time horizon at a given confidence level (Basel Committee (2008) or Kuritzkes and Schuermann (2007)). In our framework, unexpected losses can arise because of credit risk or adverse interest rate shocks.

For credit and interest rate risk, we follow standard convention and measure unexpected losses as the difference between the Value at Risk (VaR) and expected losses. More precisely, the VaR of the credit risk loss distribution VaR^y_{CR} at a confidence level $y \in (0,1)$ is defined as the smallest number l such that the probability of L exceeding l is not larger than $(1-y)$:

$$VaR^y_{CR} = \inf[l, P(L \geq l) \leq (1-y)] \qquad \textbf{(9)}$$

For risk management purposes the confidence level is generally high with $y \geq 0.9$. We set economic capital against credit risk EC^y_{CR} at the confidence level y so that it covers the difference between expected and unexpected losses up to VaR^y_{CR}. Or formally

$$EC^y_{CR} = VaR^y_{CR} - E(L) \qquad \textbf{(10)}$$

In analogy with (9), we define the VaR of the NI distribution VaR^z_{NI} at a confidence level $z \in (0,1)$ as the smallest number ni such that the probability of NI exceeding ni is not larger than *(1-z):*

$$VaR^z_{NI} = \inf[ni, P(NI \geq ni) \leq (1-z)] \qquad \textbf{(11)}$$

NI provides positive contributions to net profits, so we are interested in the left tail of the distribution. Therefore z is in this case below or equal to 0.1. Given that the focus is on the left tail, economic capital $(EC^{(1-z)}_{NI})$ is meant to cover unexpectedly low NI outcomes at the confidence level *(1-z)*:

$$EC^{(1-z)}_{NI} = E(NI) - VaR^z_{NI} \qquad \textbf{(12)}$$

Given this definition, economic capital set at the 99% confidence level covers all unexpected low outcomes of NI between the VaR_{NI} at the 1% level and expected NI. Note that VaR_{NI} and EC_{NI} do not incorporate defaulted coupons. As we argue in Section 3, these are an important part of the analysis and they can be accounted for equivalently in the income calculation **(2)** or

[10] As excess profits are invested in cash rather than a risk-free asset, we can add up net profits across time without taking account of the time value of money. As pointed out in footnote 7 we also undertook a sensitivity test investing net profits in risk-free assets. Results differ only marginally and do not change the main message of the paper.

in the credit risk loss calculation **(1')**. We follow the first route and construct VaR and EC statistics for realised net interest income *RNI*, which incorporates the loss of payments on defaulted assets. The definitions of VaR_{RNI} and EC_{RNI} are analogous to equations **(11)** and **(12)**.

Ultimately, we are interested in risk measures for the net profit distribution. Risk managers obviously do not focus on the right tail of this distribution, which constitutes the up-side risk for a bank, but on the left tail. In line with VaR_{NI}, we define the VaR of the net profit distribution VaR_{NP}^{z} at a confidence level $z \in (0,1)$ as the smallest number *np* such that the probability of *NP* exceeding *np* is not larger than *(1-z)*:

$$VaR_{NP}^{z} = \inf[np, P(NP \geq np) \leq (1-z)] \quad \textbf{(13)}$$

Mechanically we could set capital against net profits such that it buffers all unexpected low outcomes; ie we could set it as the difference between *E(NP)* and VaR_{NP}^{z}. Mathematically this definition would make sense. Economically, however, it does not because it implies that the bank also holds capital against low but positive profits, even though banks hold, as discussed above, capital to buffer (unexpected) losses. To clarify this, say a bank manages its capital to a 95% confidence level and $VaR_{NP}^{5\%} > 0$. Such a bank would not hold any capital as it knows that it makes positive profits with a 95% likelihood. Even if it manages capital to a confidence level of 99% and $VaR_{NP}^{1\%} < 0$, the bank would not set capital as the difference between *E(NP)* and the VaR because it does not make sense to 'buffer' positive profits. Insofar as the bank only holds capital against net losses, a more sensible definition of the economic capital $EC_{NP}^{(1-z)}$ at a confidence level *(1-z)* is

$$EC_{NP}^{(1-z)} = \begin{cases} 0 & \text{if } VaR_{NP}^{z} \geq 0 \\ -VaR_{NP}^{z} & \text{if } VaR_{NP}^{z} < 0 \end{cases} \quad \textbf{(14)}$$

The intuition behind equation **(14)** is illustrated in Figure A1 in the annex. Here $VaR_{NP}^{z} > 0$ at a confidence level *(1-z),* so no capital is needed. Using a higher confidence level *(1-y)* some unexpected negative net profits (ie net losses) can materialise and the bank would set capital to buffer the possible negative outcomes.

As discussed in the introduction, we are ultimately interested in assessing whether additive rules are conservative. This amounts to asking whether the sum of economic capital against credit and income risk is an upper bound relative to capital set directly against net profits. We assess this by looking at the following measure for confidence level *y*

$$M_{EC}^{y} = \frac{(EC_{CR}^{y} + EC_{RNI}^{y}) - EC_{NP}^{y}}{(EC_{CR}^{y} + EC_{RNI}^{y})} \quad \textbf{(15)}$$

The larger M_{EC}, the more conservative simple economic capital is. Conversely, if M_{EC} is negative then simply adding up the two capital measures independently would underestimate the risk of the total portfolio. [11]

[11] It is well known that VaR is not a coherent risk measure. However, expected shortfall is not coherent in our set-up either as credit and interest rate risk interact in a non-linear fashion. Therefore we only report economic capital numbers based on VaR measures. The insights from all results remain when using expected shortfall instead. Results are available on request.

In our framework, EC_{NP} covers negative net profits (ie net losses) rather than looking at the difference between expected net profits and unexpected net profits as EC_{RNI} and EC_{CR} do. This is economically sensible, because profit fluctuations have a direct impact on bank capital independently of whether they are expected or not. With perfect competition and risk neutral pricing, average profits would be zero and the difference would not be material. However if banks earn rents (for example by pricing customer deposits below the risk-free rate, as we can observe empirically) expected profits are positive, which increases M_{EC}. In other words, rents may introduce a further wedge between 'simple' and 'integrated' economic capital.

We maintain that M_{EC} is the most appropriate measure in this context, but to control for this issue we also provide an alternative measure M_2 that takes into account the mean of the net profit distribution:

$$M_2^y = \frac{(EC_{CR}^y + EC_{RNI}^y) - (E(NP) - Var_{NP}^{(1-y)})}{(EC_{CR}^y + EC_{RNI}^y)} \qquad \textbf{(16)}$$

Given that we model a banking book, EC_{CR} and EC_{RNI} do not take account of changes in the mark-to-market valuations of the exposures; hence, they do not capture aspects of, and interactions between, credit and interest rate risk which arise when assets are marked to market (we briefly discuss this in the conclusions). It can also be argued that EC_{CR} and EC_{RNI} do not fully disentangle credit and interest rate risk, in the sense that the former incorporates the effect of higher interest rates on default probabilities and the latter the effect of higher (actual or expected) credit risk on income. These issues should be certainly kept in mind throughout the discussion of our results. The key point, though, is that our framework represents a plausible description of how current capital models for the banking book capture these risks. As already discussed, the current regulatory approach to credit risk and the commonly used 'earnings at risk' approach to interest rate risk do not take changes in market valuations into account. Furthermore, some credit risk models include a set of macroeconomic risk factors and hence capture (directly or indirectly) some of the links between interest rates and credit risk. This is for instance the case for CreditPortfolioView (Wilson (1997a,b)), the classic example of such an economic capital model. To the extent that our EC_{CR} and EC_{RNI} definitions reflect limitations and ambiguities that are common to many widely used risk management tools, the model should provide a plausible benchmark for our 'simple economic capital' setting. Our pricing model represents of course a departure from standard modelling practices. Most interest rate risk models do not take account of the possible repricing of assets beyond changes in the risk-free rate. Hence, by modelling endogenous spreads we add a layer of realism and complexity to the analysis. However, in line with standard approaches to model interest rate risk, we also undertake a sensitivity test where all spreads are excluded (see Section 6.1).

4 Implementation

Most quantitative risk management models currently used can be described as a chain starting with shocks to systematic risk factors feeding into a model that describes the joint evolution of these factors and finally a component that calculates the impact on banks' balance sheets (see Summer (2007)). Depending on the distributional assumptions and the modelling framework, the loss distribution can be derived either analytically or by simulating this chain repeatedly. We follow this approach, and obtain our distributions by simulation techniques. At time zero the balance sheet is fixed and all initial coupons are priced based on the observed macroeconomic conditions. Figure A2 in the annex shows how the simulation works for every subsequent quarter $t=1, \ldots,4$. At the beginning of $t=1$, we first draw a vector of random macroeconomic shocks and use a Global VAR (in the spirit of eg Pesaran *et al* (2004)) to determine the state of the macroeconomy, including a risk-free yield curve. Using a simple set of regression models, we then obtain PDs conditional on the new macro conditions. At this point the bank can reprice all assets and liabilities in the first repricing bucket, which already allows us to calculate *NI.* We then simulate (conditionally independent) defaults to derive *L* and *RNI* and hence net profits *NP.* At the end of the quarter the bank rebalances its balance sheet in line with the behavioural assumptions presented in Section 3.2. The remaining forecast periods follow the same structure, except that the repricing mechanism becomes increasingly complex as different assets and liabilities are repriced at different points in time as discussed in Section 3.2.

Our initial macroeconomic and balance sheet data are end-2005, and the forecast horizon is one year. We simulate 10,000 macro scenarios. In each of these scenarios, we draw one realisation per quarter of the portfolio loss distribution using Monte Carlo methods.

4.1 The hypothetical bank

Table A1 in Annex 3 provides an overview of the balance sheet used for the simulation. It represents the banking book of a simplified average UK bank, with exposures in various risk and repricing buckets derived by averaging the published balance sheets of the top ten UK banks.

In order to limit the number of systematic risk factors we have to model, we assume that the bank only has exposures to UK and US assets. We look at seven broad risk classes in both the United Kingdom and the United States: interbank; mortgage lending to households, unsecured lending to households; government lending; lending to PNFCs (private non-financial corporations); lending to OFCs (other financial corporations, ie financial corporations excluding banks); and ‘other’. Exposures within an asset class are homogenous with respect to PDs and LGDs. We assume that the bank is fully funded by UK deposits. These consist of interbank, household, government, PNFC, OFC, subordinated debt, and ‘other’.

Contrary to DSS, we model a portfolio which is not infinitely granular. Since no data are available on the size of the exposures, we construct a hypothetical loan size distribution for each asset class. We assume that asset sizes are log-normally distributed with variance one and a mean of £300,000 for household mortgage exposures, £50,000 for unsecured household lending, £100 million for PNFC lending and £200 million for OFC lending. The resulting distributions are shown in Figure A3 in the annex. This parameterisation is very much ‘back of the envelope’, but it delivers a size distribution which looks similar to the size distribution in other countries where detailed data are available.[12]

[12] We also undertook a sensitivity test to assess the implications of an infinitely fine-grained portfolio. This only reduced the tail of the credit risk loss distribution in the standard fashion (see Alessandri and Drehmann, 2009).

All exposures are assumed to be non-tradable and held to maturity using book value accounting. In line with accounting standards, assets and liabilities are allocated to five repricing buckets as shown in Table A1. For the actual analysis assets, liabilities and off balance sheet items in the last three buckets are assumed to be uniformly distributed over quarters within each bucket. For the last bucket we assume that the maximum time to repricing is ten years. The interest rate sensitivity gap is the difference between assets and liabilities in each repricing bucket.

It is important to stress that we are using repricing buckets rather than maturity buckets in order to correctly capture the impact of changes in the macroeconomic environment on the bank's net interest income. This means that, for example, a flexible mortgage with a 20-year maturity that reprices every three months is allocated to the three-month repricing bucket. As DSS show, the repricing characteristics are the key determinant of interest rate risk in the banking book. The interest rate sensitivity gap relative to total assets of our balance sheet is fully in line with the average interest rate sensitivity gap of the top ten UK banks in 2005. Given that in the UK mortgage borrowers predominantly borrow on a flexible rate basis, a high proportion of assets are allocated to the 0-3 months repricing bucket (see Table A1).[13]

In contrast to DSS we do not look at interest sensitive off balance sheet items. UK banks on average use these items to narrow the repricing gap between short-term borrowing and long-term lending. Hence, the interest rate risk estimated in this paper should be more significant than for the actual average UK bank. The repricing structure of the balance sheet is crucial in determining interest rate risk, so we perform a number of sensitivity tests on our baseline assumptions.

4.2 Macro model, PDs and LGDs

To model the macro environment, we implement a two-country version of Pesaran *et al's* (2004) Global VAR model. We treat the United Kingdom as a small open economy and the United States as a closed economy that is only subject to domestic shocks.[14] Variables and data are the same as in Dees *et al* (2007). For the United Kingdom, these include real output, consumer price inflation, real equity prices, an overnight nominal interest rate, a 20-year synthetic nominal bond interest rate and the real exchange rate against the dollar. For the United States, the latter is replaced by oil prices. The model is estimated over a 1979 Q1–2005 Q4 sample. Our simulations are thus driven by (sequences of) macroeconomic shocks drawn from a multivariate normal distribution based on the estimated historical variance-covariance matrix. Our pricing model requires a full risk-free nominal yield curve. We choose the simplest possible specification, and obtain the curve by a linear interpolation of the overnight and 20-year UK rates.

[13] The average interest rate sensitivity gap relative to total assets in the United Kingdom is stable over time, but economic and institutional conditions generate substantial cross-country variation. For an average US bank, at the end of 2005 50.2% of loans and securities had a time to repricing of one year or more; in the United Kingdom, where fixed-rate mortgages are less common, the figure was only 20.7%. The liability side looks more similar for the average UK and US bank. For the latter 12.5% of liabilities have a remaining time to repricing of more than a year, whereas the proportion in the United Kingdom is 8.3% (for US data see FFIEC (2006)).
[14] From a UK perspective, this can be interpreted as a GVAR based on a degenerate weighting scheme whereby the 'rest of the world' only consists of the United States. Given that we only model two countries, we cannot rely on Pesaran *et al*'s (2004) asymptotic weak exogeneity result. However, given the relative size of the two countries, our small/big economy assumption holds reasonably and allows us to estimate the model by a standard OLS procedure.

As mentioned in Section 4.1, we assume that loans within a particular asset class are homogenous with respect to their risk characteristics, ie they all have the same *PD* and *LGD*. This assumption is dictated by data limitations, as only aggregate default frequencies for corporate and household lending are available in the United Kingdom. To estimate the impact of macro factors on PDs we use simple equations in the spirit of Wilson (1997a,b). In particular, each asset's default frequency is modelled as a function of output growth, return on equity and interest rates. We use plain linear regressions, modelling the log-odd transformation of the default frequency to guarantee that all implied PDs are bounded between zero and one; the resulting regressions have R-squared coefficients ranging from 5% to 30%. We assume that *LGDs* are fixed. Broadly in line with average industry numbers, we assume an *LGD* of 40% for interbank loans, 30% for mortgage loans, 100% for credit card loans and 80% for corporate loans.

Both the GVAR and the PD equations were developed as part of a large systemic risk modelling project currently under way at the Bank of England. Alessandri *et al* (2009) describe the prototype version of this model, providing more details on the estimation and calibration of these components as well as the underlying data. Aikman *et al* (2009) discuss a more recent version of the model, placing more emphasis on funding liquidity risk. We stress that the accuracy of macro model and PD equations is actually not central to our argument: what we need is a plausible, if basic, characterisation of the main sources of comovement between macroeconomic variables, interest rates and defaults. In principle it is of course possible to incorporate in our framework more sophisticated yield curve, PD or LGD models. It would also be interesting to re-estimate the models including observations on the recent crisis. This may give a significantly different picture of how sensitive and volatile the systematic component of credit risk actually is, though arguably the models would need to explicitly incorporate some form of time-variation in the parameters. We leave this extension to future research.

4.3 Pricing of assets and liabilities

We calculate coupons on loans using the risk-neutral pricing model proposed in DSS (see Annex 1). Given the non-linearity of the model, we can only implement the framework by introducing two approximations. These are discussed in detail in Annex 2, where we also show that they do not bias our results. It is well known that there is no simple mapping from actual *PDs*, which we simulate, into risk-neutral *PDs*, which we require for pricing (see eg Duffie and Singleton (2003)). At this stage it is not possible to find an approach in the literature which could be easily implemented in our already complex model. Hence, we simply introduce a set of fixed risk premia (see Table A2 in Annex 3), undertaking various sensitivity tests to make sure that these assumptions do not drive our results.

In theory, the bank's liabilities should be priced similarly to assets using the bank's own PD and LGD. While this seems to be the case for banks' debt instruments, it is well known that shorter-term customer deposit rates are generally below the risk-free interest rate even when accounting for non-interest costs and fees (eg see Corvoisier and Gropp (2002)). While an economic rationalisation of negative spreads can be found for short maturities, it is not convincing for medium to long maturities. We assume that, as the time-to-repricing increases, the interest paid by the bank on deposits gradually converges to the risk-free interest rate. Other liabilities pay the risk-free interest rate or, in the case of subordinated debt, interbank and other liabilities, the risk-free interest rate plus a fixed 15 basis point spread. All liability spreads are summarised in Table A3 in the annex. We stress that balance sheets and calibration are based on pre-crisis data: exposures, pricing maturities and implied risk premia changed substantially over the last two years, and banks' funding costs displayed an exceptional behaviour in terms of both levels and volatilities. Recent events have shown not only that liquidity is crucial, but also that liquidity risk should ideally also be incorporated in an integrated economic capital framework; a possible modelling strategy is suggested in Aikman *et al* (2009).

5 Results

5.1 Macro factors, PDs and interest rates

Since we use (log)linear models with normally distributed shocks, all macro variables and PDs are roughly normally distributed. Average growth is around 2%, but the GVAR generates several recessionary scenarios where growth turns negative. Interest rates change by 100 basis points or more quite often over the four quarters. On the whole, default probabilities are fairly low and not very volatile (for instance, the annualised UK unsecured personal loan PD has a 90% confidence interval of about 4.3%-6.5%). This is partly due to the initial conditions: PDs were indeed very low in 2005 by historical standards. But it also reflects the relatively weak impact of macro factors on default rates in the PD model used for the simulation.[15]

5.2 The impact on the bank

Figure 2 and Table 1 provide an overview over various components of the profit and loss distribution. Even though macro variables and PDs are roughly normally distributed, credit risk losses show the characteristic fat tail due to lumpy exposures (Panel A). Credit risk losses range from a minimum of £0.8 billion to a maximum of £16 billion. Interestingly, mean credit risk losses are around £1.37 billion, which fits reasonably closely with the reported average provisions of UK banks of £1.59 billion for 2006 – the year we forecast – even though our balance sheet is highly stylised and losses do not map one-to-one into provisions.

In line with the distribution of simulated interest rates, net interest income (Panel B) is roughly normally distributed and it shows a much smaller variance than the credit risk loss distribution.[16] The mean realised net interest income, which also accounts for defaulted coupons, is £4.8 billion. This is lower than the reported average net interest income of £6.32 billion for 2006, possibly because the spreads we add to the risk-neutral coupon rates are not high enough. Clearly, this may also be a result of our assumed balance sheet as our bank is only funded in one currency. Panel B also shows that the impact of defaulted coupons on realised net interest income (*RNI*) is relatively small in absolute terms. As expected, the reduction in net interest income due to defaulted coupon rates (Panel C) is exactly in line with the credit risk loss

[15] For a detailed discussion of outcomes for macro variables and PDs see Alessandri and Drehmann (2009).

[16] Throughout the paper we assume that assets and liabilities are priced fairly at the beginning of the simulation. As an additional robustness check we also ran simulations assuming that assets and/or liabilities are 20% over or underpriced. The initial mispricing changes only the mean of the net profits distribution but not its shape in line with the results shown in Section 6.1 therefore not discussed further. Results are available on request.

distribution (Panel A). Overall, the net profit distribution (Panel D) shows a significant negative fat tail, even though net profits are positive in more than 98% of the simulations.

5.3 Economic capital

Table 2 provides an overview of economic capital against different risks at different confidence levels. Given the skew of the credit risk loss distribution, economic capital against credit risk (EC_{CR}) is non-linearly increasing in the confidence level. This is less pronounced for economic capital against changes in net interest income (EC_{NI} and EC_{RNI}) because the underlying net income distributions only show a slight skew. The ratio of EC_{RNI} to EC_{CR} therefore decreases from around 30% at the 95% confidence level to 11% at the 99.9% confidence level. These numbers seem broadly in line with banks' practices. For example, the IFRI-CRO Forum (2007) report suggests that for an average bank the ratio of the capital set against interest rate risk relative to capital set against credit risk is 16%. But given different balance sheet structures, this ratio exhibits a significant variance and can reach 50% or more.

The key question of this paper is whether simple economic capital, namely the sum of EC_{RNI} and EC_{CR}, is larger than integrated economic capital (EC_{NP}). Simple economic capital is positive at all confidence levels. However, taking the complex dynamic interactions of credit and interest rate risk into account, the bank makes positive net profits in more than 95% of the scenarios. Therefore, integrated economic capital at this confidence level is zero. Even at the 99% confidence level, integrated economic capital would be minimal and less than 3% of simple economic capital. Only at the 99.9% percentile does economic capital against net profits reach a substantial amount; and even at that level, it is still only around 50% of simple economic capital.

In the narrow context considered here, the difference between simple and integrated economic capital is very large. The bottom of the table shows that this gap is mostly due to the fact that integrated capital covers only unexpected negative profits. As we explain in Section 3.4, M_2 is an alternative measure that treats profits in the same way as credit risk losses, assuming that capital is set aside against unexpectedly low profits independently of whether these are positive or negative. By this metric, integrated capital is again lower than simple capital but only by an 8% to 20% margin (depending on the confidence level). In Section 3.4 we argue that M_2 is not an economically sensible indicator, so in the reminder of the discussion we focus on M_{EC} and report M_2 purely for completeness. In any case, our main result proves to be extremely robust: in all the cases we consider, simple economic capital provides an upper bound independently of whether we look at M_{EC} or M_2. Section 6 below examines the robustness of our conclusions to some of the assumptions on which our model is based. Needless to say, there are a number of dimensions that are completely excluded from our analysis, so the results cannot be generalised beyond the highly stylised case examined in the paper.

6 Sensitivity analysis

In this section we test the robustness of our results to alternative specifications of three key characteristics of the bank: pricing behaviour, repricing maturity mismatch, and funding structure (equity versus external funds).[17]

6.1 The impact of pricing

To assess the impact of different pricing assumptions, we (i) drop all spreads on deposits, (ii) drop all exogenous spreads (including those on deposits), and (iii) drop all exogenous and endogenous spreads, ie we assume that all assets and liabilities are priced as risk-free instruments. The latter test is roughly equivalent to a standard gap analysis, the simplest approach to assess interest rate risk in the banking book.

The spreads have no impact on the credit loss distribution, so EC_{CR} is exactly the same as in the base case (see Table 3). But endogenous and exogenous spreads boost income significantly: relative to the baseline, *NI* falls on average by 30% in the first case, 50% in the second and 59% in the third. In the first two cases we remove additive, exogenous spreads, so the distributions of *NI* and *RNI* only shift downward but maintain the same shape. In the third case the distribution changes in a more complex way, but again the dominant feature is the downward shift. As spreads essentially affect the mean but not the shape of the net interest income distribution, changes in EC_{RNI} are negligible (at most 3.5% relative to the base case). However, without spreads the bank incurs net losses more often, so EC_{NP} is higher than in the base case at all confidence levels. As a consequence, the difference between simple and integrated economic capital is less pronounced. However, it remains large and positive even under risk-free pricing (case (iii)).

6.2 The impact of the repricing mismatch

To assess the implications of different repricing assumptions, we examine two extreme cases. In the first one ('short L') we assume that the bank is fully funded by liabilities that are repriced at every quarter. In the second ('long L') all liabilities are assumed to have a time to repricing of more than one year. Given our one-year horizon, this means that they are never repriced and generate fixed net interest payments. Both experiments imply a much higher volatility of *NI.* Interestingly, though, volatility is three times higher in the 'long L' case than in the 'short L' case. The reason is simple: income volatility depends on the interest rate sensitivity gap, and in absolute terms this is actually highest in the 'long L' case.[18] As Table 4 shows, higher income volatility translates into much larger EC_{RNI} estimates at all confidence levels. EC_{NP} is also consistently higher than in the baseline, whereas M_{EC} does not give a clear message. Nonetheless, once again, simple economic capital exceeds integrated economic capital in all cases.

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[17] We only report the tables on capital calculations here. More detailed results on each of these sensitivity tests are presented in Alessandri and Drehmann (2009).

[18] The interest rate sensitivity gaps for the 1-3 months bucket are -23% for 'short L', -10% for the base case and +52% for 'long L'. Note that in the 'long L' case the gap is positive, ie contrary to standard banks this bank borrows long and lends short.

6.3 *The impact of equity*

Our last set of tests concerns the bank's equity. In our baseline calibration, equity is approximately 4% of total assets. Since dividends are only paid from net profits after one year, higher capital levels affect the bank's net interest income by lowering total interest payments on liabilities. We replicated our calculations for initial equity levels of 0%, 4% and 8% of total assets, setting all exogenous asset and liability spreads to zero to better isolate the role of equity. Credit losses are not affected by the equity level, whereas the impact on the *NI* distribution is substantial: reducing equity from 8% to 4% decreases the mean *NI* by 22% and increases its standard deviation by more than 50%. Setting equity to zero decreases the mean *NI* by nearly another 40% and increases the standard deviation by an additional 26%.

Table 5 shows the corresponding economic capital levels. The higher the initial equity, the lower the model-implied capital against credit and interest rate risk losses. This is purely driven by the fact that expected net interest income is higher for higher equity because the bank does not remunerate equity holders. The difference between simple economic capital and integrated economic capital is therefore also larger for higher levels of initial equity levels. Again, simple economic capital consistently exceeds integrated capital.

7 Conclusion and discussion

This paper provides a consistent model for deriving economic capital against credit and interest rate risk in the banking book. We formulate an economic capital framework where interest and credit risk interact in a non-linear, dynamic fashion. We apply this framework to a stylised UK bank, comparing a 'simple economic capital' measure that purely adds economic capital against credit and interest rate risk to an 'integrated' measure that takes into account the interactions between them. We find that the difference between the two measures depends on various features of the bank, but that simple capital exceeds integrated capital under a broad range of circumstances, providing an upper bound relative to the bank's overall risk.

A range of factors contribute to generating this result. In our application, a relatively large portion of credit risk is idiosyncratic, and thus independent of the macroeconomic environment, and the correlation between systematic credit risk factors and interest rates is itself not perfect. Furthermore, assets in the bank's portfolio are repriced relatively frequently, and hence increases in credit risk can be partly passed on to borrowers. Our analysis also rests on a number of assumptions: for instance we do not account for prepayment risk (which is negligible in the United Kingdom but quite substantial in the United States), hedging, or subordinated debt. Given the magnitude and robustness of our results, though, our conjecture is that extending the model in these directions would not change our main conclusion for a similar portfolio. In particular, most hedging strategies are designed to reduce either interest rate or credit risk in specific states of the world. This would decrease both simple and integrated capital buffers, but it is unlikely that the size of the gap between the two will be significantly affected or even change sign.

Our results cannot be used in general to argue that an economic capital model that fully integrates different types of risk would result in lower capital than that implied by simple aggregation rules. Neither does the paper address the issue of what is the appropriate level of capital for a bank. In particular, we emphasise that, since we focus on traditional banking book risks, relating our insights to the recent crisis is not trivial. Securitisation, derivatives and liquidity management – which were at the core of the financial turmoil – remain outside the scope of this paper. We also assume that banks recover a fixed fraction of any defaulted loan, thus abstracting from the impact of asset prices on recovery rates. Furthermore, changes in the economic value of the portfolio are not taken into account as all exposures are assumed to be non-tradable and therefore valued using book value accounting. Hence, some caution is warranted on the generality of the results. Many banks manage large, complex portfolios that expose them to a wider range of risks than the ones we analyse here: our conclusions cannot be generalised to those cases. As a consequence, risk managers and regulators should work on the presumption that interactions between risk types may be such that the overall level of capital is higher than the sum of capital derived for risks independently. Our paper shows that this is unlikely for credit and interest rate risk in the banking book, but also that additive rules are in this case potentially very inefficient. From a risk management perspective, this should provide another strong incentive to move towards an integrated analysis of risks.

Table 1: Losses, income and profits

	mean	median	st.dev.	min	max	.1 %tile	1 %tile	5% tile	95 %tile	99 %tile	99.9 %tile
Credit risk losses	1,378	1,146	765	835	15,788	933	990	1,033	2,726	4,790	8,871
Net interest income (NI)	4,810	4,810	259	3,793	5,680	4,014	4,199	4,386	5,233	5,395	5,535
Net interest income including losses due to defaulted coupons (RNI)	4,782	4,781	260	3,764	5,647	3,973	4,170	4,353	5,206	5,371	5,514
Net-Profits	3,404	3,581	815	-10,991	4,570	-4,183	-112	2,031	4,061	4,251	4,434

Note: in millions.

Table 2: Economic capital

	Confidence Level		
	95%	99%	99.9%
EC_{CR}	1,348	3,412	7,493
EC_{NI}	424	611	797
EC_{RNI}	429	612	809
EC_{CR}+ EC_{RNI}	1,777	4,024	8,302
EC_{NP}	0	112	4,183
M_{EC}	100.00%	97.21%	49.62%
E(NP)-VaR $_{NP}$	*1,372*	*3,516*	*7,586*
M_2	*22.76%*	*12.62%*	*8.62%*

Note: in millions. EC_{CR} is the economic capital against credit risk; EC_{NI} is the economic capital against changes in net interest income excluding the impact of defaults on coupon payments; EC_{RNI} is the economic capital against changes in net interest income including the impact of defaults on coupon payments; EC_{NP} is the economic capital against changes in net profits. M_{EC} is the ratio of $[(EC_{CR}+ EC_{RNI})- EC_{NP}]$ over $(EC_{CR}+ EC_{RNI})$. *E(NP)* are expected net profits. VaR_{NP} is the VaR of net profits at confidence interval (1-y) where *y* is the confidence level stated in the table. M_2 is the ratio of $[(EC_{CR}+ EC_{RNI}) – (E(NP)-VaR_{NP})]$ over $(EC_{CR}+ EC_{RNI})$. See Section 3.4.

Table 3: Economic capital under different pricing assumptions

	No negative spreads on liabilities			*No additive spreads*			*Risk free pricing*		
	Confidence Level			Confidence Level			Confidence Level		
	95%	99%	99.9%	95%	99%	99.9%	95%	99%	99.9%
EC_{CR}	1,348	3,412	7,493	1,348	3,412	7,493	1,348	3,412	7,493
EC_{RNI}	415	593	783	414	593	781	420	597	797
EC_{CR}+ EC_{RNI}	1,763	4,005	8,276	1,763	4,005	8,275	1,768	4,009	8,290
EC_{NP}	0	1,621	5,686	344	2,483	6,543	836	2,955	7,050
M_{EC}	100.00%	59.52%	31.30%	80.48%	38.01%	20.93%	52.69%	26.30%	14.97%
E(NP)-VaR $_{NP}$	*1,376*	*3,518*	*7,582*	*1,374*	*3,513*	*7,573*	*1,379*	*3,497*	*7,593*
M_2	*21.97%*	*12.18%*	*8.39%*	*22.04%*	*12.29%*	*8.49%*	*21.97%*	*12.76%*	*8.42%*

See note to Table 2.

Table 4: Economic capital under alternative funding assumptions

	All short			*All long*		
	Confidence Level			Confidence Level		
	95%	**99%**	**99.9%**	**95%**	**99%**	**99.9%**
EC_{CR}	1,348	3,412	7,493	1,348	3,412	7,493
EC_{RNI}	978	1,386	1,841	3,166	4,521	5,949
EC_{CR}+ EC_{RNI}	2,326	4,798	9,335	4,514	7,934	13,442
EC_{NP}	0	386	4,471	217	1,897	5,056
M_{EC}	100.00%	91.95%	52.11%	95.19%	76.09%	62.39%
E(NP)-VaR $_{NP}$	*1,525*	*3,668*	*7,753*	*3,493*	*5,173*	*8,332*
M_2	*34.41%*	*23.55%*	*16.94%*	*22.63%*	*34.80%*	*38.02%*

See note to Table 2. All exogenous spreads are set as in the baseline simulation.

Table 5: Economic capital for initial equity levels of 0%, 4% and 8%

	0% equity			*4% equity*			*8% equity*		
	Confidence Level			Confidence Level			Confidence Level		
	95%	**99%**	**99.9%**	**95%**	**99%**	**99.9%**	**95%**	**99%**	**99.9%**
EC_{CR}	1,348	3,412	7,493	1,348	3,412	7,493	1,348	3,412	7,493
EC_{RNI}	576	820	1,086	429	614	810	281	407	537
EC_{CR}+ EC_{RNI}	1,924	4,232	8,580	1,778	4,026	8,303	1,630	3,819	8,031
EC_{NP}	1,092	3,203	7,326	408	2,549	6,615	0	1,838	5,954
M_{EC}	43.25%	24.32%	14.61%	77.06%	36.68%	20.33%	100.00%	51.86%	25.86%
E(NP)-VaR $_{NP}$	*1,395*	*3,506*	*7,630*	*1,371*	*3,513*	*7,578*	*1,366*	*3,461*	*7,577*
M_2	*27.48%*	*17.15%*	*11.08%*	*22.88%*	*12.76%*	*8.73%*	*16.20%*	*9.36%*	*5.65%*

See note to Table 3. All exogenous spreads are set to zero.

Figure 1: Timeline of the multi-period framework

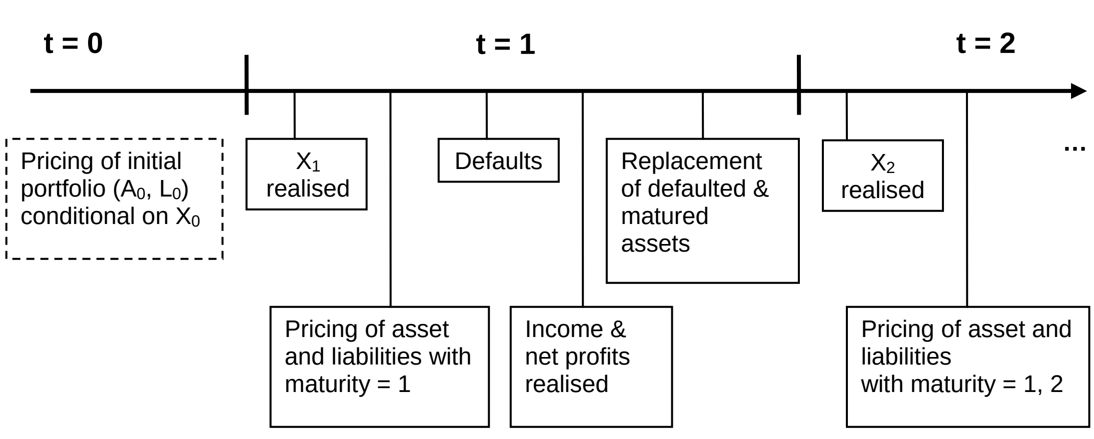
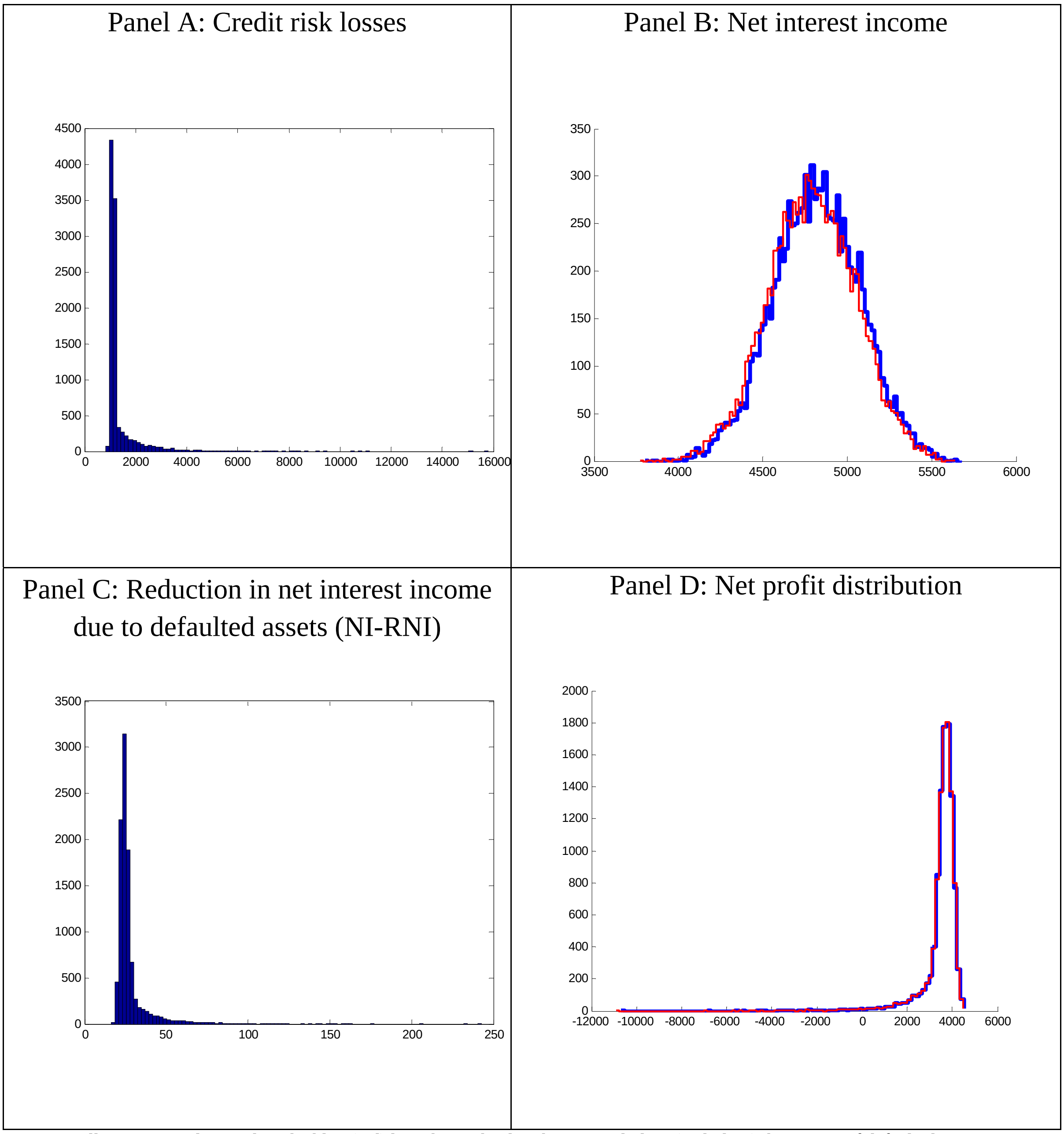


Figure 2: Annual profit and loss distributions



Note: in millions. In panels B and D, the blue (red) line shows the distribution excluding (including) the impact of defaulted coupon payments.

Appendix

Annex 1: Endogenous coupon rates

This annex is based on Drehmann, Sorensen and Stringa (2008). The economic value EVA^i of a generic asset i with time to repricing of T (which is also for simplicity equal to its maturity) is simply the risk-adjusted discounted value of future coupon payments $C_s^i(X_s)$ and the principal A. Hence at time t:

$$EVA_t^i(X_t) = \sum_{k=1}^{T} D_{t+k}^i(X_t) C_s^i(X_s) A^i + D_{t+T}^i(X_t) A^i \qquad \textbf{(A1)}$$

For simplicity we assume that all assets are equivalent to bullet bonds – ie repay the principal only at maturity and pay a constant coupon C_s^i that is determined at time $t=s$ based on the observed and expected macroeconomic variables X_s. For example, such an asset could be a fixed-interest rate bond with no embedded options or a simple bank loan. The discount function conditional on current conditions is given by:

$$D_{t+k}^i(X_t) = E\left(\prod_{l=1}^{k} \frac{1}{1 + R_{t+l-1;t+l}^i(X_t)} \right) \qquad \textbf{(A2)}$$

where R is the risk-adjusted interest rate. In continuous time, R equals the risk-free rate plus a credit risk premium equal to $PD*LGD$. However, as our application is set up in discrete time, we follow Duffie and Singleton (2003):

$$R_{t+l-1,t-l}^i(X_t) = \left(\frac{r_{t+l-1,t+l}(X_t) + PD_{t+l-1,t+l}^i(X_t) \times LGD^i}{1 - PD_{t+l-1,t+l}^i(X_t) \times LGD^i} \right) \qquad \textbf{(A3)}$$

where $r_{t+l-1,t+l}$ is the forward risk-free interest rate between $t+l-1$ and $t+l$ known at time t. LGD^i is the expected loss given default for borrower i which, for simplicity, we assume here to be constant. $PD_{t+l-1;t+l}^i$ is the risk neutral probability of default of borrower i between $t+l-1$ and $t+l$ conditional on surviving until $t+l-1$. PDs and yields depend on the same set of systematic risk factors X_t.

We do not observe empirical coupon rates and need to reprice assets and liabilities according to their contractual repricing characteristics. To do so we assume that at the time $t=0$ of issuance the economic value equals the face value of the asset. This implies that $EVA_{t=0}^i(X_0) = A^i$ in equation **(A1)**. Solving for C_0^i we obtain:

$$C_0^i(X_0) = \frac{1 - D_T^i(X_0)}{\sum_{k=1}^{T} D_k^i(X_0)} \qquad \textbf{(A4)}$$

Given **(A1)-(A4)**, we can easily prove that expected profits are zero if the banks is fully funded by external liabilities $(\sum^i A^i = \sum^j L^j = L)$, liabilities pay the risk-free rate r, and assets and liabilities have a pricing maturity of one quarter. In this case, the one-period ahead expected net profits are given by

$$\begin{aligned} E(NP) &= NI - \sum_i PD^i LGD^i (1 + C^i) A^i \\ &= \left(\sum_i C^i A^i - rL\right) - \sum_i PD^i LGD^i (1 + C^i) A^i \end{aligned} \qquad \textbf{(A5)}$$

The risk-neutral coupon rate an asset with a time to repricing of one is

$$C^i = \frac{(r + PD^i * LGD^i)}{(1 - PD^i * LGD^i)} \qquad \textbf{(A6)}$$

By substituting **(A6)** into **(A5)**, we can rewrite expected net profits as

$$\begin{aligned} E(NP) &= \left(\sum_i C^i A^i - rL\right) - \sum_i PD^i LGD^i (1 + C^i) A^i \\ &= \left(\sum_i \left(r + PD^i LGD^i\right) A^i - PD^i LGD^i A^i\right) - rL \\ &= 0 \end{aligned} \qquad \textbf{(A7)}$$

Annex 2: Empirical implementation of the pricing framework

In order to implement our framework, we rely on two approximations. The first one consists of assuming that banks use a random walk model to form expectations on future PDs, ie they assume that $E_t(PD_{t+k})=PD_t$. Using model-consistent expectations is possible but computationally very cumbersome given the high dimensionality of the model.[19] In order to assess the implications of this approximation, we replicated the baseline case using model-consistent expectations as a sensitivity test.[20] This indicates that wrongly formed expectations slightly bias income levels downwards and decrease the variance of *RNI,* which was to be expected as model-consistent expectations are less volatile. Most importantly, the error margins introduced by this approximation for M_{EC} are small and below 2% at all confidence levels.

Second, when calculating the discount factors D^i_{t+k}, we approximate equation **(A2)** as follows

$$D^i_{t+k} = E_t\left(\prod_{l=1}^{k}\frac{1}{1+R^i_{t+l-1;t+l}}\right) \approx \prod_{l=1}^{k} E_t\left(\frac{1}{1+R^i_{t+l-1;t+l}}\right) = \prod_{l=1}^{k}\frac{1-E_t\left(PD^i_{t+l-1,t+l}\right)LGD^i}{1+r_{t+l-1,t+l}} \qquad \textbf{(A8)}$$

The last equality holds as the forward yield curve is known at the time of pricing and LGDs are fixed. By looking at the product of expectations rather than the expectation of the product, though, we ignore any conditional cross-correlations between discount factors at different points in time. It is hard to quantify the bias this introduces as the simulation becomes too complex to calculate coupon rates correctly. However, we would argue that the bias does not affect our results in a significant fashion. As pointed out above, at the time of pricing the forward yield curve is known and LGDs are fixed. Therefore, the conditional correlation is driven by the conditional correlation between PDs. All PDs are by construction conditionally homoscedastic – a property they inherit from the GVAR. Hence, their conditional auto-correlations are constant over time. Furthermore, the realised unconditional autocorrelations are small and positive, and decline rapidly to zero for lag lengths greater than one.[21] This would suggest that the bias is not substantial and that the coupons we calculate are too low on average. Given the robustness tests in Section 6.1, this means that EC_{NP} in our base case is likely to be too high in comparison to the case where the approximation would not be made.

[19] For each quarter t=1, ..., 4 and scenario s=1,...,10,000 we need expectations for 6 PDs over a ten-year horizon; the implied total number of expectations to be calculated is 4*10,000*6*40 = 9,600,000.

[20] Results are available on request.

[21] We assessed correlation coefficients of PDs for six asset classes empirically by looking at the distribution of correlation coefficients implicit in the simulation. Results are available on request.

Annex 3: Additional tables

Table A1: Balance sheet

Assets		Repricing buckets: 1-3 m	3-6 m	6-12 m	1-5 y	>5 y	non i.b.	Total
Bank	UK	12,783	697	560	130	249	1,378	*14,418*
HH.Mort	UK	41,331	4,137	3,736	16,678	1,886	134	*67,767*
HH.Unsec	UK	7,278	692	607	3,320	1,000	653	*12,896*
Gov	UK	954	94	68	242	302	872	*1,660*
PNFC	UK	21,374	1,701	1,357	1,318	523	14	*26,273*
OFC	UK	15,769	1,635	1,429	5,757	4,402	1,545	*28,992*
Other	UK	16,256	1,596	1,265	3,708	6,693	24,806	*29,517*
Bank	US	19,537	1,065	855	198	381	2,106	*22,037*
HH.Mort	US	25,722	2,574	2,325	10,379	1,173	83	*42,174*
HH.Unsec	US	4,529	431	378	2,066	622	406	*8,026*
Gov	US	1,292	127	97	310	475	1,609	*2,301*
PNFC	US	13,302	1,059	844	820	325	8	*16,351*
OFC	US	9,814	1,018	889	3,583	2,740	961	*18,043*
Other	US	31,050	3,048	2,416	7,083	12,783	47,381	*56,379*
Total assets								*428,789*

Liabilities		Repricing buckets: 1-3 m	3-6 m	6-12 m	1-5 y	>5 y	non i.b.	Total
Bank	UK	38,050	2,069	1,229	680	902	1,035	*43,965*
HH	UK	69,472	2,838	2,881	2,377	350	5,409	*83,327*
Gov	UK	1,651	106	114	68	10	160	*2,110*
PNFC	UK	22,177	695	677	622	172	2,758	*27,101*
OFC	UK	57,146	1,957	1,779	1,556	367	7,324	*70,129*
Sub	UK	11,889	948	683	2,506	8,491	10,199	*34,716*
Other	UK	61,240	4,195	3,483	7,892	7,917	63,828	*148,555*
Total liabilties								*409,902*
Shareholder funds							18,887	

Note: in millions.

Table A2: Pricing of assets

Asset class	Modelling of cash flow
UK interbank unsecured[1]	Risk-free rate +15bps
UK household secured (mortgage)	Coupon from net interest income model +50bps
UK household unsecured	Coupon from net interest income model +50bps
UK government	Risk-free rate
UK PNFC	Coupon from net interest income model +50bps
UK OFC	Risk-free rate +15bps
UK other assets[2]	Risk-free rate
US interbank unsecured[1]	Risk-free rate +15bps
US household secured (mortgage)	Coupon from net interest income model +50bps
US household unsecured	Coupon from net interest income model +50bps
US government	Risk-free rate
US PNFC	Coupon from net interest income model +50bps
US OFC	Risk-free rate +15bps
US other assets[2]	Risk-free rate

Note: (1) Unsecured interbank loans + derivatives + certificates of deposit. (2) Includes reserve repos.

Table A3: Pricing of liabilities

Liability class	Modelling of cash flow
Unsecured interbank[1]	Risk-free rate +15bps
Household	Risk-free rate minus variable negative spread[2]
Government	Risk-free rate
PNFC	Risk-free rate minus variable negative spread[3]
OFC	Risk-free rate
Subordinated liabilities	Risk-free rate +15bps
Other liabilities[4]	Risk-free rate +15bps

Note: (1) Unsecured interbank deposits + derivatives. (2) The negative spread on household deposits is 200bps in the 0-3 months repricing bucket, 150bps in the 3-6 month bucket, 100bps in the 6-9 month bucket, 50bps in the 9-12 month bucket and 0bps at longer maturities. (3) The negative spread on corporate deposits us 100bps in the 0-3 months repricing bucket, 75bps in the 3-6 month bucket, 50bps in the 6-9 month bucket, 25bps in the 9-12 month bucket and 0bps at longer maturities. (4) Includes debt securities and repos

Annex 4: Additional figures

Figure A1: A stylised net profit distribution in the one period set-up with fixed coupons

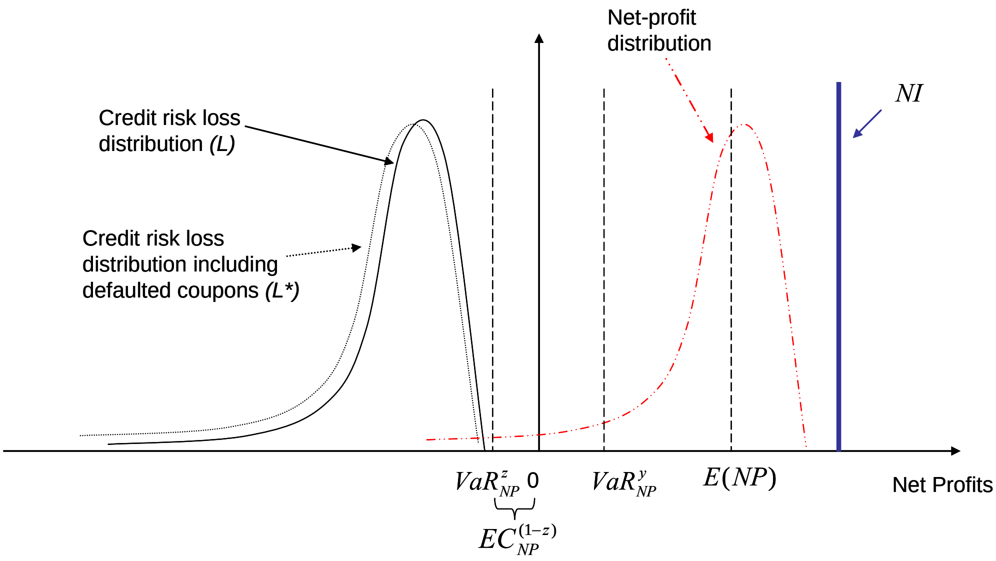


Figure A2: Implementation of the framework

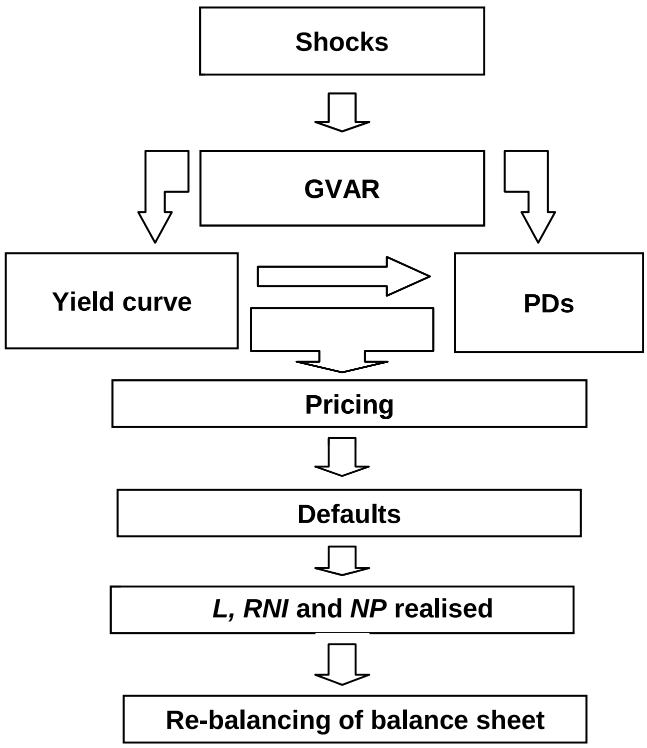
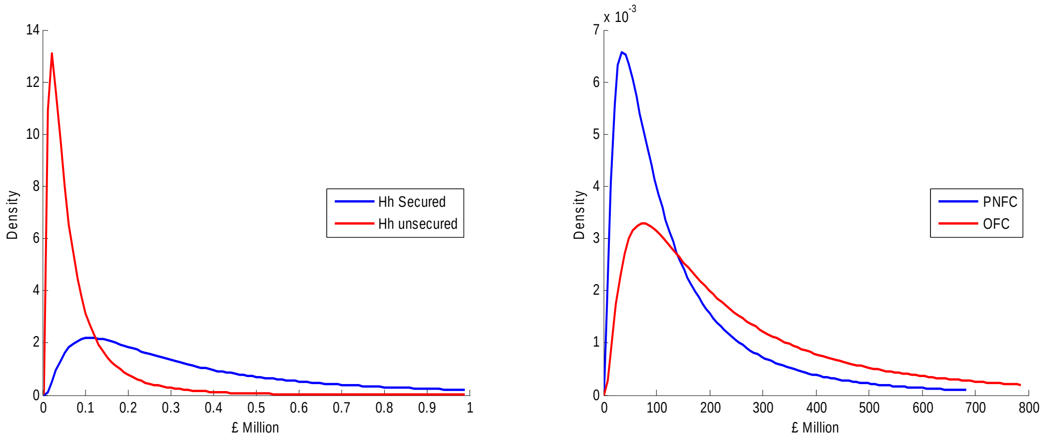


Figure A3: Size distribution of the hypothetical portfolio



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