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RESEARCH ARTICLE

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Proprietary trading losses in banks: do banks invest sufficiently in control?

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Abstract This paper analyzes management and control issues linked to the employment of traders who engage in proprietary trading activity for their employer (a bank). The bank can invest in control and monitoring of these traders, and the paper evaluates the profitability of such investments. We find that the investment in control is distorted due to interfering market microstructure effects. The bank is inclined to underinvest in control of its traders because traders who are not too closely monitored generate extra liquidity in the market. Bank supervision might be needed, therefore, to correct for such effects. We evaluate the effectiveness of the value-at-risk capital adequacy requirement proposed by the Bank for International Settlements, and find that this approach correctly targets the banks that are the most vulnerable, i.e. those that are the most at risk of underinvesting in its control and monitoring systems.

Keywords Liquidity · Operational risk · Value-at-risk

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1 Introduction

This paper analyzes management and control issues linked to the employment of traders who engage in proprietary trading activity for their employer (a bank). Concerns have been raised that the private control investments may not be sufficient to

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curb the operational risk of proprietary trading activities, see the Basel Committee on Banking Supervision (2001a). Whereas banks recognize that lax control can lead to losses there is also a secondary concern that regulation of risk management can be detrimental to corporate profits. It is the trade off between risk and profits that is the main concern here. We take it as given that the bank solves the problem of private control investments by measuring the economic profitability of such investments. We argue, however, that cutting control and monitoring investments increases the supply of liquidity to the market. An increase in market liquidity is in itself good news for the bank, so the decision to cut control investments appears, therefore, more attractive than it should be due to the extra risk involved. Therefore, regulation may be needed to correct for the distortive market microstructure effects.

The analysis is motivated on two accounts. First, there is no question that the issue of control and monitoring of employed traders is a relevant one, illustrated by some recent high-profile cases such as Daiwa in 1994, Barings in 1997, Morgan Grenfell in 1996, and Allied Irish Banks in 2002 to mention a few. In all of these cases the trading losses were huge, and in the Barings case even caused an institutional collapse. There are few other industries in which the actions of one or a few individuals (who are not necessarily high ranking in the institutional hierarchy) can cause losses of a similar magnitude. Second, there is also no question that the stability of the financial system comes under extreme stress when one of its institutions experiences financial distress. Therefore, uncovering factors that contribute to the risk of trading losses is of interest in order to anticipate and manage such distress situations.

Of critical importance to our argument is the fact that the ability of the employed traders to make trading profits is not known to the bank. The bank can, of course, never observe trader ability but it can invest in technology that reports quickly and accurately the outcomes of the trader's actions. Such investments have the advantage that it facilitates a remuneration scheme which discriminates sufficiently between high ability and low ability traders to influence behavior. High ability traders are encouraged to trade actively and low ability traders are encouraged to remain more restrained in their trading activity. In the absence of control and monitoring investments, therefore, the link between remuneration and trading profits becomes more tenuous. It becomes easier for traders of low ability to "mimic" the behavior of their able counterparts without the associated risk of a cut in bonus. This is to some extent supported by empirical observations. Traders incurring trading losses are often able to collect high bonus payments for some time. For instance, in the Allied Irish Banks case losses were carried forward for a period of 5 years, and in the Daiwa case a staggering 11 years, during which the trader in question collected generous bonus payments. This was mainly due to false reporting, which we argue was made possible by insufficient internal control investments.

The control and monitoring investment decision is, we argue, distorted by market microstructure effects. If the bank fails to invest in monitoring and control systems, it implicitly encourages also the traders with low ability to trade actively, and this makes the market more liquid. The increased liquidity feeds back to the ability of the bank to make profits on its trading operations. The distribution of trading profits for the bank is affected by the bank's internal control regime. This effect can cause the expected profits of the bank to increase at the same time as increasing the left hand tail of the loss distribution. Therefore, both the risk of losses as well as the expected profits may increase at the same time. The private and social incentives to manage bank risk may, therefore, diverge with regard to monitoring and control investments.

We recognize that the model is set in the context of a single bank – single trader case, so obviously there is an underlying assumption that the single trader hired by the bank is large enough to influence the liquidity of the market in which he operates. This may appear unrealistic. There have nonetheless been instances in practice in which a single trader or institution has been so dominant as to influence the liquidity of the market in which it operates. This applies in particular to the Barings cases mentioned above. On average, however, individual institutions exert little direct influence on market liquidity. There is, however, no doubt that banks generate a significant portion of trading volume observed in financial markets from proprietary trading alone. Whereas we do not rigorously investigate here how the feedback effect may propagate throughout the banking sector we conjecture that equilibria in reasonable multi-bank model variants of ours involve similar cuts in control investments. We believe the argument carries over into a more general and, ultimately, more realistic model of proprietary trading in banks.

Feedback effects of the type we investigate are not new in the literature, and they have been examined in a different context in Dow and Gorton (1997). They argue, however, that these effects are due to contracting failures caused by limited liability on the part of the employed traders. We argue that contracting failures may also be due partly to control and verification failures. Moreover, this is a failure that is controllable in the sense that the bank can (and in some cases should) make the necessary control investments to make it go away. The contribution here is to investigate the incentives to invest in private control of employed traders.

We extend the analysis to look at the ways in which a regulatory response to the problem of underinvestment in control could be mitigated. The Bank for International Settlements proposes that financial institutions hold a capital reserve to meet the risk of operational losses of this kind, where the reserve depends on the risk the institution is exposed to. There are many ways in which this link can be expressed, and indeed the Basel Committee on Banking Supervision (2001b) proposes several approaches – the basic indicator approach, the standardized approach, and the internal measurement approach. The new Basel Accord also argues that a loss distribution approach be considered for future implementation, where reservation capital is determined by the value-at-risk for the various business lines. These approaches have all been criticized, for instance by Goodhart (2001), on the grounds that they do not necessarily incentivize the institutions to implement internal control to mitigate operational risk factors. This prompts the question of how we should evaluate regulatory approaches to mitigate operational risk factors in banks. There are two criteria we see as necessary in order that an approach can work. The first is that the approach targets the right institutions, i.e. the banks exposed to the greatest risk. The second is that the necessary investments in control should reduce the capital reserve needed to meet the operational risk the bank is exposed to. We show in the second part of this paper that the value-at-risk approach proposed by the new Basel Accord satisfies both criteria.

The academic literature on the operational risk of trading is fairly thin although there are several papers that look at the problem of remunerating traders where the control problem analyzed here is not an issue, see e.g. Danielsson et al. (2002) and Palomino and Prat (2003). Palomino and Prat (2003) look at the delegated portfolio choice problem when the portfolio manager chooses both own effort and portfolio risk. The Palomino and Prat (2003) model assumes that the portfolio manager can report lower portfolio profits than the actual profits but cannot report greater portfolio profits than the actual. Danielsson et al. (2002) look at the principal-agent relationship between the shareholders of a bank and its risk manager when the environment is partially controlled by a bank regulator. They find that the bank's incentives to carry out internal risk management are influenced by the external regulatory environment. Goodhart (2001) evaluates the Basel Committee's proposals and argue they are not likely to create the necessary incentive structure within the banks to control trading activities. Instefjord et al. (1998) analyze the problem of controlling traders in a setting which recognizes this incentive structure, but their model does not recognize the external feedback effect (the market microstructure effect) of delegated securities trading. Dow and Gorton (1997), which is the paper that is the closest to ours, recognize these feedback effects but do not consider the case that internal control investments can influence these effects by making changes to the contracting environment.

The remainder of this paper is organized as follows. Section 2 describes the model. Section 3 derives the equilibria for fixed control and monitoring investment. Section 4 examines the optimal control and monitoring investment policy. Finally, section 5 discusses the regulatory response to the problem of underinvestment in control of employed traders, and section 6 concludes.

2 The model

The model consists of a bank who considers hiring one of two individuals. One has high ability and possesses private information about the asset payoffs (the "insider"), and the other has low ability and is uninformed. It utilizes an imperfect screening technology to identify the good trader, who is hired. Next, the bank decides on whether to invest in control and monitoring technology which produces accurate information about the hired trader's trading profits. Finally, the model assumes a trading game that consists of two distinct periods, the trading period and the settlement period. In the trading period the agent trades the asset, and in the settlement period the true asset value and the agent's trading profit are realized, and the trader puts together a trading report on the basis of which he is remunerated.

2.1 The asset market

We assume the asset market is a forward or futures market with zero risk neutral drift (i.e. there is no time value of money). This allows us to assume the value of the asset evolves from zero at the beginning of the trading period to v, where v is normally distributed random variable with mean zero and variance Σ. Traders trade the asset in a Kyle (1985) market, where a competitive risk neutral market maker quotes a price conditional on the total demand Z, which consists of the demand of the insider, possibly the low ability trader, and a set of noise traders.

The Kyle (1985) model demonstrates the existence of a linear equilibrium where the price p^* takes the form

$$p^* = \lambda Z = E[v|Z] \tag{1}$$

where the second equality ensures that the price is competitive in a risk neutral world. The parameter λ is a key parameter in our model. To understand this parameter intuitively we refer to Kyle's (1985) model where the parameter arises in the context of a game between the market maker and an insider. The more aggressively the insider uses his private information when submitting his market orders, the more sensitive the market maker becomes to changes in the order flow. As the market maker makes the price setting more sensitive to changes in the aggregate order flow, however, the smaller profits does the insider expect to make. Therefore, there is some optimal insider trading strategy for any given λ. The market maker chooses the λ for which the expected asset value conditional on the aggregate order flow equals its current price. If the market maker expects to make money on the order, he will be undercut by competing market makers. If the market maker expects to lose money on the order, it is suboptimal to quote the current price. An equilibrium level of λ will therefore arise where the asset price is informationally efficient as indicated by (1), and the insider submits optimal market orders. This intuition carries over into our framework in a straightforward manner.

2.2 Agents' preferences

There are three types of traders; an insider, an uninformed trader and a number of liquidity traders. We let x, y and u denote the trading quantities of the insider, the uninformed trader and the liquidity traders, respectively. We assume that the insider and the uninformed trader are risk-neutral and have zero initial endowment. We also assume the trader type is private information.

The insider (sometimes referred to as the high ability trader) has a perfect information about the liquidation asset value and seeks to profit from informed speculation. This is the individual the bank seeks to hire. If not employed by the bank, the high ability trader trades on his own account at a transaction cost. The high ability trader's trading profit is $(v - p^*)x - dp^*x$, where p^* is the transaction price, x is the high ability's trading quantity and d is the cost parameter. If not employed by the bank the equilibrium trading strategy of the high ability trader x_n^* is

$$x_n^* = \arg\max_x E[(v - (1 + d)p^*)x|v] \tag{2}$$

The high ability trader works for the bank only if the expected wage level is equal to or greater than the expected trading profit when not employed. This means that the bank can employ the high ability trader if the expected wage level $E[w]$ satisfies the following condition.

$$E[w] \geq E[(v - (1 + d)p^*)x_n^*] \tag{3.1}$$

If employed by the bank the insider can trade without the transaction cost. Then the equilibrium trading strategy becomes

$$x_e^* = \arg\max_x E[(v - p^*)x|v] \tag{4}$$

The uninformed trader (sometimes referred to as the low ability trader) does not know the value of v. When not employed by the bank, the low ability trader does not trade on his own account in order to to avoid trading losses. When employed by the bank the trader may trade if the wage contract incentivizes him to do so. The participation constraint for the low ability trader is

$$E[w] \geq 0 \tag{3.2}$$

A number of liquidity traders are never employed by the bank and trade randomly for exogenous reasons. Their aggregate demand for the asset u is normally distributed with mean zero and variance σ^2. We assume that the random variables v and u are independent.

The difference in transaction costs between trading in employment and outside employment makes it possible for the bank to hire a trader at his reservation wage and still make trading profits. The bank will not trade unless hiring a trader, as the bank has no information advantage over other traders in the market. The bank seeks, therefore, to delegate its proprietary trading activity to a hired trader. Since the trader's type is private information the bank is exposed to the risk of hiring the uninformed trader. We assume that the bank screens job applicants and finds the high ability informed trader with probability γ and the low ability uninformed trader with probability $1-\gamma$. In our model we assume the probability γ is independent of the bonus scheme of the employed trader. Dow and Gorton (1997) assume, in contrast, that certain contracts attract "a flood of incompetents" and, therefore, influence γ. In practice, however, banks tend to start the selection procedure from a restricted set of candidates. For instance, advertisements for traders' jobs usually stipulates a certain minimum qualification level such as relevant practice and education. Since the set of potential traders is limited, we expect the screening outcome is independent of the bonus scheme offered to the hired trader. The assumption that γ remains constant is, therefore, relatively realistic in our setting.

2.3 Bonus schemes

The bank offers one of the two wage contracts, depending on the control and monitoring investment, which is a fixed deadweight cost θ. We assume this investment involves investments in human capital as well as IT technology. The gulf between the knowledge of the managers, or controllers of traders, and the traders themselves can be a serious problem in practice. Instefjord et al. (1998) argue that the internal controllers of traders are often "retired" traders. These individuals should be best placed to carry out the control function. However, they often find that their knowledge becomes obsolete very quickly. This motivates our decision to require that the bank incurs costs to maintain an up-to-date system to monitor its employees' trading activities at all times. Without this investment the system deteriorates and can be played by the employed traders who develop strategies for manipulation of trading reports.

The first bonus scheme determines the payment level conditional on its agent's realized trading profit, and this is feasible of the control and monitoring investment has been made. We call this contract the ex post wage contract. The second type of wage contract determines the payment level conditional on the trader's reported trading profits. Under this contract the bank cannot verify the trader's realized trading profit and therefore pays, in effect, a type of lump sum wage ex ante. This contract is labeled an ex ante wage contract. We assume there is an "epsilon" cost of falsifying trading reports, but we do not incorporate this cost formally into the model as we only utilize it at a single point in the analysis.

We assume that all contracts take the form

$$w = \alpha G \tag{5}$$

where α is a constant and G is the gross trading gain, before netting the wage payment. In a risk neutral framework this assumption is not really restrictive. The problem of finding the optimal functional form of the wage contract is in a general framework non-trivial due to risk sharing concerns. Even with risk averse agents, however, Sung (1995) demonstrates the optimality of linear wage schemes in a continuous time Kyle (1985) setup. Our assumption carries over, therefore, to a risk averse framework with little loss of generality.

The bank's expected profit from delegating trading operations offering an ex post wage contract is

$$\begin{aligned} E[\Pi^p] &= E[G^* - w^*] - \theta \\ &= E[(v - p^*)(\gamma x^* + (1-\gamma)y^*) - w^*] - \theta \end{aligned} \tag{6}$$

Similarly the bank's expected profit from delegating trading operations offering an ex ante wage contract is

$$\begin{aligned} E[\Pi^a] &= E[G^* - w^*] \\ &= E[(v - p^*)(\gamma x^* + (1-\gamma)y^*) - w^*] \end{aligned} \tag{7}$$

The bank's objective is to maximize (6) or (7) given set of conditions. The choice of the wage contract depends on the values of $E[\Pi^p]$ and $E[\Pi^a]$.

3 The equilibrium

This section derives the equilibrium in the asset market under three scenarios. First, when the bank does not hire any trader, second when the bank hires a trader under an ex post wage contract. And finally, when the bank hires a trader under an ex ante wage contract.

3.1 The no hiring equilibrium

We first derive the equilibrium when the bank does not hire a trader. Since we assume that the bank does not have any inherent advantage in trading the asset the bank does not trade on its own. Similarly, the uninformed trader also does not trade since his expected trading profit is negative. Then the agent participating in the market are the informed trader and a number of liquidity traders. The total demand for the asset is

$$Z = x + u$$

which needs to be met by the risk neutral market maker. The following lemma states the trading equilibrium.

Lemma 1 *Suppose that the bank does not hire a trader. Then the uninformed trader is not active. The optimal trading strategy for the informed trader is given as follows.*

$$x = \frac{v}{2(1+d)\lambda} \tag{8.1}$$

and the market maker's optimal linear price setting strategy is as follows

$$p = \lambda(x+u) \tag{8.2}$$

where

$$\lambda = \frac{1}{2(1+d)}\sqrt{\frac{\Sigma}{\sigma^2}(1+2d)} \tag{9}$$

Proof Provided in Appendix A1. □

This lemma is a variant of the Kyle (1985) one-shot equilibrium with a transaction cost d. The high ability trader trades more aggressively as the cost decreases. The expected trading profit of the informed trader is

$$\begin{aligned} E[(v-(1+d)p^*)x] &= E[(v-(1+d)\lambda(x+u)x] \\ &= \frac{1}{2}\sqrt{\frac{\Sigma\sigma^2}{1+2d}} \end{aligned}$$

which is decreasing in d as the trading quantity is decreasing in d.

3.2 The ex post wage equilibrium

The equilibrium consists of a pricing rule p^*, a strategy for the informed trader's trading x^*, a strategy for the uninformed trader's trading y^*, and a bonus scheme w^*. We identify the expected wage level $E[w^*]$ and the expected profit from delegating trades $E[\Pi^p]$.

It is clear that the uninformed trader never trades, regardless of employment status. The low ability trader expects to earn negative trading profits trading on his own, and when employed by the bank the expected wage level is negative due to the negative expected trading profit. Thus it is also optimal to be inactive. The low ability trader's equilibrium trading strategy is therefore $y^* = 0$. The high ability informed trader's equilibrium trading strategy is derived from equations (2) and (4). The high ability trader seeks to maximize $E[(v-p^*)x - dp^*x|v]$ outside employment and $E[(v-p^*)x|v]$ in employment (the difference is due to the transaction cost outside employment). The total demand is, therefore, $Z = x + u$ where x is a function of the employment status of the high ability trader. Substituting for Z, we find that the high ability trader maximizes $E[(v-(1+d)\lambda_p(x+u))x|v]$ outside employment and $E[(v-\lambda_p(x+u))x|v]$ in employment. The first order conditions are

$$\frac{\partial}{\partial x}E\left[(v-(1+d)\lambda_p(x+u))x|v\right] = 0$$

which yields (using subscript "n" for not in employment)

$$x_n^* = \frac{v}{2(1+d)\lambda_p}$$

and (subscript "e" for in employment)

$$x_e^* = \frac{v}{2\lambda_p}$$

The market maker uses a linear pricing rule (1) and the price sensitivity parameter λ_p (subscript "p" for ex post wages) is derived as follows.

$$\lambda_p = \frac{\mathrm{cov}(v, x^*)}{\mathrm{var}(x^*) + \mathrm{var}(u)} = \frac{\frac{\Sigma}{2\lambda_p}\frac{1+\gamma d}{1+d}}{\frac{\Sigma}{4\lambda_p^2}\left(\frac{1+\gamma d}{1+d}\right)^2 + \sigma^2}$$

Solving for λ_p we find

$$\lambda_p = \frac{1}{2(1+d)}\sqrt{\frac{\Sigma}{\sigma^2}(1 + 2d(1+\gamma d) - \gamma^2 d^2)} \tag{10}$$

The value of λ_p depends on the relative variance of the asset and aggregate liquidity demand. If Σ is high relative to σ^2 the equilibrium price is sensitive to the total demand. If Σ is low relative to σ^2 the price is insensitive to the total demand. The equilibrium under ex post wage contracts is outlined in Proposition 1.

Proposition 1 *Suppose that the bank uses an ex post wage contract to remunerate its agent. Then the equilibrium is characterized as follows.*

$$x_e^* = \frac{v}{2\lambda_p} \tag{11.1}$$

$$x_n^* = \frac{v}{2(1+d)\lambda_p} \tag{11.2}$$

$$y^* = 0 \tag{12}$$

$$p^* = \lambda_p(x^* + u) \tag{13}$$

The bank pays zero bonus to the inactive low ability (or uninformed) trader. The bank pays bonus payments with the following expected value to the high ability (or informed) trader.

$$E[w^*] = \frac{1}{2}\sqrt{\frac{\Sigma\sigma^2}{1 + 2d(1+\gamma d) - \gamma^2 d^2}} \tag{14}$$

The bank's expected profit from hiring a trader to engage in proprietary trading is given by

$$E[\Pi^p] = \frac{\gamma d}{2}\sqrt{\frac{\Sigma\sigma^2}{1 + 2d(1+\gamma d) - \gamma^2 d^2}} - \theta \tag{15}$$

The expected trading profit for the bank is positive if

$$\sigma^2 \geq \sigma_p^2 \equiv \frac{4\theta^2}{\Sigma\gamma^2 d^2}(1 + 2d(1 + \gamma d) - \gamma^2 d^2) \tag{16}$$

Proof Provided in Appendix A2. □

In equilibrium, the bonus payments depend on the hired trader's ability to make trading profits. We notice the bank is able to differentiate between the types since it has made an investment in a system to perfectly verify the employed trader's realized trading profit. Also, we can verify that $\frac{1}{\lambda_p} < \frac{1}{\lambda}$ for all feasible sets of parameters. Therefore, the market is less noisy when the bank employs a trader than when it does not. This is due to the cost of capital component d which the trader must meet when not employed. When the high ability trader is able to trade without incurring this extra cost, he trades more aggressively. In response, the market maker increases the price sensitivity to the total demand. Consequently the market becomes less liquid when the bank invests in control and monitoring of its hired traders.

3.3 The ex ante wage equilibrium

This subsection derives the equilibrium under the ex ante wage contract. The hired trader can obtain the same expected bonus payment regardless of trading profits by falsifying trading reports. Since the high ability trader accepts to work for the bank only if the wage satisfies the condition in equation (3.1), the low ability trader in effect free rides on the high ability trader's participation constraint. Thus the bank is exposed to the risk of incurring trading losses as well as to paying excessive wages.

In equilibrium, the employed high ability trader trades so as to maximize the trading profit for the bank (when employed), and the employed low ability trader mimics the trading strategy of the employed high ability trader (also when employed). There is no bonus effect associated with implementing trading strategies that are not profit maximizing, but there is a disutility associated with falsifying trading reports unnecessarily. Therefore, the high ability trader always trades in employment such as to achieve maximum profits for the bank.

Total market demand is $Z = x^* + y^* + u$. If the high ability informed trader is employed by the bank and the low ability uninformed trader is not, the equilibrium trading strategies are

$$x_e^* = \frac{v}{2\lambda_a}$$
$$y_n^* = 0$$

If the high ability informed trader is not employed by the bank and the low ability uninformed trader is, the equilibrium trading strategies are as follows.

$$x_n^* = \frac{v}{2(1+d)\lambda_a}$$
$$y_e^* = \frac{\hat{v}}{2\lambda_a}$$

where v and $\hat{v}$ are independently and identically distributed random variables. The price sensitivity parameter λ_a is given by

$$\lambda_a = \frac{1}{2}\sqrt{\frac{\Sigma}{\sigma^2}}\sqrt{2\left(\frac{1+\gamma d}{1+d}\right) - \left(\frac{1+\gamma d}{1+d}\right)^2 - (1-\gamma)^2} \tag{17}$$

Appendix A3 derives these results. The results show that the high ability trader trades more aggressively under the ex ante wage contract than under the ex post wage contract. As is explained in the next paragraph, this is so since the price quoted by the market maker is less sensitive against the total demand for the asset under the ex ante wage contract than under the ex post wage contract. Therefore, the liquidity under the ex ante wage scheme is higher than that under the ex post wage scheme, since $\frac{1}{\lambda_a} \geq \frac{1}{\lambda_p}$ for any feasible sets of parameters.

The extra noise generated by the excessive trading activity of the employed uninformed trader has several effects. First, the bank expects to lose money on its trading operations in the instances where its screening technology fails and it hires a low ability trader. This trader is, moreover, remunerated as if he is a high ability trader so the bank will make additional losses in the form of excessive bonus payments. There is a second contervailing effect. The extra noise makes the market maker's sensitivity to changes in the aggregate order flow smaller. Therefore, the expected trading profits of informed traders increase. Thus, when the bank's screening technology has produced a success and a high ability trader is hired, the bank expects to make greater trading profits than before. Proposition 2 below outlines the instances where the bank can expect to make positive trading profits under an ex ante wage contract.

Proposition 2 *Suppose that the bank uses an ex ante wage contract to remunerate its trader. Then the equilibrium is characterized as follows.*

$$x_e^* = \frac{v}{2\lambda_a} \tag{18.1}$$

$$x_n^* = \frac{v}{2(1+d)\lambda_a} \tag{18.2}$$

$$y_e^* = \frac{\hat{v}}{2\lambda_a} \tag{19.1}$$

$$y_n^* = 0 \tag{19.2}$$

$$p^* = \lambda_a Z \tag{20}$$

$$w^* = \frac{1}{2(1+d)}\sqrt{\frac{\Sigma\sigma^2}{2\frac{1+\gamma d}{1+d} - \left(\frac{1+\gamma d}{1+d}\right)^2 - (1-\gamma)^2}} \tag{21}$$

$$E[\Pi^a] = \left(\gamma - \frac{1}{2}\frac{2+d}{1+d}\right)\sqrt{\frac{\Sigma\sigma^2}{2\frac{1+\gamma d}{1+d} - \left(\frac{1+\gamma d}{1+d}\right)^2 - (1-\gamma)^2}} \tag{22}$$

The bank makes positive profits on its proprietary trading activity if

$$\gamma \geq \frac{1}{2}\frac{2+d}{1+d} \tag{23}$$

Proof Provided in Appendix A3. □

4 The optimal choice of bonus scheme

We now examine the bank's choice of the wage contracts. The following theorem states the result.

Theorem 1 *In equilibrium, the bank chooses not to engage in proprietary trading if $\sigma^2 < \sigma_p^2$ and $\gamma < \frac{1}{2}\frac{2+d}{1+d}$. Otherwise, the bank hires a trader under an ex post wage contracts if $\sigma^2 \geq \sigma_p^2$ and $\sigma^2 > \overline{\sigma^2}$, and the bank hires a trader under an ex ante wage contracts if $\gamma \geq \frac{1}{2}\frac{2+d}{1+d}$ and $\sigma^2 \leq \overline{\sigma^2}$. The critical value of the liquidity demand $\overline{\sigma^2}$ is given by*

$$\overline{\sigma^2} \equiv \frac{\theta^2}{\Sigma}\frac{1}{\left[\frac{\gamma d}{2}\sqrt{\frac{1}{1+2d(1+\gamma d)-\gamma^2 d^2}} - \left(\gamma - \frac{1}{2}\frac{2+d}{1+d}\right)\sqrt{\frac{1}{2\left(\frac{1+\gamma d}{1+d}\right)-\left(\frac{1+\gamma d}{1+d}\right)^2-(1-\gamma)^2}}\right]^2} \tag{24}$$

Proof Provided in Appendix A4. □

This result seeks firstly to identify the parameter interval where the bank optimally does not engage in trading activities, and secondly to find the optimal control investment in the parameter interval where the bank does. It is not optimal to engage in trading when the hiring technology is sufficiently poor (i.e. γ is sufficiently low), or when the exogenous noise in the asset market is sufficiently low (i.e. σ^2 is sufficiently low). These effects are easy to understand. If the bank's hiring technology decreases, the region where it expects to make no or negative trading profits $(1-\gamma)$ increases. Similarly, if the exogenous noise in the asset market decreases, the bank's expected profits in the region where it makes profits (γ) also decreases. In either case the parameters hit a lower barrier where the aggregate profits are zero.

If the bank does engage in trading activities, the problem is to balance the relative costs and benefits of the ex post and the ex ante wage contracts. There is obviously a direct cost involved in maintaining an ex post wage contract, and as this cost (the parameter θ) increases the bank is more likely to make cuts in its control investments. But there are indirect costs as well. Recall that when the bank cuts control investments, it implements the ex ante wage contract. When this happens, the bank sometimes expects to lose in terms of increased trading losses and increased wage payments by cutting control investments. This happens when its screening technology fails (probability $1-\gamma$) because now the hired trader becomes active but will on average incur trading losses. The bank also sometimes expects to gain in terms of increased trading profits by cutting control investments. This happens when its screening technology delivers a success (probability γ)

and the hired trader is able to trade more actively in a noisier market. Theorem 1 outlines the cases where these effects aggregate into a positive overall profit through a cut in control investments. If the bank's hiring technology becomes more precise, such that γ becomes small (but not so small that trading is unprofitable), the bank becomes more inclined to cut control investments. The intuition is fairly straightforward. Since the bank expects to make losses only if the screening technology fails, these losses carry less weight if the probability of failures decreases. As the exogenous noise σ^2 becomes smaller (but not so small that all trading is unprofitable) the bank is more likely to cut control investments. The intuition here is also clear. When the exogenous noise is large, the extra noise generated endogenously has little impact. The extra profits generated over the success region (probability γ) become therefore small, so the trade off is largely determined by the extra costs incurred in the failure region (probability $1 - \gamma$).

What do cuts in control investments mean in practice? As touched on early in the analysis, we imagine that such cuts can take many forms. The simplest is the type of cuts made in the Barings case: that front-line traders are also given control of back-office control functions. This may save staffing costs but is of course extremely vulnerable to abuse. Another type can take the form of cuts in investments in "intangible" control cultures, where traders feel less inclined to carry out a high degree of monitoring among their peers, their subordinates and their superiors. Again, peer-monitoring can be very effective and failing to maintain an internal control culture makes the bank more vulnerable to trading losses. And finally, we can think of such cuts in the form of "out-sourcing" of trading operations from in-house trading desks to awarding trading operations to third parties (such as hedge funds).

Figure 1 shows the bank's equilibrium decision with respect to delegating proprietary trading to traders under the various control regimes. The parameter values used are $\Sigma = 1$, $d = 0.2$ and $\theta = 0.1$.

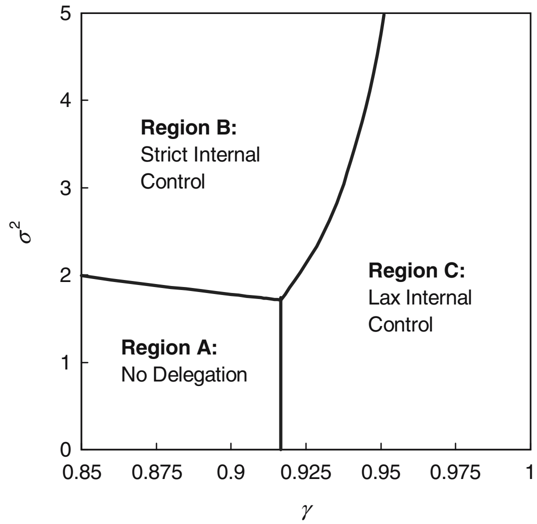

Fig. 1 The optimal trading/control decision for the bank

There are three regions. The curve decreasing in γ plots σ_p^2 in equation (16). The bank makes positive profits when delegating proprietary trading under ex post wages when γ and σ^2 are above this curve. The vertical line at approximately $\gamma = 0.92$ is the restriction given in equation (23) ($\gamma \geq \frac{1}{2}\frac{2+d}{1+d}$). The bank makes positive profits when delegating proprietary trading under ex ante wages to the right of this line. The curve increasing in γ is the critical value of $\overline{\sigma^2}$ given in equation (24), which determines the cutoff point where the delegation of proprietary trading gives the same profits regardless of bonus scheme. In region A, which lies below the curve for σ_p^2 and to the left of the line $\frac{1}{2}\frac{2+d}{1+d}$, the bank does not delegate its proprietary trading activity at all since the net profit is negative. In region B the ex post wage scheme dominates, and in region C the ex ante wage scheme dominates.

5 Regulatory control of operational trading risk

In the previous section we show that the banks sometimes make cuts in the internal control investment as a means of boosting expected trading profits although it increases the risk of losses. This problem is potentially a serious one for regulators if the underinvestment in control by a limited number of banks triggers larger, systemic, crises in the banking sector (a survey on systemic risk can by found in Dow 2000). The Bank for International Settlements (2001a, b, 2003) has, therefore, proposed several approaches to manage operational risk of this nature to mitigate the risk posed by financial distress in financial institutions. We examine in this section how the risk management approach proposed by the BIS affects the bank's decision to invest in control and verification systems of trading profits. We begin with deriving the bank's profit-loss distribution for the two wage schemes separately. The bank's realized profit from the trading operations under the ex post wage contract is written as follows.

$$\Pi^p = \gamma \frac{d}{1+d}\frac{v^2}{4\lambda_p} - \theta \tag{25.1}$$

The equation is derived in Appendix A5. Similarly, the bank's realized profit from the trading operations under the ex ante wage contract is written as follows.

$$\begin{aligned}\Pi^a = {} & \gamma\left(\frac{v^2}{4\lambda_a} - \frac{vu}{2}\right) + (1-\gamma)\left(\frac{v\hat{v}}{4\lambda_a} - \frac{\hat{v}^2}{4\lambda_a} - \frac{\hat{v}u}{2}\right) \\ & - \frac{1}{2(1+d)}\sqrt{\frac{\Sigma\sigma^2}{2\frac{1+\gamma d}{1+d} - \left(\frac{1+\gamma d}{1+d}\right)^2 - (1-\gamma)^2}}\end{aligned} \tag{25.2}$$

Appendix A5 shows the derivation of this equation. The variables v, $\hat{v}$ and u are drawn from mutually independent normal distributions. Figure 2 shows the histograms of Π^p given parameter values $(\gamma, d, \frac{\sigma^2}{\Sigma}, \theta) = (0.75, 0.2, 10, 0.1)$ and $(\gamma, d, \frac{\sigma^2}{\Sigma}, \theta) = (0.95, 0.2, 10, 0.1)$. Similarly Figure 3 shows the histograms of Π^a given parameter values $(\gamma, d, \frac{\sigma^2}{\Sigma}) = (0.75, 0.2, 10)$ and $(\gamma, d, \frac{\sigma^2}{\Sigma}) = (0.95, 0.2, 10)$.

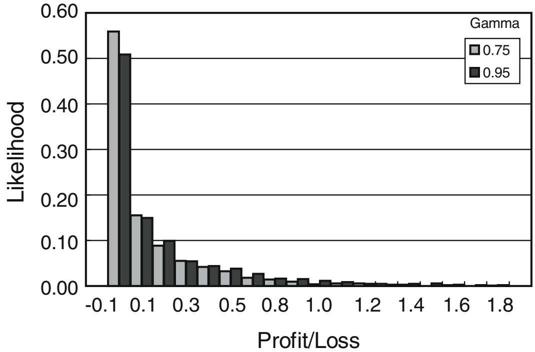

Fig. 2 Histograms (ex post wage)

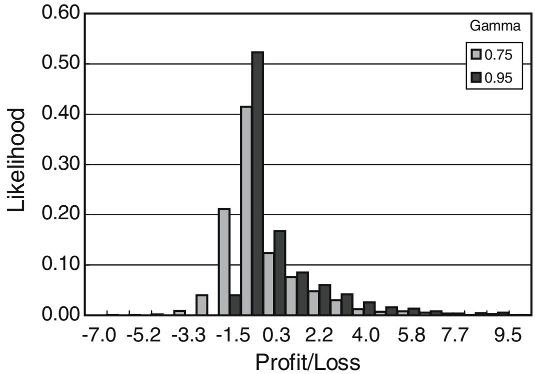

Fig. 3 Histograms (ex ante wage)

The figures show that the profit–loss distributions are significantly different for banks with different levels of hiring/screening technology and different wage contracts. Figure 2 shows the profit–loss distribution under the ex post wage contract. The distribution has a χ^2-shape due to the v^2 term in (25.1). Figure 3 shows the profit–loss distribution under the ex ante wage contract. This distribution has considerably fatter left hand tails. This is due to the mixed χ^2 distributions caused by the v^2 and $-\hat{v}^2$ terms in (25.2).

Given these properties of the profit–loss distributions we examine the effectiveness of the loss distribution approach proposed by the Basel Committee on Banking Supervision (2001b). This approach is described by a two-stage process in which the bank first estimates the profit–loss distribution for business lines and uses the distribution to determine a reservation level of capital to meet a given risk, the so called value-at-risk. Let e and VaR denote the critical probability and the value at risk, respectively. The value at risk is then defined as $\Pr\{\Pi \leq \text{VaR}\} = e$, which means that the loss of the bank's delegated trade exceeds the critical level of VaR with a given probability e.

We consider the situation that the bank is required to meet a value at risk target but that the bank has a fixed amount of risk capital available. In effect, the bank scales its trading operations to meet the capital requirement rather than acquiring new risk capital. This is realistic of course only if the cost of new risk capital is very high, but it illustrates perfectly the incentive effects of the loss distribution approach. We distinguish between the two control regimes (superscript p for "ex post bonus" and a for "ex ante bonus") and define two functions of the success parameter γ, for which $\Phi^p_{\text{VaR}}(\gamma) \equiv \Pr\{\Pi^p \leq \text{VaR}|\gamma\} = e$ and $\Phi^a_{\text{VaR}}(\gamma) \equiv \Pr\{\Pi^a \leq \text{VaR}|\gamma\} = e$. We can invert these equalities to identify the critical parameters γ^p and γ^a, for which the capital adequacy requirement with a fixed supply of risk capital is just met under ex post and ex ante bonus schemes, respectively. Thus,

$$\gamma^p \equiv (\Phi^p_{\text{VaR}})^{-1}(e) \quad \gamma^a \equiv (\Phi^a_{\text{VaR}})^{-1}(e)$$

The following theorem states the conditions that the bank changes its wage structure or withdraws from its trading operations when constrained by its access to risk capital.

Theorem 2 *Suppose the ex ante contract is optimal for an unregulated bank, which holds if σ^2 is not too high and γ is not too low* (*specifically* $\sigma^2 \leq \overline{\sigma^2}$ *and* $\gamma \geq \frac{1}{2}\frac{2+d}{1+d}$, *see Theorem* 1). *Suppose a regulator requires that losses are limited to VaR with probability* $1-e$. *If* $\gamma \geq \gamma^a$ *regulation has no effect. If* $\gamma^p \leq \gamma < \gamma^a$ *and* $\sigma^2 \geq \sigma_p^2$ *the bank switches to an ex post wage contract to comply with regulation. Finally, if* $\gamma < \gamma^p, \gamma^a$ *the bank must cease trading to comply with regulation.*

This result is straightforward from the discussion above. The theorem states that the VaR regulation reduces the problem of trading by low ability traders when the bank's hiring/screening technology is sufficiently low, i.e. when $\gamma < \gamma^a$. This is true even if $\sigma^2 \geq \sigma_p^2$. The regulation has bite, therefore, if the cut-off probability e is chosen in such a way that γ^a satisfies $\sigma^2 \geq \sigma_p^2$. This suggests that the value at risk approach targets specifically the bank exposed to the largest operational risk. The bank benefits, therefore, from adopting a tighter internal control regime in these cases since the cost of non-compliance is relatively high. Looking at Figure 2 and 3 we see why the value at risk method is so effective, as a lax control environment can have a dramatic impact on the left hand tail of the bank's profit distribution.

A relevant question is whether regulation can be achieved through other means. At a trivial level, if a regulator can observe the bank's control investment decision there is of course scope for imposing direct external control if inefficiencies arise. This may, however, not be a realistic proposition as the type of control investments we have in mind are of an intangible nature – typically we look at investments in a vigilant control culture which is notoriously difficult to evaluate by third parties. At a more non-trivial level the issue is whether regulation which aims at imposing restrictions on trader behavior (e.g. trading limits) or trader remuneration (bonus schemes) can work. We believe that regulatory imposed trading limits are likely to be ineffective as these limits can be violated unless the bank invests in strict control – i.e. when regulation is not really needed in the first place. Imposing limits on trader remuneration can be effective, as it limits the incentive of low ability traders to "mimic" the aggressive trading styles of traders with higher ability. The downside with this type of regulation is that it may make it difficult for banks to attract high calibre traders in the first place, thereby introducing an adverse selection component in the hiring process. A trader demonstrating willingness to be employed can signal low ability. The optimal design of the regulatory response to the type of problem analyzed in this paper may, therefore, warrant further investigations.

6 Conclusion

This paper analyzes the operational risk caused by delegated proprietary trading operations in banks. We find that banks may be encouraged to cut control and monitoring investments that yield both higher trading profits in expectation but also higher probability of significant trading losses. External control by a regulator may, therefore, be needed to mitigate the problem of private underinvestment in control and monitoring of proprietary trading operations.

The paper evaluates the effectiveness of the risk capital allocation approach proposed by the BIS. We find that a value-at-risk type loss distribution approach mitigates this underinvestment problem. The banks that are the most at risk of underinvestment also face the highest cost of compliance and have, therefore, also the most to gain from spending more on control internally.

Appendix a: mathematical derivations

A1 Proof of Lemma 1

The informed trader knows that the total demand is always $Z = x + u$. Substituting Z into the high ability trader's profit function in equation (2) we have $E[(v - (1 + d)\lambda(x + u))x|v]$. The first order condition with respect to x is

$$\frac{\partial}{\partial x} E\left[(v - (1 + d)\lambda(x + u))x|v\right] = 0$$

which yields the trader's optimal trading strategy

$$x = \frac{v}{2(1 + d)\lambda} \tag{26}$$

The market maker sets the price sensitivity λ conditional on the total demand $Z = x + u$. The λ coefficient is given by

$$\lambda = \frac{\operatorname{cov}(v, x)}{\operatorname{var}(x) + \operatorname{var}(u)} = \frac{\operatorname{cov}\left(v, \frac{v}{2(1+d)\lambda}\right)}{\operatorname{var}(\frac{v}{2(1+d)\lambda}) + \operatorname{var}(u)} = \frac{\frac{\Sigma}{2(1+d)\lambda}}{\frac{\Sigma}{4(1+d)^2\lambda^2} + \sigma^2}$$

Solving for λ we find

$$\lambda = \frac{1}{2(1 + d)}\sqrt{\frac{\Sigma}{\sigma^2}(1 + 2d)} \tag{27}$$

This proves the lemma. $\square$

A2 Proof of Proposition 1

What is left is to find the expected bonus payments and the bank's expected profit in equilibrium. The high ability trader accepts to work for the bank if the expected value of the wage is not less than the expected trading profit when not employed by the bank. Therefore, the expected wage level equals the high ability trader's expected trading profit when not employed, or

$$E[w^*] = E[(v - (1+d)p^*)x^*]$$

Substituting x^* and p^* into the equation yields

$$E[w^*] = E[(v - (1+d)\lambda_p(x_n^* + u))x_n^*] = \frac{\Sigma}{4(1+d)\lambda_p}$$

Substituting λ_p in equation (29) of Appendix A2

$$E[w^*] = \frac{\Sigma}{4(1+d)\frac{1}{2(1+d)}\sqrt{\frac{\Sigma}{\sigma^2}(1+2d(1+\gamma d)-\gamma^2 d^2)}} = \frac{1}{2}\sqrt{\frac{\Sigma\sigma^2}{1+2d(1+\gamma d)-\gamma^2 d^2}} \tag{28}$$

We then obtain the bank's expected profit from delegating its proprietary trading. The gross trading profit is G (before netting out the bonus payments). If the bank employs a high ability informed trader the expected trading profit equals $E[(v - p^*)x_e^*]$, while if it employs a low ability uninformed trader the expected gross trading profit is zero since the uninformed trader is inactive. The expected gross trading profit is, therefore,

$$E[G^*] = \gamma E[(v - p^*)x_e^*] = \gamma \frac{\Sigma}{4\lambda_p}$$

Substituting λ_p in (10) yields

$$E[G^*] = \gamma \frac{\Sigma}{4\frac{1}{2(1+d)}\sqrt{\frac{\Sigma}{\sigma^2}(1+2d(1+\gamma d)-\gamma^2 d^2)}} = \gamma \frac{1+d}{2}\sqrt{\frac{\Sigma\sigma^2}{1+2d(1+\gamma d)-\gamma^2 d^2}}$$

The bank's net expected profit is obtained by subtracting the wage payment and the investment in the verification and control system θ. We find, therefore,

$$E[\Pi^p] = E[G^* - \gamma\tilde{w}^* - \theta] = \frac{\gamma d}{2}\sqrt{\frac{\Sigma\sigma^2}{(1+2d(1+\gamma d)-\gamma^2 d^2)}} - \theta \tag{29}$$

The expected profit is nonnegative depends on the parameter σ^2. Requiring (29) to be nonnegative and solving for σ^2, we find

$$\frac{\gamma d}{2}\sqrt{\frac{\Sigma\sigma^2}{(1+2d(1+\gamma d)-\gamma^2 d^2)}} - \theta \geq 0$$

$$\sigma^2 \geq \sigma_p^2 \equiv \frac{4\theta^2}{\Sigma\gamma^2 d^2}(1+2d(1+\gamma d)-\gamma^2 d^2) \tag{30}$$

This proves the proposition. □

A3 Proof of Proposition 2

In this case, the wages paid to the traders are equivalent to an ex ante lump sum independent of the hired trader's ability. Since there is a small cost associated with falsifying trading reports, the high ability trader always seeks to maximize the trading profits of the bank if in employment. Suppose that the high ability trader is employed and the low ability trader is not employed by the bank. In this case the employed high ability knows that the total demand is $Z = x_e + u$ since the low ability trader is not active when not employed, i.e. $y_n^* = 0$. The high ability trader's expected trading profit is, therefore,

$$E[(v - p^*)x_e|v] = E[(v - \lambda_a(x_e + u)x_e|v]$$

Evaluating the first order condition for maximization wrt x, we find the high ability's optimal trading strategy is given by $x_e^* = \frac{v}{2\lambda_a}$.

Next we consider the case that the high ability informed trader is not employed and low ability uninformed trader is employed by the bank. Without knowledge about the value of v, the bank does not know the high ability trader's equilibrium trading strategy and knows only its distribution as $N\left(0, \frac{\Sigma}{4\lambda_a^2}\right)$. The low ability uninformed trader then minimizes the probability of being detected by the bank if he randomizes his trading over this distribution. That is, the low ability trader's equilibrium trading strategy is a random draw from the distribution of the high ability trader's equilibrium strategy.

$$y_e^* = \frac{\hat{v}}{2\lambda_a}$$

where v and $\hat{v}$ are independently and identically distributed.

Given y_e^*, the non-employed high ability trader seeks to maximize the trading profit. The non-employed high ability trader's expected trading profit is

$$E[(v - (1 + d)p^*)x_n] = E[(v - (1 + d)\lambda_a(x_n + y_e^* + u))x_n]$$

Evaluating the first order condition for maximization wrt x, we find the non-employed high ability trader's optimal trading strategy is given by $x_n^* = \frac{v}{2(1+d)\lambda_a}$.

We need to derive the price sensitivity λ_a, the wage w, and the bank's profit Π^a. Noticing that v, $\hat{v}$ and u, are independent, the linear projection theorem yields λ_a as

$$\lambda_a = \frac{\mathrm{cov}(v, Z)}{\mathrm{var}(Z)} = \frac{\frac{\Sigma}{2\lambda_a}\frac{1+\gamma d}{1+d}}{\frac{\Sigma}{4\lambda_a^2}\left(\frac{1+\gamma d}{1+d}\right)^2 + (1-\gamma)^2\frac{\Sigma}{4\lambda_a^2} + \sigma^2}$$

Solving for λ_a we find

$$\lambda_a = \frac{1}{2}\sqrt{\frac{\Sigma}{\sigma^2}}\sqrt{2\left(\frac{1+\gamma d}{1+d}\right) - \left(\frac{1+\gamma d}{1+d}\right)^2 - (1-\gamma)^2} \tag{31}$$

The high ability trader's profit when not employed by the bank is

$$\begin{aligned}E[(v-(1+d)p^*)x_n] &= E\left[(v-(1+d)\lambda_a(x_n^*+y_e^*+u)x_n^*\right] \\ &= \frac{\sqrt{\Sigma\sigma^2}}{2(1+d)\sqrt{2\left(\frac{1+\gamma d}{1+d}\right)-\left(\frac{1+\gamma d}{1+d}\right)^2-(1-\gamma)^2}}\end{aligned}$$

which implies that the expected bonus payments is

$$w^* = \frac{1}{2(1+d)}\sqrt{\frac{\Sigma\sigma^2}{2\left(\frac{1+\gamma d}{1+d}\right)-\left(\frac{1+\gamma d}{1+d}\right)^2-(1-\gamma)^2}} \tag{32}$$

Next we derive the bank's expected gross profit, $E[G^*]$.

$$\begin{aligned}E[G^*] &= \gamma E[(v-p^*)x^*] + (1-\gamma)E[(v-p^*)y_e^*] \\ &= \frac{2\gamma-1}{2}\sqrt{\frac{\Sigma\sigma^2}{2\left(\frac{1+\gamma d}{1+d}\right)-\left(\frac{1+\gamma d}{1+d}\right)^2-(1-\gamma)^2}}\end{aligned}$$

Since there is no investment in a control and verification system the bank's net expected profit is

$$\begin{aligned}E[\Pi^a] &= E[G^*-w^*] \\ &= \left(\gamma-\frac{1}{2}\frac{2+d}{1+d}\right)\sqrt{\frac{\Sigma\sigma^2}{2\left(\frac{1+\gamma d}{1+d}\right)-\left(\frac{1+\gamma d}{1+d}\right)^2-(1-\gamma)^2}}\end{aligned} \tag{33}$$

The expected profit from delegating its proprietary trading is nonnegative if

$$\gamma \geq \frac{1}{2}\frac{2+d}{1+d} \tag{34}$$

This proves the proposition. □

A4 Proof of Theorem 1

We compare the expected profit of the bank under the two bonus schemes in the region where they both yield non-negative profits for the bank, i.e. when (16) and (23) hold. We set $E[\Pi^p] \leq E[\Pi^a]$ and solve for σ^2, and find

$$\sigma^2 \leq \overline{\sigma^2} \equiv \frac{\theta^2}{\Sigma}\frac{1}{\left[\frac{\gamma d}{2}\sqrt{\frac{1}{1+2d(1+\gamma d)-\gamma^2 d^2}}-\left(\gamma-\frac{1}{2}\frac{2+d}{1+d}\right)\sqrt{\frac{1}{2\left(\frac{1+\gamma d}{1+d}\right)-\left(\frac{1+\gamma d}{1+d}\right)^2-(1-\gamma)^2}}\right]^2} \tag{35}$$

The bank delegates it proprietary trading operations by offering an ex ante bonus scheme if (23) and $\sigma^2 \leq \overline{\sigma^2}$ hold. The bank delegates its proprietary trading operations by offering an ex post bonus scheme if (16) and $\sigma^2 > \overline{\sigma^2}$ hold. The bank does not engage in proprietary trading if neither (16) nor (23) hold. This proves the theorem. □

A5 Derivations of (25.1) and (25.2)

The realized gross trading profits G^* under an ex post wage contract can be written as

$$G^* = \gamma(v - p^*)x^* = \gamma\left(\frac{v^2}{4\lambda_p} - \frac{vu}{2}\right)$$

The bank's net realized profit from delegating the trading operations to its hired trader is, therefore,

$$\Pi^p = G^* - w^* - \theta = \gamma\frac{d}{1+d}\frac{v^2}{4\lambda_p} - \theta \tag{36}$$

Similarly the realized gross trading profit G^* under an ex ante wage contract is a weighted average of the profit when the bank's agent is the insider and that when it is the uninformed trader. This can be written as

$$\begin{aligned} G^* &= \gamma(v - p^*)x_e^* + (1-\gamma)(v - p^*)y_e^* \\ &= \gamma\left(\frac{v^2}{4\lambda_a} - \frac{vu}{2}\right) + (1-\gamma)\left(\frac{v\hat{v}}{4\lambda_a} - \frac{\hat{v}^2}{4\lambda_a} - \frac{\hat{v}u}{2}\right) \end{aligned}$$

The bank's net realized profit is, therefore,

$$\begin{aligned} \Pi^a &= G^* - w^* \\ &= \gamma\left(\frac{v^2}{4\lambda_a} - \frac{vu}{2}\right) + (1-\gamma)\left(\frac{v\hat{v}}{4\lambda_a} - \frac{\hat{v}^2}{4\lambda_a} - \frac{\hat{v}u}{2}\right) \\ &\quad - \frac{1}{2(1+d)}\sqrt{\frac{\Sigma\sigma^2}{2\left(\frac{1+\gamma d}{1+d}\right) - \left(\frac{1+\gamma d}{1+d}\right)^2 - (1-\gamma)^2}} \end{aligned} \tag{37}$$

□

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