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Abstract

Stress testing is a tool to analyse the resilience of a financial system under extreme shocks. In contrast to single-bank stress testing models, macro stress testing models attempt to analyse risk for the system as a whole by taking into account feedback – i.e. the transmission of risks – within the system or between the financial system and the real economy. This paper develops a simple model of macro stress testing, incorporating two types of feedback: one between credit and interest rate risks and another between the banking system and the real economy. The model is tested using hypothetical banking sector data. The results from the exercise highlight the importance of incorporating feedback effects for the assessment of total risks to the system, and of recognising more than one type of feedback effect in a model for a robust assessment of risks to financial stability.

¹ The views expressed in this paper are those of the author(s) and do not necessarily reflect the views of the Reserve Bank of New Zealand. I thank, without implication, Christie Smith, Rishab Sethi, Tim Hampton, and Leni Hunter for useful comments. Any remaining errors are the author's sole responsibility.
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1 Introduction

Stress testing is a tool to analyse the resilience of a financial system under extreme shocks. Macro stress testing attempts to model the financial system as a whole, and analyses different ways in which risks can be propagated from one bank to another within the financial system, or from the financial system to the rest of the economy. The transmission of shocks through various channels is referred to as “feedback”.

The Reserve Bank of New Zealand has been interested for some time in having a stress testing model with a particular type of feedback of shocks from the financial system to the real economy – the so-called “macro” feedback. But there are other feedback effects that are under active research in the macro stress testing literature, such as inter-bank contagion and interactions between credit and market risks.

The multiplicity of potentially important feedback effects and the ongoing nature of the research argue against building a large sophisticated model which accommodates one type of feedback but ignores others. It is better to start with a small model which can include additional feedback effects as needed and which can be improved as the research develops.

This paper develops a simple macro stress testing model with different types of feedback building on research from other central banks which are more advanced in the area. Two types of feedback are initially incorporated: correlations between credit and interest rate risks, and the transmission of shocks from the financial system to the real economy. The strategies for incorporating both types of feedback are rudimentary – especially for the macro feedback – reflecting the current state of the literature. However, the small structural model is easy to work with, and flexible enough to incorporate additional (or more complex) risk-transmission mechanisms in the future.

The model is used to stress test hypothetical banking sector data provided by the IMF. The advantage of using hypothetical banking sector data is the time saved while focusing on developing a working model. The disadvantage is that many of the results would change when the model is applied to actual New Zealand banking sector data. The latter is the next step of this research.

This paper draws two main conclusions. First, incorporating feedback effects can change the assessment of risks to financial stability. Models with feedback effects usually project larger, and sometimes much larger, aggregate losses in the banking system following a shock than a model without feedback effects. Second, incorporating more than one type of feedback in a model and not focusing solely on a particular one *a priori* can be important. This paper finds the feedback effect between credit and interest rate risks is a far more important source of risk-transmission than the “macro” feedback. Although the results are likely to change with different data, recognising the relative importance of different sources of feedback (risk-transmission mechanisms) will be an important ingredient in the analysis of financial stability.

The paper leaves a number of challenges for future research. One, already mentioned, is taking the model to New Zealand banking sector data. Another is analysing the sensitivity of the results to the calibrated coefficients, since assumptions about the parameters in the model are important in driving the results. A third challenge is extending the time frame of the analysis. The “macro” feedback effects might have a larger impact if the model is extended to allow shocks to build up over more than two periods. A fourth challenge is creating additional “modules” to incorporate more feedback effects, such as inter-bank contagions and the interaction between asset prices and banks’ portfolio adjustment.

The paper is organised as follows. Section 2 discusses the main differences between macro stress tests and individual-portfolio stress tests. Section 3 identifies four different types of feedback effects. Section 4 develops a simple macro stress testing model incorporating two types of feedback. Section 5 applies the model to stress test a hypothetical banking sector and section 6 concludes.

2 Macro stress testing

There are broadly two types of stress tests: individual-portfolio stress tests and macro (or system-wide) stress tests.

Individual-bank stress tests have evolved since the early 1990s as a risk-management tool used by the banks themselves, and more recently as a tool to determine the risk-adjusted level of capital under the Basel II framework.

Central banks have developed their own internal models to complement the results obtained by financial institutions.

Macro stress tests are more recent. The Financial Sector Assessment Program (FSAP), which is jointly sponsored by the International Monetary Fund and the World Bank, and began in the late 1990s, has provided impetus for a number of central banks to develop system-wide stress testing. More central banks are investing in macro stress testing models today as part of their broader efforts to develop tools to improve the quality of financial stability analysis.

Macro stress tests differ from individual-bank stress tests in several respects. First, a macro stress test typically allows for more than one bank in the system, and each bank can have a different portfolio. The differences in the banks' portfolios – e.g., in the riskiness of their portfolios and their exposures to particular sectors of the economy – have implications for how a given shock will affect the system. For example, macro stress tests often find that a relatively minor change in the distribution of risk exposures among the banks can substantially change the impact of a shock to the system.

Second, a system-wide model typically allows for more than one time period. Macro stress tests often find that the first-year effect of macroeconomic shocks is small relative to the level of capital in the banking system. Historical experience suggests that systemic crisis is often the result of protracted aggregate shocks that progressively weaken the cushioning capacity of capital. Lengthening the horizon of macro stress tests allows shocks to build up over time, and is likely to lead to a better understanding of the total impact of a given shock.

Third, system-wide models focus on the transmission of risks between banks or between sectors. The emphasis of single-bank stress tests is on testing the soundness of the individual portfolio. The focus of system-wide stress tests is on identifying potential sources of externalities, i.e., to assess how shocks to individual exposures can spread more widely across the system, or spill over from the financial sector to the wider macro economy.

3 Feedback effects

There are at least four different types of feedback (risk transmission mechanisms) that are considered important in the macro stress testing literature. These are:

- (i) Inter-bank contagion – how individual exposures to risk can spread more widely in the system through bilateral exposures in the inter-bank loans market;
- (ii) Correlation between credit and market risks – for example, how shocks to interest rates can raise the default risks of a bank’s borrowers, resulting in higher interest rates;
- (iii) Interactions between asset prices and the bank’s portfolio adjustment mechanisms – how shocks to asset prices can damage banks’ balance sheets, forcing sale of assets en masse, depressing asset prices even further;
- (iv) Transmission of shocks between the financial system and the real economy (the so called “macro” feedback effect)² – how shocks to the banking system can affect aggregate supply and demand and the overall economic activity, further weakening the credit environment facing the banks.

Compared to the other three, the models incorporating macro feedback effects are the least well-developed in the literature. Appendix A reviews three studies that illustrate the current state of the literature.

The next section develops a simple macro stress testing model incorporating feedback effects of type (ii) and (iv).

² The “macro” stress testing models are so-called because of their focus on the banking system as a whole (as opposed to single-portfolio stress testing models) and on analysing externalities (e.g., between banks, between risks, and between sectors). The “macro” feedback effect is so-called because it concerns the spillover of risks from the financial markets to the rest of the economy (i.e., macro economy). It is true that other feedbacks in the list are also “macro” in a sense that they are concerned with general equilibrium effects of initially local shocks – but they are not generally referred to as “macro feedbacks” in the literature.

4 The model

The model has four main components: a bank's balance sheet, interest rate risks, credit risks, and feedback effects.

The model outlined here incorporates ideas from various existing studies. The structure of the model of the bank's balance sheet and its components follows Drehmann et al (2006). The interest rate risks component follows Blaschke et al (2001). The credit risk component follows Whitley et al (2004). The strategy for integrating the credit and interest rate risks follows Drehmann et al (2006). The strategy for incorporating the macro feedback follows von Peter (2004) and Goodhart et al (especially 2005). See Appendix A for more detail.

To simplify notation, we drop the expectations operator. But all pricing or probabilistic values are expectations conditional on the information set at the time expectations are formed. We also use the subscript t to index both the value of a stock variable (such as loans) at time t and the accrued value of a flow variable (such as bank profits) between $t-1$ and t .

4.1 A bank's balance sheet

There are $b = 1 \dots B$ banks in the system, and each bank has several types of assets ($A^i, i = 1 \dots N$) and liabilities ($L^j, j = 1 \dots M$). The evolution of bank b 's assets is given by

$$\sum_{i=1}^N A_t^i = \sum_{i=1}^N (1 - PD_t^i) A_{t-1}^i + PD_t^i (1 - LGD^i) A_{t-1}^i \quad (1)$$

where

$A_t^i \equiv$ amount of asset i at time t ,

$PD^i \equiv$ probability of default of asset i ,

$LGD^i \equiv$ loss-given-default rate of asset i .

The assets are modelled as bullet bonds, which repay principal only at maturity.³ Their values are measured as the risk-adjusted present values of

³ The examples include fixed interest rate bonds and variable- and fixed-rate bank loans.

future coupon and principal payments given by the following set of equations:

$$A_t^i \equiv C_t^i A_0^i \quad (2)$$

$$C_t^i = (1 - D_t^i) \Big/ \sum_{t=1}^T D_t^i \quad (3)$$

$$D_t^i = \prod_{l=1}^T (1 + R_{t+l}^i)^{-1} \quad (4)$$

where

C_t^i \equiv fixed coupon rate for asset i with maturity T ,

D_t^i \equiv discount function, and

R_{t+l}^i \equiv expected risk-adjusted nominal interest rate paid by asset i between time $t + l - 1$ and $t + l$.

At time of the pricing of the asset and when the bank can reset the coupon, the expected income coincides with the expected credit risk of the asset, and therefore the expected economic profit is zero.⁴ In between, however, the interest rate and the credit risk associated with the asset might change while the coupon rate is fixed, which means the zero profit condition may not hold.⁵

The evolution of the bank's capital is given by

$$K_t = K_{t-1} + \pi_t \quad (5)$$

where

$$\pi_t = NIY_t - WR_t + \overline{OI}_t - \overline{OC}_t, \quad (6)$$

$$NIY_t = (CFA_t - CFL_t), \quad (7)$$

⁴ This is based on the underlying (but implicit) profit maximising behaviour of banks, also implied by the following equations in banks' profits and net interest incomes (see below; note that values are expected values as of time $l = 0$ where probabilistic arguments are concerned).

⁵ Drehmann et al (2006) and Gai et al (2008).

and

$K_t \equiv$ bank's capital,

$\pi_t \equiv$ net profit,

$NIY_t \equiv$ net interest income,

$WR_t \equiv$ loan write-off,

$\overline{OI}_t \equiv$ other income (assumed fixed),

$\overline{OC}_t \equiv$ other costs (assumed fixed),

$CFA_t^i \equiv$ cashflow from asset i , and

$CFL_t^j \equiv$ cashflow for liability j .

Thus, the bank's capital evolves with its net profit (π_t), which consists of the net interest income (NIY_t), the loan write-offs (WR_t), and other income and costs (assumed to be fixed and exogenous to the model). The net interest income in turn is given by the difference between the sum of expected total cashflows from the bank's assets (CFA_t) and the sum of expected cashflows from its liabilities (CFL_t).

The contribution of a single asset i to net interest income can be written:

$$CFA_t^i = [(1 - PD_t^i) + PD_t^i(1 - LGD^i)]C_t^i A_{t-1}^i \quad (8)$$

Writing the expression for the cashflows from the portfolio of assets is tedious, since there are N classes of assets with different PDs , $LGDs$, as well as for different maturities λ :

$$CFA_t = \sum_{i=1}^N \left(\sum_{\lambda=t}^T C_0^{i,\lambda} A_{t-1}^{i,\lambda} (1 - PD_t^i \cdot LGD^i) + \sum_{\lambda=1}^{t-1} [I_t C_t^{i,\lambda} A_{t-1}^{i,\lambda} (1 - PD_t^i \cdot LGD^i) + (1 - I_t) C_0^{i,\lambda} A_{t-1}^{i,\lambda} (1 - PD_t^i \cdot LGD^i)] \right)$$

where I_t is an indicator variable defined to equal 1 in periods after the assets in bucket λ have been repriced prior to t and to equal 0 otherwise.

The interpretation of the equation above is relatively straightforward. The first line in the big brackets sums the expected coupon payments between t and $t - 1$ from asset classes which do not reprice; the second line in the big

bracket sums the expected coupon payments between t and $t - 1$ from asset classes that have re-priced l periods prior to time t .

To keep the baseline model as simple as possible, we assume that every borrower will roll over her loan with the same maturity bucket as before, or equivalently, a bank will continue to invest in projects with the same re-pricing and risk characteristics as the maturing assets. This implies that the bank's portfolio composition changes only in line with defaulted assets.⁶

The contribution of a liability j to net interest income is similarly defined but assumes no default by the banks:

$$CFL_t^j = C_t^j L_t^j. \quad (9)$$

The expected write-off is given by:

$$WR_t = \sum_{i=1}^N PD_t^i LGD^i A_{t-1}^i. \quad (10)$$

Finally, bank b 's capital adequacy ratio constraint is given by

$$CAR_t \geq k^*, \quad (11)$$

where,

$$CAR_t = \frac{K_t}{RWA_t},$$

$$RWA_t = \sum_{i=1}^N \bar{w}^i A_t^i, \quad (12)$$

$RWA_t \equiv$ risk-weighted assets,

$\bar{w}^i \equiv$ risk-weight assigned to asset class i (assumed fixed),

$k^* \equiv$ regulatory minimum capital-adequacy ratio.

⁶ Given the behavioural assumption, the expected evolution of each asset class adjusting for default is: $A_t^i = A_{t-1}^i (1 - PD_t^i \cdot LGD^i)$ as shown in equation (1) above, where $A_0^i = A^i$ (Drehmann et al 2006).

4.2 Interest rate risks

There are two components to the interest rate risks facing a bank. One is known as the maturity-gap effect, and the other is known as the duration effect. The total interest rate risk facing the bank is given by the sum of the two effects.

The maturity gap effect

This effect captures the risk to a bank's income due to changes in the interest rate, and arises from the mismatch in the timing of repricing in banks' assets and liabilities. Suppose assets and liabilities are sorted into three time-to-repricing buckets: less than 3 months, due in 3 to 6 months; and due in 6 to 12 months. The gap in each maturity bucket λ is given by $(A_t^\lambda - L_t^\lambda)$ and the effect of a given change in interest rates on the bank's net income is given by⁷

$$\Delta NIY_t = \sum_{\lambda=1}^t (A_t^\lambda - L_t^\lambda) \cdot \Delta R_t \quad (13)$$

where

$A_t^\lambda \equiv$ Assets in repricing bucket λ at time t ,

$L_t^\lambda \equiv$ Liabilities in repricing bucket λ at time t ,

$\Delta R_t \equiv$ change in interest rates between t and $t-1$.

The duration effect

The maturity gap model captures only the effect of the changes in interest rates on the bank's income and not the effect on the value of its assets. To capture the latter, the Macaulay duration approximation is used. The duration of a bond i is defined as its weighted-average time-to-maturity (t^i), where the weight given to each cash flow is the ratio of the present value of the cash flows to the price of the bond

$$D = \sum_{i=1}^n t^i \cdot \left[\frac{PV(C^i)}{B^i} \right], \quad (14)$$

⁷ The model considers only simple parallel shifts in interest rates by ΔR_t .

where,

$$PV(C^i) = C^i e^{-Rt^i},$$

and

$$B^i = \sum_{i=1}^n C^i e^{-Rt^i}.$$

Using these equations, the interest rate sensitivity of the price of a bond can be calculated as

$$\frac{\Delta B}{\Delta R} = -\sum_{i=1}^n t^i C^i e^{-Rt^i} = -D \cdot B$$

and

$$\frac{\Delta B}{B} = -D \cdot \Delta R \quad (15)$$

Equation (15) shows the change in the value of bond portfolio is approximately equal to the average duration of the portfolio multiplied by the change in the interest rate.⁸

4.3 Credit risk

The default probabilities faced by the banks are defined using the reduced-form model proposed by Whitley et al (2004). They estimate different default probability models for different types of asset i (e.g., mortgage loans, credit card loans, corporate loans)

$$E_{t-1}(PD_t^i) = \Psi(X_t; \hat{\alpha}, \hat{\beta}) \quad (16)$$

The expected probability of default, and hence $\Psi(\cdot)$, may be non-linearly related to a vector of explanatory variables, X_t and vectors of empirically estimated coefficients, $\hat{\alpha}$ and $\hat{\beta}$.

⁸ Hull (2003), Chapter 5, p.112-113. It is an approximation because it assumes continuous compounding and the derivative holds only for a small change in the interest rate.

To keep the baseline exercise simple, I assume only one of their models applies to all assets i : the one for mortgage loans. Whitley et al (2004) use the error correction specification for the function $\Psi(X; \alpha, \beta)$ ⁹

$$\Delta \ln PD_t = \alpha_0 - \alpha_1 (\ln PD_{t-1} - \ln X_{t-1} \beta_1) + \Delta \ln X_t \beta_0 + \varepsilon_t \quad (17)$$

where X is a vector with four elements: the mortgage income gearing of the household sector ($MIGM$), the unemployment rate (UR), the loan-to-value ratio of first-time home buyers ($LVRFTB$), and undrawn housing equity ($UNDRAWN$).¹⁰ Using UK data from 1985–2000, they obtain (t-ratios in brackets):

$$\begin{aligned} \Delta \ln(PD_t) = & 0.795 - 0.83 \Delta \ln(MIGM_t) + 0.071 \Delta \ln(UR_t) \\ & (1.1) \quad (-1.3) \quad (2.1) \\ & -0.393 \Delta \ln(LVRFTB_t) - 0.916 \Delta \ln(UNDRAWN_t) + 0.431 \Delta \ln(PD_{t-1}) \\ & (-2.1) \quad (-3.1) \quad (5.5) \\ & -0.102 (ECM)_{-1} \\ & (-3.2) \\ ECM = & \ln(PD) - 2.734 \ln(MIGM) - 0.700 \ln(UR) + 3.866 \ln(LTVFTB) \\ & (-4.1) \quad (-4.4) \quad (3.0) \\ & +9.003 \ln(UNDRAWN) - 7.816 \\ & (-11.2) \quad (-1.3) \end{aligned} \quad (18)$$

Again, to keep the exercise simple, I use the long-run equilibrium relationship in the model (i.e., the relationship captured by α_1 and the β_1 's in equation 13), ignoring the short-run effects of X on PD outside of the equilibrium (i.e., α_0 and β_0 's in equation 17). Finally, I also assume that

⁹ The error correction model is only slightly non-linear and is not a great model for a probability, which is constrained to lie in $[0, 1]$. Experimenting with alternative specifications of equation (13), for example, using duration, probit, or multinomial logit models, is an area for future research.

¹⁰ $UNDRAWN$ is defined as:

$[(\text{Value of housing assets}) - (\text{Household debt})] / (\text{Value of housing asset})$.

LGD in the model is exogenous and non time-varying, so that there will be no change in LGD from the baseline to the stress scenario.¹¹

4.4 Feedback between credit and interest rate

The strategy for introducing possible interactions between the credit and interest rate risks is due to Drehmann et al (2006). The nominal interest rate paid on asset i , R^i , consists of two components – a risk-free component, r , and a risk premium, s .

$$R_t^i = r_t + s_t^i \quad (19)$$

where

$$s_t^i = PD_t^i \cdot LGD^i,$$

$R_t^i \equiv$ nominal interest rate paid by the asset i .

The decomposition in (19) holds only in continuous time. In discrete time, the correct approximation is:

$$R_t^i = \frac{r_t + s_t^i}{1 - s_t^i} \quad (20)$$

Equation (20) states that an increase in credit risk increases the interest rate. Equation (18) implies an increase in the interest rate, in turn, increases the credit risk facing the bank by implicitly raising the income-gearing ratio of borrowers.

4.5 Feedback between the financial system and the macro economy

The strategy to introduce the feedback effect from the financial system to the real economy follows von Peter (2004, 2005) and Goodhart et al (2004, 2005, 2006a, 2006b). Only two additional components are needed to introduce the feedback effects: the bank's reaction to shocks, and an equation linking the financial market to the macro economy.

¹¹ This is an area of future research.

The bank's reactions to shocks

$$A_t^l = \begin{cases} A_{t-1}^l(1 - PD_t^l) + A_{t-1}^l PD_t^l(1 - LGD^l) & \text{if } \frac{K_t}{RWA_t} \geq k^* \\ A_{t-1}^l(1 - PD_t^l) & \text{if } \frac{K_t}{RWA_t} < k^* \end{cases} \quad (21)$$

where $A_t^l \equiv$ the loan portion of the bank's assets, ($l \in i, \dots, N$).

Equation (21) states that if the bank's capital adequacy ratio falls below the regulatory minimum k^* , it will reduce its lending A_t^l in an effort to improve its capital adequacy ratio. The assumption is that the assets are sold for cash, and that cash does not attract a capital requirement.¹² Because there is no asset market in this model, the bank cannot sell its assets (loans, collateral) to rebalance its portfolio. Instead, the bank would only stop re-investing automatically in the new loans from what is recovered from the defaulted loans in the previous period –as assumed in equation (1).¹³

Feedback from the financial markets to the macro economy

$$\ln(GDP_{t+1}) = u_1 + u_2 \ln \sum_{b=1}^B \sum_{l=1}^{<N} (A_t^{b,l}) \quad (22)$$

where

$GDP_{t+1} \equiv$ GDP next period,

$\sum_{b=1}^B \sum_{l=1}^{<N} A_t^{b,l} \equiv$ the aggregate loan supply in this period.

Equation (22) states that aggregate income is a positive function of the aggregate credit supply available in the previous period.

¹² Cifuentes et al (2004).

¹³ This is another area for the future research, along with endogenising the LGDs. It would be desirable to allow LGD to interact with PDs and to allow more active portfolio-adjustment by the banks.

5 Application of the model to Bankistan

5.1 Data

The model is applied to hypothetical banking sector data provided by the IMF.¹⁴ The data is a cross section of balance sheet information (volume, maturity structure, and quality of assets and liabilities) of twelve banks operating in a hypothetical country called Bankistan. According to the brief background provided in the documentation, the country has a “non-complex” financial system (no large complex financial institutions). Its twelve banks consist of three state-owned, five domestic- and privately-owned, and four foreign-owned banks. The basic balance sheet data on the banks are given in Appendix B.

The economy of Bankistan is in bad shape, characterised by unsustainable fiscal imbalances, loose monetary conditions, high inflation, negative real interest rates, and sharply-contracting real activity. The upshot is generally weak performances of the banks, in particular the state-owned ones. The official currency of Bankistan is Bankistan dollar (B\$). The official exchange rate is fixed at 55B\$/ US\$.

5.2 Stress testing scenario

The following combination of shocks provides the stress testing scenario in this paper¹⁵:

- 300 basis point increase in interest rates across the yield curve, together with
- 20 percent fall in residential property prices,

¹⁴ The data comes with an “open access” stress testing model, called Stress Tester 2.0. Anyone interested in stress testing can start using the model by feeding her own data, or develop her own model or extensions of the given model by using the provided data. Both the data and the model are available from:

<http://www.imf.org/external/pubs/cat/longres.cfm?sk=20222.0>

¹⁵ The scenario is compiled from the list of “single-factor credit risks” and “single-factor interest rate risks” used in the 2004 Financial Sector Assessment Program (FSAP) in New Zealand. The FSAP had two “complex scenarios” (an outbreak of foot-and-mouth disease, and offshore borrowing shocks), but neither was suitable here, because these scenarios included types of risks that are not addressed in the model developed in this paper, e.g., foreign exchange rate risks, and non-parallel shifts in the yield-curve.

- 4 percent decline in the real disposable income, and
- 4 percentage points increase in the unemployment rate, from 5 percent to 9 percent.

The shocks are deterministic and assumed to take place simultaneously. How these shocks affect the banks' balance sheets is determined by the components of the model described in Section 4.

I run the chosen scenario on three different versions of the model: (i) the model without feedback effects, (ii) the model with feedback effects between credit and interest rate risks *but no macro feedback effects*, and (iii) the model with macro feedback effects *but no feedback effect between credit and interest rate risks*. Figure 1 outlines the timing of the shocks and how the model with or without feedback is affected by the shocks.

Figure 1

Timing of shocks and model with and without feedbacks

[Figure 1 here]

5.3 Additional assumptions

In addition to the structural assumptions in the model, I make the following assumptions about the parameters and initial values as shown in Table 1.

Table 1

Exogenous parameters and initial values

[Table here]

5.4 Results

Table 2 reports the results of the stress test under the scenario above but using three different versions of the model.

Table 2

Impacts of the stress scenario on the hypothetical banks – profits and losses

(In \$B billions; ratios in percent)

[Table here]

The top panel in Table 2 shows the impact of the shocks on the banks' profit in billions of Bankistan dollars (B\$). The second and the third panels show the impact on profits as a ratio of the banks' risk-weighted assets (RWA) and of the total capital, respectively. The bottom two panels show the impact of shocks in terms of the pre- and post-capital adequacy ratios, and the number of banks whose total capital falls below the regulatory minimum $k^* = 8$ percent, and below zero.

Overall, the results suggest that Bankistan's banks will suffer large losses as a result of the shocks in all versions of the model. The aggregate loss in the system varies from B\$1.6 trillion (4 percent of RWA, 30 percent of total capital) to B\$3.2 trillion (9 percent of RWA, 60 percent of total capital).

The largest impact on the banks happens in model (ii) which introduces feedback effects between the credit and interest rate risks but no macro feedback effects. Under this model, there is a positive correlation between credit and interest rate risks facing the banks. The initial shock to interest rates will affect both interest rate risks and credit risk facing the banks, the latter by raising the risk of default by borrowers. The increase in the default risk will feed back into a higher interest rate by raising the risk premium in the next period, setting off the second-round losses for the banks by raising the interest rate risk and a further increase in default risk by borrowers. Seven out of the 12 banks will have their total capital fall below the regulatory minimum $k^*=8$ percent and 4 out of the 12 banks will have negative capital.

The next largest impact happens in model (iii) which incorporates the macro feedback effect but not the credit-interest rate feedback. Under this model, there is a positive correlation between the aggregate credit supply by the banks and the real economy. After the initial shocks, banks assess their portfolios and some will cut back lending in order to increase their capital-adequacy ratios. A fall in the aggregate credit supply will lower the aggregate demand in the following period, setting off the second-round losses for the banks by raising the default risk by borrowers. Six out of the 12 banks will have their total capital fall below the assumed regulatory minimum $k^*=8$ percent, and 2 out of the 12 banks will have negative capital.

Why does the model with macro feedback predict smaller losses than the model with feedback between credit and interest rate risks? The result can be driven by the model's assumptions as well as the nature of the data at

hand. In terms of the model's assumptions, for example, the fact that the macro feedback effect is assumed to work primarily through the credit risk channel (and not through both credit and interest rate risk channels) to generate the second-round losses may result in limiting the extent of losses predicted under the model with macro feedback. Alternatively, the parameters of the model pertaining to the sensitivity of default risk to various shocks (equation 18), the banks' response to shocks (equation 21), or the sensitivity of the aggregate demand to changes in the aggregate credit supply (equation 22) can each be important determinants of the losses experienced by banks under a particular model. In terms of the data, the banks' capital buffer, their exposures to credit risk versus the interest income risk or the market value risk will, *inter alia*, change both the absolute and the relative size of the predicted losses under different versions of the models.

Although the results of stress testing will always depend in part on the data at hand and in part on the parameters and other structural assumptions of the model, it will nevertheless be important to see if the results are particularly sensitive to certain parameters or whether the macro feedback grows larger if the time dimension of the model is extended beyond the current two-period. These are among the next steps of this research project.

6 Conclusions

This paper describes the development of a simple macro stress testing model with different types of feedback, and tests the model on hypothetical banking sector data. The main findings are:

- Introducing feedback effects into stress testing can change the assessment of financial stability risks. For a given scenario of shocks, the models with feedback effects suggest larger losses in the banking system than the model without feedback effects;
- Of the two types of feedbacks that are modelled in this paper, one matters more than the other: the positive feedbacks between credit and interest rate risks doubles the impact of the shocks to the system, while the macro feedback effect increases them by only 10 percent;

- The differences in the results underscore the importance of recognising more than one type of feedback effects in a model, and not focusing on a particular type of feedback *a priori*;
- The assumptions in the model are important in driving the results. The exact size of the losses, and the relative losses under alternative form of feedbacks, depend on both the underlying banking sector data and the assumptions of the model.

The next steps of this research include:

- Applying the model to actual New Zealand banking sector data;
- Carrying out sensitivity analyses on the parameters of the model (e.g., for the probability of default and the elasticity of aggregate income to the credit supply);
- Extending the time horizon of the model to allow shocks to build up for longer;
- Exploring richer stories of macro feedback (e.g., introducing the negative feedback between the portfolio adjustment by the banks and the house prices, in addition to the negative feedback between the portfolio adjustment by the banks and the credit supply);
- Introducing other types of feedback effects (e.g., inter-bank contagions and the interactions between asset prices and banks' portfolio adjustment).

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Table 1
Exogenous parameters and initial values

No	Description	Parameter or variable	Value	Source
1	Impact on RWA/ impact on assets (%)	..	100	IMF
2	Impact of real interest rate/ impact on nominal interest rate (%)	..	100	IMF
3	Average LGD (%)	<i>LGD</i>	30	Drehman et al (2006)
4	Elasticity of PD to changes in macro variables	β_1	(various)	Whitley et al (2004)
5	Speed of adjustment per quarter	α_1	0.102	Whitley et al (2004)
6	Elasticity of GDP to credit supply	u_1	0.1	Goodhart et al (2004)
7	Household debt (N\$bn)	UNDRAWN	139	NZ 06Q4
8	Initial value of housing stock (N\$bn)	UNDRAWN	559	NZ 06Q4
9	Regulatory capital adequacy ratio (%)	k^*	8	Basel II
10	Pre-shock nominal interest rate (%)	R	10	arbitrary
11	Pre-shock probability of default (%)	..	2	arbitrary
12	Share of mortgage debt in total claims to banks (%)	..	100	arbitrary
13	Share of credit card debt in total claims to banks (%)	..	0	arbitrary
14	Share of corporate debt in total claims to banks (%)	..	0	arbitrary
15	Impact on household income/ Impact on GDP (%)	..	100	arbitrary

Table 2
Impacts of stress scenario on banks in Bankistan –
profits and losses

(In \$B billions; ratios in percent)

(i) In billions of dollars			
	Without feedbacks	With - interaction	With - macro feedback
Total	-1,621	-3,188	-1,765
Mean	-135	-266	-272
Median	-41	-102	-46
Min	-542	-925	-569
Max	58	59	55
(ii) As a percentage of risk-weighted assets			
	Without feedbacks	With - interaction	With - macro feedback
Total	-4.4	-8.7	-4.8
Mean	-4.1	-8.7	-4.6
Median	-3.6	-7.6	-4.0
Min	-13.1	-20.7	-13.4
Max	10.3	10.4	9.7
(iii) As percentage of total capital			
	Without feedbacks	With - interaction	With - macro feedback
Total	-29.8	-58.6	-32.4
Mean	155.9 a/	117.1 b/	126.9 c/
Median	-25.0	-54.4	-27.0
Min	-137.5	-225.2	-147.0
Max	2,380.0 a/	2,415.8 b/	2,238.0 c/
(iv) CAR pre-shock			
	Without feedbacks	With - interaction	With - macro feedback
Total	14.9	14.9	14.9
Mean	13.5	13.5	13.5
Median	12.1	12.1	12.1
Min	0.4	0.4	0.4
Max	27.9	27.9	27.9
(v) CAR post-shock			
	Without feedbacks	With - interaction	With - macro feedback
Total	10.8	6.6	10.6
Mean	9.7	5.1	9.2
Median	9.7	6.0	9.2
Min	-3.2	-14.4	-4.7
Max	26.7	24.1	26.3
(vi) Others			
	Without feedbacks	With - interaction	With - macro feedback
No. of banks with CAR ^{d/} below k*=8%	4/12	7/12	6/12
No. of banks with capital below zero ^{e/}	2/12	4/12	2/12

Note: a/ Due to extreme values for DB2. Without it, Mean = -46.4, Max = 0.9

b/ Due to extreme values for DB2. Without it, Mean = -91.9, Max = -16.9

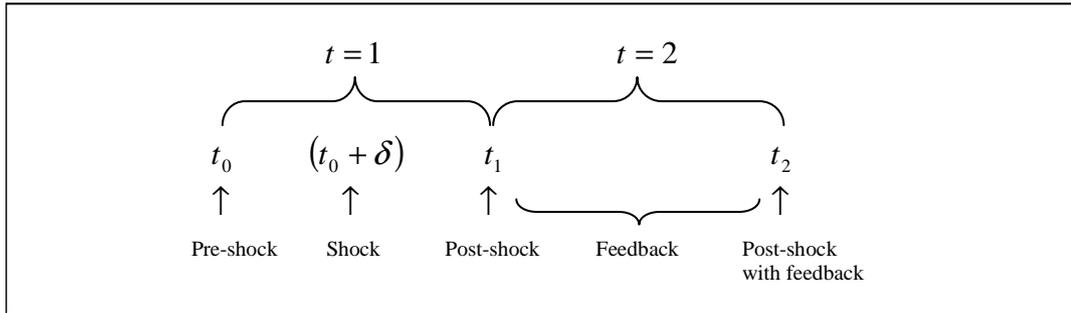
c/ Due to extreme values for DB2. Without it, Mean = -50.6, Max = -5.5

d/ Number of banks with CAR below k*=8% pre-shock: 3/12 (SB1,SB2,DB2)

e/ Number of banks with capital below 0 pre-shock: 0/12

Figure 1

Timing of shocks and model with and without feedbacks



Appendix

A Existing models with macro feedback effects

The Reserve Bank of New Zealand has been interested for some time in having a stress testing model with “macro” feedback effects – i.e., feedback between the financial sector and the real economy. This appendix reviews the existing studies that have incorporated macro feedback effects in the context of structural macro stress testing models: Goodhart et al (2004, 2005, 2006a, 2006b), von Peter (2004, 2005), and Shimizu (1997).^{16,17}

Introducing the macro feedback in a stress testing model essentially involves adding two key components to the model: (i) banks’ reactions to shocks and (ii) the actual feedback effect from the financial to the real economy.¹⁸ I review these three studies on the basis of how they define these two key components.

The main conclusion from the review is that while each study provides a useful idea of how we might begin incorporating macro feedback effects, none seems to be fully operational yet.

- Goodhart et al (2004, 2005, 2006a, 2006b) develop a two-period general equilibrium model which captures possible feedback effects among the banks (inter-bank contagion) and between the financial sector and the real economy (macro feedback effect). Banks are assumed to solve a comprehensive optimisation problem, trading off costs and benefits of lending and borrowing in markets for deposits, consumer loans, and inter-bank loans. Banks are also allowed to default in both inter-bank and deposit markets and to violate regulatory minimum capital requirement subject to constraints. The macro feedback effect in this model occurs through a credit crunch: after initial shocks to the system, some banks cut back lending in order to increase their capital ratios. A fall in the aggregate credit supply

¹⁶ These studies are reviewed in the surveys of new developments in macro stress testing methodologies by Sorge (2004) and Sorge and Virolainen (2005).

¹⁷ There are studies that seek to capture macro feedback effects using purely empirical approaches, e.g., using VAR or principal components techniques. Sorge and Virolainen (2005) review some of the recent studies in this area. Bardsen et al (2006) provide a broader review of macro-empirical models in the financial stability analysis. Sorge and Virolainen (2005) and Cihak (2004, 2005, 2007) discuss limitations of purely empirical approaches to modelling feedback effects.

¹⁸ Sorge (2004).

will lower the GDP and further aggravate the default probability of the households.

The banks' reactions to shocks in this model are given by the solutions to the optimisation problem:

$$\max_{\bar{m}^b, \mu^b, \mu_d^b, v_s^b, s \in S} \Pi^b = \sum p_s \left[\frac{\pi_s^b}{10^{10}} - c_s^b \left(\frac{\pi_s^b}{10^{10}} \right)^2 \right] - \sum p_s \left[\lambda_{ks}^b \max[0, (\bar{k}^b - k_s^b)] + \frac{\lambda_s^b}{10^{10}} [\mu^b - v_s^b \mu^b] + \frac{\lambda_s^b}{10^{10}} [\mu_d^b - v_s^b \mu_d^b] \right] \quad (\text{A1})$$

subject to

$$\bar{m}^b + A^b = \frac{\mu^b}{(1+\rho)} + \frac{\mu_d^b}{(1+r_d^b)} + e_0^b + \text{Others}^b \quad (\text{A2})$$

$$v_s^b \mu^b + v_s^b \mu_s^b + \text{Others}^b + e_0^b \leq v_{s,b}^{h^b} (1+r^b) \bar{m}^b + (1+r^A) A^b, \quad s \in S \quad (\text{A3})$$

where

$$\pi_s^b = \Delta(\text{A3})$$

$$e_s^b = e_0^b + \pi_s^b, \quad s \in S \quad (\text{A4})$$

$$k_s^b = \frac{e_s^b}{\bar{w} v_{s,b}^{h^b} (1+r^b) \bar{m}^b + \tilde{w} (1+r^A) A^b}, \quad s \in S \quad (\text{A5})$$

$\Delta(x) \equiv$ difference between RHS and LHS of inequality in (x)

$p_s \equiv$ probability that state $s \in S$ will occur

$c_s^b \equiv$ coefficient of risk aversion in the utility function of bank $b \in B$

$\lambda_{ks}^b \equiv$ capital requirements' violation penalties imposed on bank b in state s

$\bar{k}^b \equiv$ capital adequacy requirement for bank b

$\lambda_s^b \equiv$ default penalties on bank b

$\mu^b \equiv$ amount of money that bank b owes in the inter-bank market

$\mu_d^b \equiv$ amount of money that bank b owes in the deposit market

$v_s^b \equiv$ repayment rate of bank b to all its creditors in state s
 $\bar{m}^b \equiv$ amount of credit that bank b extends in the loan market
 $A^b \equiv$ the value of market book held by bank b
 $e_s^b \equiv$ amount of capital that bank b holds in state s
 $Others^b \equiv$ the “others” items in the balance sheet of bank b
 $r^b \equiv$ lending rate offered by bank b
 $r_d^b \equiv$ deposit rate offered by bank b
 $\rho \equiv$ inter-bank rate
 $r^A \equiv$ the rate of return on market book
 $v_{s,b}^{h^b} \equiv$ repayment rate of agent $h^b \in H^b$
 $\bar{w} \equiv$ risk weight on loans,
 $\tilde{w} \equiv$ risk weight on market book.

The feedback from the financial sector to the real economy is driven by the reduced-form equation:

$$\ln(GDP_s) = u_{1,s} + u_{2,s} [\ln(\bar{m}^\gamma) + \ln(\bar{m}^\delta) + \ln(\bar{m}^\tau)] \quad (A6)$$

where

$GDP_s \equiv$ GDP in state s of the second period.¹⁹

Equation (A1) states that each bank chooses the levels of credit supply, deposits, and repayment in the inter-bank loans market to maximise its profit, subject to the balance sheet constraints (A2), the income (liquidity) constraint (A3), and the capital adequacy constraint (A4–A5). Equation (A6) says that the GDP in each state is a positive function of the aggregate supply of credit in the previous period.²⁰

Goodhart et al. (2005) apply this model to UK banking data demonstrating that the model is tractable and can be used as a stress testing tool. Goodhart

¹⁹ The model has been developed as 2-period model, except in their latest paper in 2006, which extends the model to an infinite-period model. The discussion of their model here is based on their earlier papers.

²⁰ Because the coefficients are state-dependent, the model can allow for a possible “non-linearity” in the relationship under normal conditions and under stress.

et al. (2006b) extend the model to an infinite-horizon setting to show how financial fragility may build up over time using actual UK time-series data.

The Goodhart et al. model is the most developed and operationalised of the three studies, but it has some issues. First, the model is primarily focused on studying inter-bank contagion and not the macro feedback effect. As seen from the equations (A1) and (A6), the model gives much more attention to describing the inter-bank relationships and much less to describing the feedback from the financial to the real economy. Second, the model is relatively large and complex (54 simultaneous equations and 135 unknowns) so that interpretation of the stress testing results is a real challenge. The authors have tried to demonstrate that the model is tractable, but they do so only by subjecting the model to relatively simple, single-shock tests. Third, and related, the types of shocks the authors consider to demonstrate the capability of the model as a practical stress testing tool are slightly unusual (e.g., expansionary monetary policy, positive shock in deposit supply, positive shock in capital endowment of one of the banks, increase in fees for violating capital adequacy requirement, positive shock to GDP). As a result, it remains uncertain whether the model produces reasonable results for more standard shocks (e.g., changes in default probability, interest rates, or asset prices) or whether the model remains tractable where the combinations of these shocks are considered.

- von Peter (2005, 2006) proposes a simpler model to capture the feedback between the financial system and the real economy. The model is an infinite-period overlapping generations model with a single bank, a firm (“borrower”), and a household (“saver”). The feedback between the financial system and macro economy occurs through a credit crunch as in Goodhart et al. After an adverse macro shock, if a bank suffers a large loss it restricts lending to meet a binding capital-adequacy constraint. Reduced credit supply raises the interest rate, reduces the firm profits, and lowers the aggregate demand.

The bank’s reaction function is given by:

$$q_t H \leq \frac{R}{R-1} K_t = \begin{cases} qH & \lambda \leq (R-1)K \\ qH - \frac{R}{R-1} [\lambda - (R-1)K] & (R-1)K \leq \lambda \leq RK \\ 0 & \lambda \geq RK \end{cases} \quad (\text{A7})$$

where

$q_t H \equiv$ loan supply (also the loan demand, asset value, and the productivity of assets)

$R_t \equiv (1+r)$, where r is the steady-state interest rate

$K_t \equiv$ capital

$\lambda \equiv$ write-offs

$k^* \equiv \frac{R}{R-1} K_t$ in this model, because of the structure of the model.

The first line of equation (A7) shows that if a bank's loss is less than its profit buffer, the loan supply in the economy remains at the steady-state level. The second line says if the bank's loss cuts into its capital, the loan supply becomes a multiple of the bank's capital. The last line says when the loss exhausts the bank's capital, there is no credit supply in the economy.

The feedback effect in this model is given by the two equations:

$$q_t H = \frac{\alpha(1-\tau)p_{t+1}y}{R_t} + \frac{q_{t+1}H}{R_t} \quad (\text{A8})$$

$$p_t y = \begin{cases} s_t + [p_t y + q_t H - Rq_t H + \lambda] + (R-1)K - \lambda & \text{if } \lambda \leq (R-1)K \\ s_t & \text{if } \lambda \geq (R-1)K \end{cases} \quad (\text{A9})$$

where

$\alpha \equiv$ productivity of asset (H)

$\tau \equiv$ size of the initial shock, $\tau \in [0,1]$

$p_t y \equiv$ aggregate demand

The first is a capital-constrained asset pricing function, which also “doubles” as a credit demand function in the model. The second is the aggregate demand function. The feedback effect happens automatically in this model since, by the nature of the model, the bank credit ($q_t H$) equals household wealth which also equals the only productive asset used by the firm to produce output. The credit-constrained equilibrium is the set of prices $\{p, q, R\}$ which reduces both the credit demand (A8) and the aggregate demand (A9) to levels consistent with the credit supply (A7).

Apart from the automatic feedback effects driven by identities, the issue with this model is that it is not developed as a diagnostic tool for financial stability analysis with actual banking sector data in mind. The single bank, single asset, and single borrower overlapping generations model is not easily adaptable to the practical stress testing framework.²¹

What is attractive about this model, however, is the reduced-form characterisation of the bank's reaction function after the shocks. Instead of solving a complicated optimisation problem, the model shows that the bank's response to shocks can be characterised by a simple function of a credit loss and of the capital adequacy requirement which generates the credit crunch. von Peter's model, therefore, suggests an alternative avenue to Goodhart et al to capture the credit crunch as a possible source of macro feedback effects.

- Shimizu (1997) provides an even simpler framework to illustrate the main mechanism through which feedback effects can be introduced into a static stress testing model.

$$\underbrace{f_{i,t}(x_t) \rightarrow f_{i,t+1}(x_t + dx)}_{\text{Stress test without feedback}} \rightarrow \underbrace{f_{i,t+2}(x_t + dx)}_{\text{Portfolio rebalancing}} \rightarrow \underbrace{f_{i,t+2}(x_t + dx + dx')}_{\text{Stress test with feedback}} \quad (\text{A10})$$

where,

$f_{i,t}(x_t) \equiv$ portfolio value of the i th agent at time t

$x_t \equiv$ value of assets included in the portfolio, depending on the time t risk factors

$dx_t \equiv$ initial (exogenous) shock to the value of assets

$dx' \equiv$ second-round changes in the value of assets

Suppose there is only one type of asset (x_t) and a given stress scenario reduces the value of the asset by dx . The initial change in portfolio value due to the shock is given by $f_{i,t}(x_t + dx)$ if we assume no portfolio rebalancing by agent i (i.e., $f_{i,t} = f_{i,t+1}$). A typical (static) macro stress testing model stops here.

²¹ The model is intended to explain asset-price and financial crisis, and is applied to the case studies of Japan, Nordic countries, and the US during the Great Depression.

Suppose, however, agents are allowed to respond to the shock by rebalancing their portfolios. The change in the portfolio mix from $t + 1$ and $t + 2$ is given by $f_{i,t+1}(x_t + dx) \rightarrow f_{i,t+2x_t+dx}(x_t + dx)$.

The response by all agents in the market will have an aggregate demand and supply effect on the assets, which will generate further changes in the asset price (dx'). The total impact of the shock to agent i 's portfolio is given by $f_{i,t+2}(x_t + dx + dx')$.

Shimizu (1997) provides a numerical example to show how this conceptual framework might work in practice.

The banks' numerical reaction function is given by:

$$\begin{cases} \text{Agent 1:} & x_{1,t} = x_0 & \text{"No trade"} \\ \text{Agent 2:} & x_{2,t} = b/x_t & \text{"Dollar - cost - average"} \\ \text{Agent 3:} & x_{3,t} = c \cdot dx_t & \text{"Insurance with dynamic hedging"} \end{cases} \quad (\text{A11})$$

where $x_0 = 1,000$, $b = 2,000$, $c = 5$, and $dx = -6.5$.

The feedback effect on the asset price after the portfolio adjustment by the banks is given by:

$$dx' = \kappa \left(\sum_{i=1}^n \frac{df_i(x)}{dx} \right) \quad (\text{A12})$$

where,

$dx' \equiv$ change in market price of asset x induced by the agent's rebalancing of portfolio

$\sum_{i=1}^n \frac{df_i(x)}{dx} \equiv$ aggregate trade imbalance (or net supply) in the market caused

by agents' trading

$\kappa(\cdot) \equiv$ some function linking the net trade imbalance to trade

Unfortunately, the model ends here, and the feedback loop from the asset price to the real economy is not articulated.²² But the overall framework for thinking about the feedback effect in (A10), and the idea of using a stylised set of reaction rules (in a similar vein as von Peter's) are useful in demonstrating that there are simple ways to start incorporating macro feedback effect in a standard (static) stress testing models with no feedback.

In Section 4 in the main text, we develop a small structural model with feedback effect taking the eclectic approach to incorporating ideas from the three existing studies examined here.

²² In this sense, her model is not a model with macro feedback effect but a model with the feedback effect of type (iii) discussed in Section 3 in this note.

Appendix B

Table B1

Balance sheets of the hypothetical banks

(In \$B billions; duration in years)

	All Banks	SB1	SB2	SB3	DB1	DB2	DB3	DB4	DB5	FB1	FB2	FB3	FB4
Total assets	72,366	2,901	3,119	14,501	344	1,794	4,827	2,176	4,221	14,520	18,033	5,011	919
Cash and T-bills	4,507	250	178	987	10	150	390	185	298	1,100	450	450	59
Long-term government bonds	5,280	131	85	352	16	112	407	143	343	1,892	780	921	98
Total loans	60,017	2,113	2,681	12,350	317	1,340	3,976	1,557	3,534	11,337	16,534	3,540	740
Other assets	2,562	408	175	812	1	192	53	291	47	191	269	100	22
Total liabilities	72,366	2,901	3,119	14,501	344	1,794	4,827	2,176	4,221	14,520	18,033	5,011	919
Deposits	61,820	2,299	2,687	12,511	294	1,472	4,178	1,965	3,493	12,458	15,407	4,300	756
Demand deposits	29,914	1,124	982	5,921	137	638	2,211	782	1,598	6,801	7,290	2,091	339
Term deposits	31,906	1,175	1,705	6,590	157	834	1,967	1,183	1,895	5,657	8,117	2,209	417
Total capital (equity)	10,546	602	431	1,990	50	321	648	211	728	2,063	2,627	712	163
Interest rate sensitivity gap (assets - liabilities)													
< 3 months	-15,777	273	-1,996	-3,018	239	3,146	-1,856	-1,953	1,419	-4,826	-3,489	-2,486	-1,229
3-6 months	367	361	743	-474	-567	0	-55	1,240	77	-5,436	5,600	-1,608	487
6-12 months	13,482	1,065	21	269	0	0	5,132	1,733	338	5,721	300	-1,367	271
Average duration of bonds held	...	3.8	3.3	1.9	2.3	4.1	4.0	1.9	3.7	3.8	4.1	3.0	4.2

Figure B1
Impact on write-offs
(Median for the group in \$B billions)

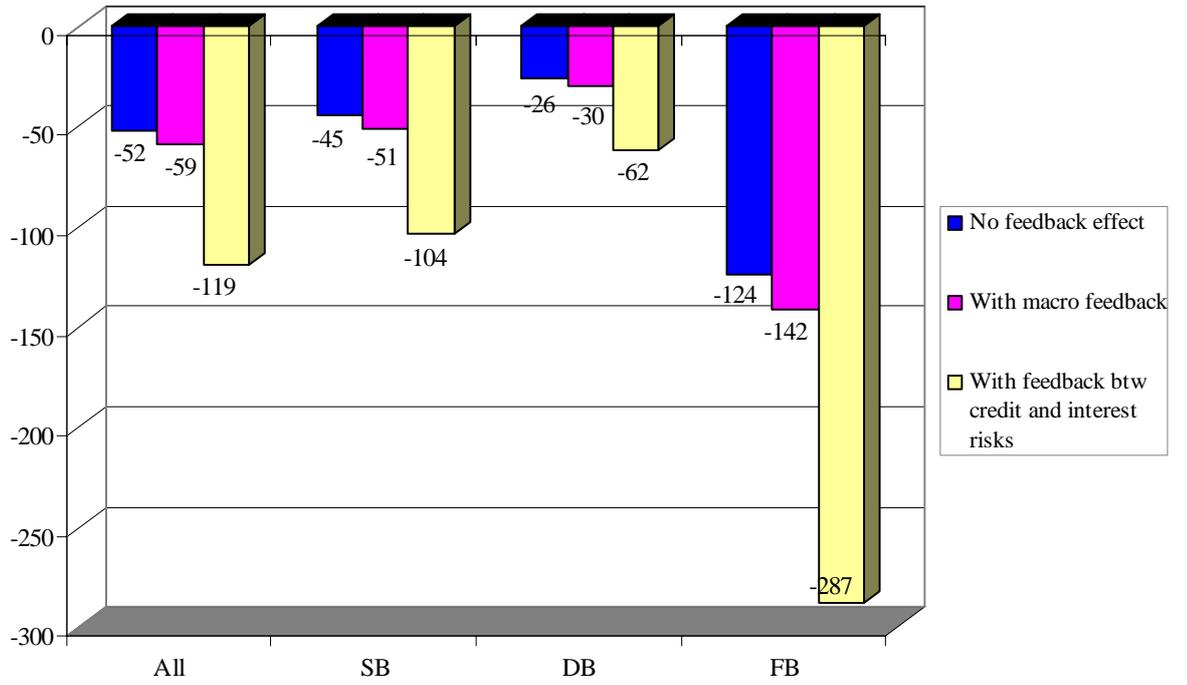


Figure B2
Impact on net interest income
(Median for the group in \$B billions)

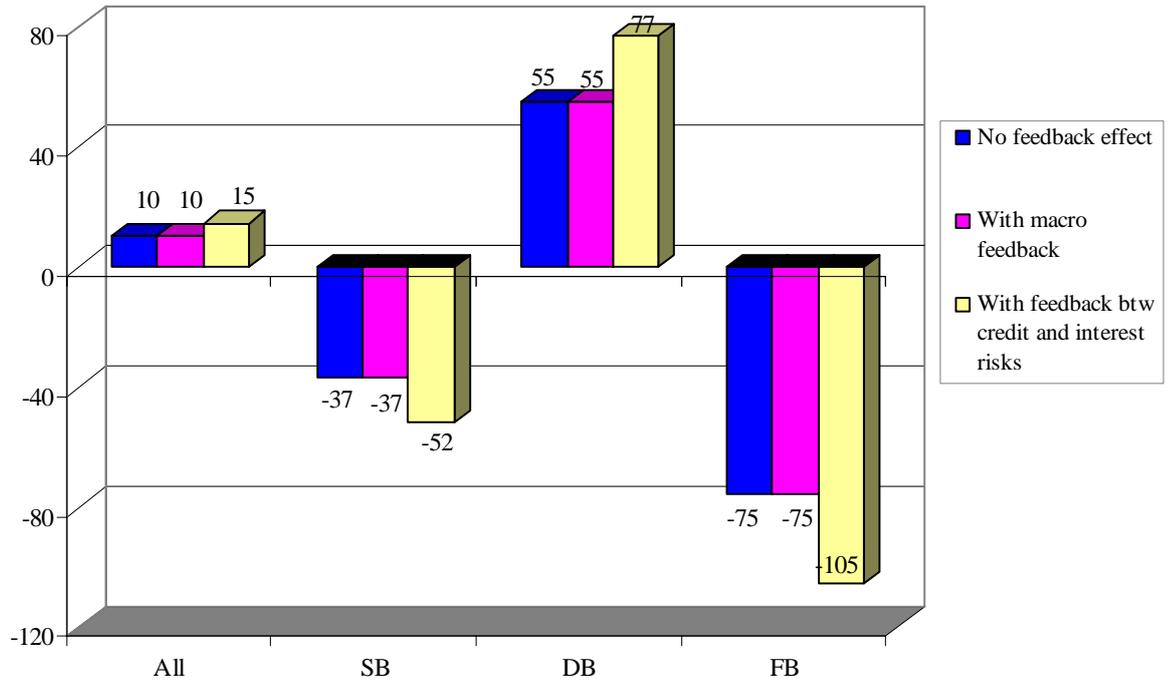


Figure B3
Impact on net profit
 (Median, B\$ billion)

