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# Optimal Preventive Bank Supervision

## Combining Random Audits and Continuous Intervention

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# Optimal preventive bank supervision: combining random audits and continuous intervention

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**Abstract**

Early regulator interventions into problem banks is one of the key suggestions of Basel II. However, no guidance is given on their design. To fill this gap, we outline an incentive-based preventive supervision strategy that eliminates bad asset management in banks. Two supervision techniques are combined: continuous regulator intervention and random audits. Random audit technologies differ as to quality and cost. Our design ensures good management without excessive supervision costs, through a gradual adjustment of supervision effort to the bank's financial health. We also consider preventive supervision in a setting where audits can be delegated to an independent audit agency, showing how to induce agency compliance with regulatory instructions in the least costly way.

**Keywords:** banking supervision, random audit, incentives, moral hazard, delegation

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# 1 Introduction

*"The regulators substituted a more detailed look at the banks with just looking at outputs from models. They got lazy."*
Select Committee on Economic Affairs Report (2009)

The recent financial crisis has proved once again the need for effective preventive banking supervision. If regulators had been able to detect potential threats at early stages, many of the negative consequences of bank distress could have been avoided. To some extent, this inability to anticipate problems can be explained by an excessive regulatory reliance on the outcomes of stress-testing models, and the concomitant lack of deeper analysis of bank management practices. The lightening progress of information technology has significantly contributed to this tendency, so that business intelligence has largely replaced human intelligence in the supervisory process. However, another plausible explanation for the lack of effective supervision in the pre-crisis period is the unclear official instructions on the supervision process. In fact, even though Basel II suggests implementing early supervisory measures for the troubled banks, it does not specify their design: the regulator is left to draw information from the financial markets, taking supervisory measures based on the warning signals they send.

Indeed, in practice, the regulator is faced with numerous challenges related to supervision design. One of the basic problems is how to determine the optimal frequency and duration of supervision events. On the one hand, higher frequency makes banks more inclined to conform with regulatory rules, and longer duration of regulatory interventions improves the quality of regulatory information, thereby, potentially resulting in better design of any corrective measures. On the other hand, more supervision has a cost and regulatory resources are limited. Another problem is the choice of supervision technology. The quality of supervision technology strongly depends on its cost. For instance, on-site inspection of a bank would be much more costly than external balance sheet examination, but would provide a better picture of the bank's financial health, through better access to reliable information. To sum up, the fundamental issue of supervision design can be stated as follows: how can effective supervision be ensured without excessive supervision spending?

Surprisingly, very few studies address the design of preventive supervision. Most authors[1] consider supervision as an adjunct to capital regulation, ignoring its preventive effect. Nevertheless, appropriate theoretical background

[1] See, for instance, Merton (1978), Dangl and Lehar (2002), Bhattacharya et al. (2002).

can be found in Décamps et al. (2004) and Rochet (2004). Both papers suggest realizing continuous regulatory interventions in order to combat moral hazard in bank asset management.[2] However, pure continuous intervention may be too costly, and the same incentive effect on banks can be achieved at lower cost through the use of random audits as a part of supervision process.

In this study we propose an alternative preventive supervision strategy that relies on a combination of two supervision techniques: random audits and continuous intervention. By gradually adjusting the level of supervision in line with the bank's financial health, this strategy allows the regulator to induce the bank to adopt good management practice without excessive supervision costs.

First, we consider the benchmark case, where the regulator has a single perfect audit technology at his disposal. We show that combining random audits with continuous intervention allows the regulator to prevent moral hazard in the bank and immediately yields significant cost savings compared to the pure intervention strategy. Moreover, supervision costs can be kept to a minimum through optimal choice of random audit frequency. Ideally, audit frequency should be continuously adjusted to the financial health of the bank, increasing with any depreciation in the value of bank assets. However, in practice it may be quite difficult to ensure credible commitment to this supervision strategy. Given that audit frequency is contingent on bank asset value, the bank would find it difficult to estimate real audit frequency. Inability to make this internal assessment will lead to a lack of confidence in the regulatory strategy, destroying its incentive effect. To avoid this, we propose a practical solution involving several random audit regions with stepwise adjustable audit frequency.

Second, we consider the case where the regulator owns a continuum of audit technologies that differ in quality and cost. We show that, generally, there is no need to use the perfect (and most expensive) audit technology all the time, as the same incentive effect on the bank can be achieved with lower audit quality, and therefore at lower cost. Thus, given the option of adjusting audit frequency, it appears optimal to maintain only the audit technology that delivers the lowest "cost/quality" ratio.

Another current challenge to supervisory practice addressed in this study is the delegation of supervisory functions. Basel II actively encourages participation by external audit firms in the supervisory process, but there is no clear guidance on contracts. We allow for a setting where audit technology is delegated to an independent audit agency which can provide better quality audits at the same cost, but whose effort level is unobservable by the regu-

[2] Intervention can be interpreted as temporary regulator administration of the bank.

lator. In this context the regulator is faced with a problem of double moral hazard: given that lower audit quality implies lower cost, the agency may be tempted to shirk its duty. As a result, the bank will lose the incentive to maintain good management, which will destroy the preventive effect of supervision.

To eliminate double moral hazard, the regulator needs to offer the agency a contract containing incentives to promote good management in the bank. The basic idea behind this contract design is to link agency welfare to bank financial health. We show that the agency's choice of audit effort depends on the contract's continuation value, which represents the current expected value of all future profits that the agency can extract from the contract. Thus, the regulator can induce the bank to good management at minimum cost, by providing the agency the minimum incentive contract continuation value. In the end, it is precisely this minimum incentive contract continuation value that conditions the overall design of incentive supervision.

The rest of the paper is organized as follows. In Section 2 we review the literature. Section 3 presents the concept of preventive supervision. Section 4 examines the optimal supervision design in the nondelegation framework. In Section 5 we discuss the optimal supervision strategy in a setting where random audit technology can be delegated to an independent audit agency. Section 6 concludes. All proofs are provided in Appendix B.

# 2 Literature review

The literature can be divided into two strands offering different views on the role of supervision. According to the traditional view, supervision is used to reinforce capital regulation. In fact, many studies (see, for instance, Rochet (1992), Hellmann et al. (2000), Fries et al. (1997)) argue that even risk-based capital requirements, if implemented alone, are insufficient to curb the excessive risk-taking propensity of banks. Consequently, the regulator needs to use additional tools as a reinforcement. The most explicit argument for assigning this role to supervision is provided in Merton (1977). Examining regulator liabilities under an option-pricing approach, he shows that it is possible to mitigate excessive risk-taking incentives for banks by reducing the time between regulatory inspections. Given the preceding result, Merton (1978) introduces supervision in the form of the random audit. This design has been adopted by many studies in the same field. For example, Dangl and Lehar (2002) examine the combined effect of capital requirements and random audits on risk-taking in banks. They show that the risk-weight capital regulation of Basel II requires less audit effort than the building-block approach of Basel I. Bhattacharya et al. (2002) find that higher random audit frequency makes it possible to reduce minimum capital requirements. Milne and Whalley (2001) show a positive relationship between audit frequency and capital buffer. Finally, Elizalde (2007) applies a risk-sensitive concept of capital requirements to supervisory process and shows that riskier banks should be audited more frequently.

None of the above papers, however, raises the question of optimal audit frequency, although this directly affects supervision costs. They also consider audit technology as perfect. Within a non-random audit framework, however, Pages and Santos (2001) define the optimal time between regulatory interventions, comparing a gain from immediate bank closure and the expected gain from a postponed closure decision. Whereas Andersen and Harr (2008) make the quality of audit technology increasing on costly audit effort and show that, under growing competition in the banking sector, the regulator will optimally choose lower audit quality.

A second strand of the literature on supervision asserts its incentive effect on management technology in banks. Based on Dewatripont and Tirole (1994), this approach sets aside the excessive risk-taking issue and proceeds from the problem of moral hazard in bank asset management. In this view, moral hazard implies a socially inefficient choice of management technology. It arises when bank management technology is unobservable from outside. In this context, supervision serves to detect management quality and to impose early corrective measures if necessary. Consistent with this idea, Décamps et al. (2004) interpret moral hazard as the irreversible decision by the bank to cease costly monitoring of assets. To prevent moral hazard, two regulatory solutions are possible. The first is to introduce minimum capital requirements that will prevent the bad management choice. However, this would impose stricter regulatory closure rules on banks. The second solution is to complement the existing closure rules by continuous regulator intervention. Intervention should cover the whole region where moral hazard arises, in order to prevent bad bank management. Taking this concept a step further, Rochet (2004) considers reversible management technology and takes into account supervision costs, showing the existence of an optimal combination of closure thresholds and intervention thresholds that maximizes social welfare.

Our study continues in the vein of the second strand of the literature, seeking the optimal preventive supervision design. As using continuous intervention throughout is too costly, we partially replace it with random audits while still eliminating moral hazard. However, in contrast to the random-audit literature cited above, we consider random audits as the regulatory incentive tool which will completely eliminate misbehavior in the bank. Our study also explores the optimal choice of both audit frequency and audit quality.

On the question of delegating audit technology to an independent audit agency, we refer to the literature on optimal contracts in the continuous-time principal-agent framework. Generally, this literature considers a setting where the principal delegates some stochastic production technology to the agent. In this case, the optimal contract should specify the agent's effort and remuneration. Holmstrom and Milgrom (1987) show that, for exponential utility function and single terminal payoff, the optimal contract will linearly depend on aggregated outcome. Cvitanic et al. (2009) consider a general form of utility function. They find that the optimal contract is non-linear in this case, but also depends on the final outcome value. Williams (2009) considers continuous agent rewards and shows that the optimal contract can be specified by two adjoint state processes: promised utility and marginal cost of agent consumption. Working in a similar setting, Sannikov (2008) builds the optimal contract on a single state variable – the agent continuation value which represents the agent expected utility. He finds that the agent can be retired in two cases: either when his continuation value falls to zero or when it becomes sufficiently large, making it too costly for the principal to compensate the agent for his effort.

Our study, too, seeks the optimal contract between the regulator (the principal) and the audit agency (the agent). But the nature of the problem we consider is quite different: we deal with a tripartite framework where the moral hazard of the agency automatically implies the moral hazard of the bank. Consequently, the choice of the optimal audit effort will be constrained by the need to create incentives for the bank. Thus, in our model the optimal audit effort determines the incentive-compatible contract continuation value, the latter being used to derive the optimal compensation scheme. It should be noted that the problem of double moral hazard was studied in Strausz (1996) in a one-period discrete-time game. However, he allows for two incentive contracts (one for the independent supervisor and one for the agent) and takes the quality of monitoring technology as being independent of monitoring effort.

# 3 The model

We consider the problem of moral hazard in bank asset management and construct our model based on Rochet (2004). First, we briefly recall the modeling background. Then, we present our concept of mixed supervision.

## 3.1 Moral hazard in bank asset management

Consider a risk-neutral environment with two agents, a bank and a regulator, discounting their future at rate $r$. The bank is financed by deposits, $D$, fully insured by the Deposit Insurance Fund (DIF). The deposits are continuously repaid with coupon $rD$.

The bank's asset value evolves following a continuous-time process:

$$dx_t = \mu x_t dt + \sigma x_t dW_t, \tag{1}$$

where $\mu$ is the expected asset return rate per unit of time, $\sigma$ is the asset return volatility and $\{W_t\}_{t\geq 0}$ is a standard Wiener process.[3]

Bank assets continuously generate cash-flow $bx_t$ until the moment of bank liquidation. Since a large part of bank assets consists of loans, the bank's asset performance entirely depends on the borrowers' productive technology, unobservable by the bank. To ensure the high expected asset return $\mu = \mu_G$, the bank managers need to make a costly monitoring effort,[4] spending a constant amount $\gamma r$ per unit of time. In the absence of monitoring effort, asset quality deteriorates and the expected asset return decreases to $\mu_B < \mu_G$. Hereafter, we employ the term *good management technology* to indicate the presence of asset monitoring effort and the term *bad management technology* otherwise. Management technology is reversible: managers can switch from good management to bad and vice versa. To focus on the moral hazard problem, we assume that monitoring effort does not affect asset volatility, i.e., $\sigma$ remains constant under both management technologies. However, the model can easily be extended to a case where asset volatilities are different.

Liquidation of a bank occurs when its asset value hits the regulator closure threshold $x_R$. We assume that, because of the incomplete transferability of private bank information to a new owner, the resale market value of assets at the moment of liquidation, $\lambda x/(r-\mu)$, is lower than their economic value, $x/(r-\mu)$. Thus, given $\mu_B < \mu_G$, bad management will impose higher liabilities on DIF in the case of bank liquidation. We also consider $\lambda > b/(r-\mu_B)$ to ensure that liquidation of the bank is better than perpetual bank continuation under bad management. In such a context, bad management technology appears socially inefficient, and therefore its use should be prevented by the regulator.

Rochet (2004) has shown that, under limited liability, managers will optimally choose bad management when the bank's asset value becomes rel-

[3]We assume $\mu - 1/2\sigma^2 > 0$.

[4]There is no agency problem, i.e., bank managers act in the best interests of shareholders.

atively small. Thus, the regulator can set an optimal closure rule $x_R^*$ that would prevent the bad management choice:[5]

$$x_R^* = \left(\frac{-\beta_2(D+\gamma)+\gamma r/\Delta\mu}{1-\beta_2}\right)\left(\frac{r-\mu_G}{b}\right) \tag{2}$$

where $\beta_2$ is a negative root of $1/2\sigma^2\beta^2 + (\mu_G - 1/2\sigma^2)\beta = r$.

However, liquidation threshold $x_R^*$ can be too high, potentially leading to a large number of bank closures. This makes $x_R^*$ costly to implement in practice. In this study we consider an arbitrary[6] regulatory closure rule $x_R < x_R^*$ that creates the conditions for moral hazard. We intend to show how the regulator can prevent moral hazard by means of optimally-designed supervision.

## 3.2 Mixed supervision strategy as a regulatory response

In order to ensure preventive supervision without excessive supervision costs, we propose adjusting the strictness of supervision to the bank's financial health. This idea underlies a *mixed supervision strategy* that combines two supervision techniques: random audits and continuous regulator intervention. The random audit implies a spot check on the management process in a bank. Audit events follow a Poisson process with frequency $\psi(x)$ and carry the cost $\alpha cr$ per audit. Regulatory intervention can be interpreted as a temporary regulatory administration, during which the regulator tries to extract the bank from the distress. In contrast to the random audit, regulatory intervention may last for some time, carrying instantaneous cost $cr$ per unit of time. We assume that instantaneous audit costs do not exceed instantaneous costs of continuous intervention, i.e., $\alpha \leq 1$.[7]

The concept of a mixed supervision strategy is presented by Fig. 1. For a given closure rule $x_R$, the regulator should set two supervision thresholds (their design is discussed below), audit threshold $x_A$ and intervention threshold $x_I$, in such a way that the interval $[x_R, x_A]$ would cover the whole moral hazard region. It can easily be shown that it is always optimal to implement random audit technology when the bank's asset value is not too low, and to undertake continuous intervention in the neighborhood of the liquidation threshold. Thus, $x_R < x_I < x_A$.

[5] We generalize the result of Rochet (2004) for $b \neq r - \mu_G$.

[6] It is also possible to endogenize the closure rule, maximizing social welfare (see Rochet(2004)).

[7] The case $\alpha > 1$ is feasible as well, but would lead to low audit intensity.

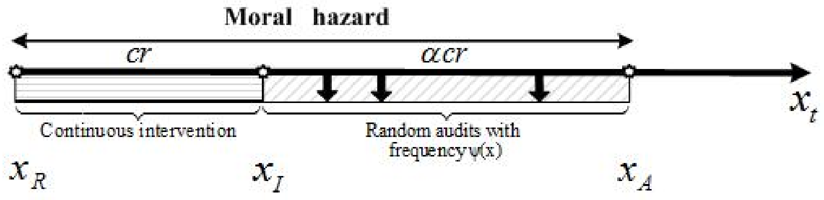


Figure 1: Concept of mixed supervision

We assume that the regulator knows the bank's asset value.[8] As long as $x \geq x_A$, he remains inactive. In the region $[x_I, x_A)$ he implements random audits in order to check the management technology employed in the bank. If bad management is revealed during the audit, the bank will be liquidated, i.e., shareholders will be deprived of equity. In the region $[x_R, x_I)$ the regulator undertakes intervention in order to maintain good management in the bank. Intervention continues until either the bank's asset value is restored $(x \geq x_I)$ or decreases to liquidation point $x_R$.

Now consider the design of supervision thresholds. Recall that the main aim of the regulator is to maintain good asset management in the bank. The bank managers maximize the bank's equity value. At each moment of time they optimally choose the effort level $e_t$, where:

$$e_t = \begin{cases} 1 & \text{good management technology} \\ 0 & \text{bad management technology} \end{cases}$$

We introduce operator $A(e)$ such that:

$$A(e)f(x) = 1/2\sigma^2 x^2 f''(x) + (\mu_B + \Delta\mu e)xf'(x) - rf(x), \tag{3}$$

where $\Delta\mu = \mu_G - \mu_B$ and $f(x)$ is any contingent claim.

Then, the optimization program of the bank managers can be written as:

$$\max_{e_t \in \{0,1\}} \{A(e_t)E(x_t) + bx_t - rD - \gamma r e_t\} = 0, \tag{4}$$

where $E(x_t)$ denotes the bank's equity value.

Consequently, managers will choose good management technology when

$$\Delta\mu x E'_G(x) \geq \gamma r, \tag{5}$$

[8]This assumption stems from the efficient-market hypothesis. It would be interesting to consider in further research a setting with imperfect market information, where regulator and market agents can improve information content. For instance, Lehar et al. (2007) show that supervision effort may reduce incentives for market agents to monitor bank fundamentals, making market signals less informative.

where $E_G(x)$ (defined in Appendix A.1) denotes the bank's equity value under good management.

Expression (5) shows that, in the absence of supervision, a switch to bad management would be optimal when the expected instantaneous loss of equity value becomes less than instantaneous monitoring costs. Moreover, as the lower bank asset value results in lower "costs" for the bad technology choice ($\Delta\mu x E'_G(x)$ is increasing on $x$), we conclude that moral hazard increases with depreciation of a bank's asset value.

Let $x_A$ denote the bank asset value that provides equality in (5). In the absence of supervision, bank managers will maintain good management technology for $x \geq x_A$ and choose bad management for $x < x_A$. Consequently, any audit threshold lower than $x_A$ will raise moral hazard, while any audit threshold higher than $x_A$ will incur useless random audit costs. Thus, for the rest of the paper, the audit threshold is set at $x_A$.

Anticipating moral hazard for $x < x_A$, the regulator will start performing random audits below the audit threshold. To focus on the incentive effect of random audits, we consider here that audit technology is perfect, i.e., it always reveals the true management technology employed by the bank.[9] Therefore, by choosing bad management on $x < x_A$, bank managers can lose equity value with probability $\psi(x)dt$ in a small period of time $dt$. This increases the expected instantaneous costs of a bad management choice and modifies managers' optimization program as follows:

$$\max_{e_t \in \{0,1\}} \{A(e_t)E(x_t) + bx_t - rD - \gamma r e_t + \psi(x_t)E(x_t)(e_t - 1)\} = 0, \tag{6}$$

where $x < x_A$. Solving this problem yields the following incentive-compatibility constraint:

$$\Delta\mu x E'_G(x) + \psi(x)E_G(x) \geq \gamma r \tag{7}$$

Let $x_I(\psi)$ denote the bank asset value that ensures equality in (7). Note that random audits allow the regulator to induce the bank to use good management practice when $x \in [x_I(\psi), x_A)$. When $x \in [x_R, x_I(\psi))$ the random audit effort becomes insufficient to create incentives and regulatory intervention becomes necessary to ensure continuing good management. As the left part of (7) is increasing on $\psi(x)$, the feasible set of inspection thresholds will be given by $x_I \in [x_I(\psi), x_A]$. Thus, under a mixed supervision strategy with audit threshold $x_A$ and inspection threshold $x_I \in [x_I(\psi), x_A]$, the bank will never use bad management technology, i.e., supervision will have a preventive effect.

[9] In Section 4.2 we examine supervision design under imperfect audit quality.

To conclude this section, we consider the total costs of mixed supervision. Their current value represents the expected discounted value of future regulatory spending (i.e., the total continuous intervention and random audit costs), conditional on the current bank asset value $x_0 \geq x_A$:

$$C(x_0) = E_0 \left[ \int_0^{\tau_R} e^{-rt} (crI_{x_t \in [x_R, x_I)} + \psi(x_t) \alpha crI_{x_t \in [x_I, x_A)}) dt \right], \tag{8}$$

where $\tau_R$ denotes the first time when the bank's asset value reaches regulatory closure threshold $x_R$ and $I$ is an indicator function.

Note that $C(x_0)$ can be also presented as the expected cost of the pure continuous intervention minus a cost gain from random audits:

$$C(x_0) = E_0 \left[ \int_0^{\tau_R} e^{-rt} crI_{x_t \in [x_R, x_A)} dt \right] - E_0 \left[ \int_0^{\tau_R} e^{-rt} cr(1 - \alpha\psi(x_t)) I_{x_t \in [x_I, x_A)} dt \right] \tag{9}$$

This representation makes it possible to capture a crucial feature of mixed supervision:

**Lemma 1** *For any audit frequency $\psi \leq 1/\alpha$, mixed supervision reduces supervision costs when compared to pure continuous intervention.*

Indeed, condition $\psi(x) \leq 1/\alpha$ implies that the expected instantaneous audit costs $\psi(x)\alpha cr$ do not exceed the instantaneous costs of continuous intervention, $cr$. This will ensure an immediate cost gain from mixed supervision as compared to the pure continuous intervention strategy.

# 4 Optimal preventive supervision

This section discusses the optimal design of a mixed supervision strategy. First, we examine a benchmark case which implies a single perfect audit technology and we consider three different random audit set-ups: with constant, continuously adjustable and stepwise adjustable audit frequency. The audit set-up with continuously adjustable audit frequency allows for the most efficient design of preventive supervision, since it ensures the lowest supervision costs. However, in practice, banks have difficulty estimating continuously adjusted audit frequency. For this reason, we propose a practice-relevant solution that implies several random audit regions, with audit frequency constant in each audit region but potentially differing from region to region. Second, we construct the optimal supervision design for a setting with a continuum of audit technologies.

## 4.1 Optimal mixed supervision with perfect audit technology: benchmark case

Let us first examine the benchmark case, where the regulator has a single perfect audit technology. Under perfect audit technology, bad management is always detectable during random audits. In such a context, the regulatory problem is to choose a function $\psi(x), x \in [x_I, x_A)$ and the inspection threshold $x_I$ that will induce good management in the bank with minimum expected supervision costs:

$$\underset{\psi(x),x_I}{\text{Min}} \quad C(x_0)$$

$$\text{s.t. } \Delta\mu x E'_G(x) + \psi(x)E_G(x) \geq \gamma r, \ \forall x \in [x_I, x_A)$$

where $C(x_0)$ is given by (8).

### 4.1.1 Constant audit frequency

We start with a simple set-up where the regulator keeps audit frequency constant over the whole random audit region. Given any arbitrary audit frequency $\psi$, the optimal inspection threshold results from the binding incentive constraint of the bank, i.e., $x_I = x_I(\psi)$. Indeed, any $x_I > x_I(\psi)$ would generate excessive continuous intervention costs, while bank incentives can be created by random audits alone. Taking the first derivative of both parts of (7) on $\psi$, we obtain the following:

**Lemma 2** *Inspection threshold $x_I(\psi)$ is decreasing on $\psi$.*

Thus, the solution of the above maximization program will be completely determined by the optimal audit frequency. However, since the inspection threshold depends on $\psi$, the impact of audit frequency on supervision costs is ambiguous. A higher random audit frequency would allow the regulator to set a lower inspection threshold and, thereby, to reduce the costs of continuous intervention. But this would extend the random audit region, raising the total random audit costs.

In the absence of an analytical solution for $\psi$, we resort to numerical simulations in order to illustrate the cost gain from the optimally designed mixed supervision. Simulations are based on the parameter values from Table 1.[10] The optimal audit frequency obtained varies from 0.16 to 0.24 depending on

[10] This parameter set is calibrated to maintain a reasonable balance between spending and gains, as well as to satisfy a condition of Rochet (2004), under which moral hazard is possible: $\frac{\gamma}{D} < \frac{(1-\beta_2)}{\lambda\beta_2}\frac{b}{r-\mu_G} - 1$.

Table 1: Parameter set

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| $r$ | 0.04 | $\sigma$ | 0.25 |
| $\mu_G$ | 0.025 | $\lambda$ | 0.7 |
| $\mu_B$ | 0.015 | $b$ | 0.02 |
| $\gamma$ | 0.06 | $\alpha$ | 1 |
| $c$ | 0.04 | $D$ | 1 |

Instantaneous asset return gap is taken as 1%. To benefit from this technology gain, the bank should be charged by monitoring costs $\gamma r$ that constitute 24% of the gain. Supervision costs are less than asset monitoring costs and amount to 16% of technology gain. Random audit cost coefficient $\alpha$ is set at 1 in order to equalize instantaneous audit costs and instantaneous intervention costs.

$x_R$, which approximately corresponds to 5-6 audits per year. The cost gain generated by optimal mixed supervision as compared to the pure continuous intervention strategy (where $x_I = x_A$) varies from 53% to 74%, which explicitly confirms a significant cost advantage of mixed supervision.

#### 4.1.2 Continuously adjustable audit frequency

The second audit set-up allows for continuous adjustment of audit frequency to bank asset value. In this case, minimum supervision costs will be ensured by an audit frequency which makes the incentive-compatibility constraint (7) binding, hereafter denoted as $\psi^B(x)$. First, note that $\psi^B(x)$ will deliver the minimum audit costs, while maintaining bank incentives for good management practice. Second, as the bank becomes less and less inclined to maintain good management when its asset value goes down, $\psi^B(x)$ will increase with depreciation of $x$. According to Lemma 1, the maximum feasible value it can attain is $1/\alpha$. But equality $\psi^B(x_I) = 1/\alpha$ also yields the lowest incentive-compatible inspection threshold, thereby ensuring the lowest total continuous intervention costs. Then we can state:[11]

**Proposition 1** *Under a single perfect audit technology, the optimal design of mixed supervision implies:*

- *a continuously adjusted audit frequency on $x \in [x_I^B, x_A)$:*

$$\psi^B(x) = (r\gamma - \Delta\mu x E_G'(x))/E_G(x) \tag{10}$$

- *an inspection threshold $x_I^B$: $\psi^B(x_I^B) = 1/\alpha$.*

[11] The proof is omitted.

However, continuous adjustment of audit frequency may lead to some problems in practice. First, continuous adjustment requires up to date and reliable information about the bank's asset value. In reality, although the regulator has access to various information sources, the probability of inaccurate data is rather high. Moreover, even when data is reliable, we cannot rule out information delay. Yet when audit frequency is determined on the basis of inaccurate data, it may be insufficient to maintain bank incentives. Second, it is easier to commit to a simple incentive mechanism that banks can clearly understand. A more sophisticated regulatory strategy risks being misunderstood and therefore not producing the required incentive effect. In this context, a compromise solution might involve several random audit regions, with audit frequency varying from region to region.

#### 4.1.3 Stepwise adjustable audit frequency

Consider $n$ random audit regions $[x_I, x_2)$,$[x_2, x_3)$,..., $[x_n, x_A)$, where audit frequencies $\{\psi_i\}_{i=1..n}$ are constant over each region. In order to homogenize notation, denote $x_1 = x_I$ and $x_{n+1} = x_A$. Regulatory thresholds $x_1, .., x_n$ can be either endogenous (i.e., resulting from a regulatory cost-minimization program) or exogenous. Thus, the optimal audit frequencies result from the binding incentive-compatibility constraint on each audit region: $\psi_i = \psi^B(x_i)$, $i = 1..n$. Indeed, any $\psi_i < \psi^B(x_i)$ would be insufficient to create incentives for good management on region $[x_i, x_{i+1})$, while any $\psi_i > \psi^B(x_i)$ would incur useless audit costs. Obviously, $\psi_i$ is stepwise decreasing with the bank's asset value.

Regulatory thresholds, defining audit regions, can be set in accordance with the rating classifications of international rating agencies. An example of a possible supervision strategy with stepwise-adjustable audit frequency is provided by Fig. 2. Given exogenous regulatory thresholds $x_I, x_2$ and $x_3$, continuously adjusted audit frequency (a thick dotted line) is used to specify the optimal audit frequencies for each random audit region. Thus, healthy banks (with $x \geq x_A$) can be free of any supervision. The lower the rating assessment, the more frequent audits should be. Finally, for banks whose asset value is close to the liquidation threshold, continuous regulator intervention becomes inevitable.

### 4.2 Optimal mixed supervision under a continuum of audit technologies

In the previous section we discussed preventive supervision under the perfect audit technology. However, in practice audit quality varies depending

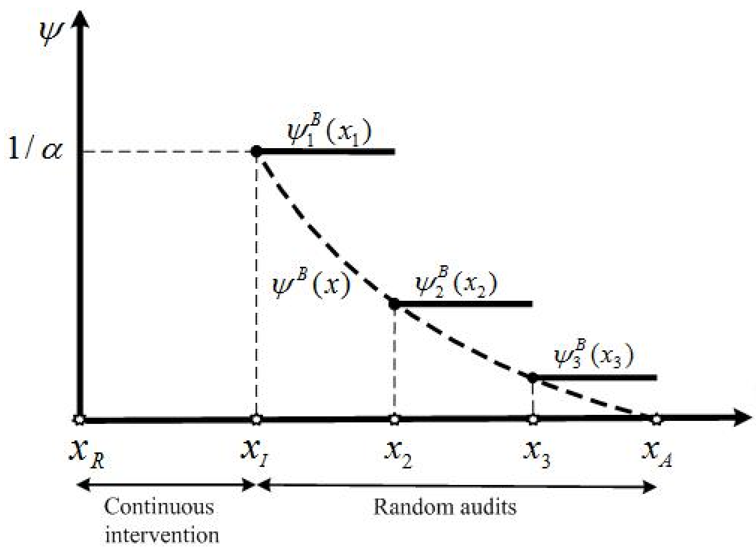


Figure 2: Mixed supervision with stepwise adjustable audit frequency

on many factors, such as number of supervisory staff involved, professional skills and remuneration of supervisors, scale of examination, audit technique employed. For example, the regulator can examine the bank's accounting, relying on the compulsory bank reports and involving a minimum of staff. Alternatively, a high-skilled audit team can realize on-site investigation of the internal management process in the different departments. Obviously, the latter audit technology would provide a better estimation of the bank's financial health, but would require larger supervisory resources and greater spending.

In this section we investigate the optimal supervision strategy in a setting where the regulator has many different audit technologies at his disposal and can continuously adjust both audit frequency and audit quality over the audit region. Denote $T = [\underline{\alpha}, \overline{\alpha}]$ a continuum of audit technologies which differ as to quality and cost $\alpha cr$. Audit quality depends on audit effort, $\alpha$, and is measured by probability $p(\alpha) \in [0, 1]$ of uncovering bad management in the bank, given that the bank operates under bad management technology.[12] Function $p(\alpha)$ is concave and strictly increasing on $\alpha$ with $p(\underline{\alpha}) = 0$ and $p(\overline{\alpha}) = 1$.

When audit quality is imperfect, the probability of detecting bad management in a small interval $dt$, given that bank managers have switched to bad management technology, is reduced to $\psi p(\alpha)dt$. As audit quality is freely

[12]We assume that, if the bank operates under good management, the probability of uncovering bad management technology as a result of an audit is zero.

observable by bank managers, this will reduce their incentives to choose good management as compared to the benchmark case. Thus, audit quality choice becomes an additional supervisory tool that will affect the optimal supervision design, and the new regulatory problem can be stated as follows:

$$\underset{\psi(x),\alpha(x),x_I}{\text{Min}} \quad C(x_0)$$

$$\text{s.t. } \Delta\mu x E'_G(x) + \psi(x)p(\alpha(x))E_G(x) \geq \gamma r, \ \forall x \in [x_I, x_A)$$

We are looking for $\psi(x)$, $\alpha(x)$ and $x_I$ that minimize the total expected supervision costs, complying with the incentive-compatibility constraint of the bank.[13] Note that both instantaneous random audit costs and inspection threshold are determined by $\alpha(x)\psi(x)$. Using the incentive-compatibility constraint of the bank, we are able to present the optimal audit frequency as a function of audit quality, $\psi(x) = \psi^B(x)/p(\alpha(x))$. This representation shows that instantaneous random audit costs are increasing with "cost/quality" ratio $\alpha/p(\alpha)$. But the inspection threshold, provided by $\alpha\psi(x) = 1$, is also increasing with this ratio.

**Proposition 2** *Under a continuum of audit technologies and continuously adjustable audit frequency, the optimal design of mixed supervision implies:*

- *a single audit quality* $\alpha^\star = \text{argmin}\, \alpha/p(\alpha), \alpha \in T$*;*
- *a continuously adjusted audit frequency* $\psi^\star(x) = \psi^B(x)/p(\alpha^\star)$*;*
- *an inspection threshold* $x_I^\star = [\psi^\star]^{-1}(1/\alpha^\star)$*.*

Note that in the particular case where the regulator has at his disposal only two audit technologies to choose from randomly at each audit event, it will be optimal to use a single audit technology throughout, since the "cost/quality" ratio will be monotonic on $\alpha$ in this case.

We conclude this section with a brief illustration of the optimal supervision strategy in a discrete case with several random audit regions and stepwise-adjustable audit frequency.

**Example 1** *Optimal supervision under stepwise-adjustable audit frequency.*

[13] Note, that under constant audit frequency, the optimal audit quality results from the binding incentive constraint of the bank and the problem solution is completely determined by the optimal choice of random audit frequency.

$\square$ As in practice it is easier to commit to a discrete supervision strategy, we consider a random audit environment which allows for $i = 1..n$ exogenously fixed audit regions. Audit frequencies $\psi_i$ and audit technologies $\alpha_i$ are supposed to be constant for each audit region. Proceeding as in the continuous case, it can easily be shown that the optimal audit quality is still given by $\alpha^\star = \operatorname{argmin} \alpha/p(\alpha), \alpha \in T$ across all audit regions, while audit frequency should be adjusted as follows:

$$\psi_i(x_i) = \psi^B(x_i)/p(\alpha^\star), \ i = 1..n \tag{11}$$

where $x_1 = x_I$, $x_{n+1} = x_A$ and $\psi^B(x)$ is given in (10).

Indeed, for any exogenous regulatory thresholds $x_i, i = 1..n$, such a supervision strategy would maintain the incentive constraint of the bank for each audit region, incurring minimum supervision costs. It directly follows from this result that, in the particular case with a single audit region and constant audit quality, the optimal audit quality will be given by $\alpha^\star$ and the optimal intervention threshold will result from $\alpha^\star \psi^\star(x_I) = 1$. $\blacksquare$

# 5 Optimal preventive supervision with delegated random audits

So far we have assumed that the supervision process was entirely undertaken by the regulator. Hereafter, we refer to that setting as the *nondelegation* framework. In the current section we consider the case where the regulator is able to hire an independent audits agency to perform random audits at the bank, but may still perform some audits himself.[14]

The agency is more efficient in audit performance than the regulator: under the same level of audit effort $\alpha \in [\underline{\alpha}, \overline{\alpha})$, the agency has a higher probability $q(\alpha)$ of uncovering bad management in the bank[15] than the regulator, i.e., $q(\alpha) > p(\alpha)$ and $q(\overline{\alpha}) = 1$. Given that the audit effort of the agency is unobservable by the regulator, audit delegation leads to a problem of double moral hazard: the audit agency may be tempted to shirk, enjoying instantaneous cost savings.[16] As a result, the preventive effect of supervision will be destroyed: observing no audit effort, the bank will adopt a bad management technology. Therefore, in order to prevent moral hazard in the bank, it is essential to prevent moral hazard in the agency. This can be realized through an incentive contract that induces the agency to promote good management in the bank. In other words, in a delegation framework, the regulator should launch a "chain" of incentives: an incentive contract will induce the agency to exert appropriate audit effort, which will induce the bank to maintain good management technology.

The aim of the regulator in the current setting is still to ensure good management in the bank at the minimum supervision cost. However, now an independent audit agency can replace the regulator, performing random audits on the *delegation region*, hereafter termed $[\underline{x}, \overline{x}) \in [x_R, x_A)$, while outside this region the regulator will follow the optimal supervision strategy stated in Proposition 2. For any given delegation region $[\underline{x}, \overline{x}) \in [x_R, x_A)$, the contract with the independent audit agency should specify:

- (i) audit parameters $\alpha(x)$ and $\psi(x)$;
- (ii) the asset-based remuneration $R(x) \geq \alpha(x)cr$ that the agency will receive at each audit event;[17]

[14] In contrast to random audits, continuous intervention can be performed only by the regulator.

[15] If the bank really operates under bad management.

[16] We exclude the possibility of collusion between the agency and the bank.

[17] We assume that the agency has limited liability and will accept a contract only on condition that each payment provides non-negative profit.

- (iii) a contract termination rule $x_T \leq \underline{x}$, such that the contract with the agency will expire when the bank's asset value reaches $x_T$ for the first time;[18]
- (iv) a lump-sum terminal payoff $R_T \geq 0$ to the agency at the contract termination date.

The remainder of this section is organized as follows. First, we examine the agency's choice of audit effort and outline a new regulatory problem. Then, we determine the minimum incentive-compatible contract with the agency and discuss the optimal supervision strategy in the nondelegation framework.

## 5.1 Moral hazard in the agency and the new regulatory problem

First, we consider the agency's choice of audit effort, given any arbitrary contract. The agency maximizes contract continuation value $K(x) \geq 0$, which is contingent on current bank asset value $x$ and represents the total expected value of future contract pay-offs, net of audit costs:

$$K(x) = E\left[\int_0^{\tau_T} e^{-rt}\psi(x_t)(R(x_t) - \alpha(x_t)cr)I_{x_t \in [\underline{x},\overline{x})}dt + e^{-r\tau_T}R_T\right], \tag{12}$$

where $\tau_T$ is the first time bank asset value reaches termination threshold $x_T$.

Let us fix a delegation region $[\underline{x}, \overline{x}) \in [x_R, x_A)$. For any arbitrary audit frequency $\psi(x)$, we define the audit quality $\alpha_\psi(x) \in T$ that makes the incentive constraint of bank binding:

$$\alpha_\psi(x) = q^{-1}(\psi^B(x)/\psi(x)), \ x \in [\underline{x}, \overline{x}) \tag{13}$$

where $\psi^B(x)$ is given by (10).

The agency has two options: either to induce good management in the bank, or to let the bank operate under bad management. In the interests of maintaining good management in the bank, the agency will optimally use audit quality $\alpha_\psi(x)$, as this induces the bank to maintain good management technology, incurring minimum audit cost. Otherwise, the agency will not exert audit effort at all, since any $\alpha \in [\underline{\alpha}, \alpha_\psi(x))$ generates useless audit cost, without creating any incentive effect on the bank. The choice between

[18]Strictly speaking, the contract with the agency should specify retirement time $\tau_T$. However, as we are dealing with a stationary problem, $\tau_T$ represents the first time the bank's asset value reaches a termination threshold $x_T$.

these two options is driven by expected instantaneous cost savings on the one hand and expected loss of contract continuation value on the other. Indeed, by exerting no effort during the audit, the agency saves the amount $\alpha_\psi(x)cr$. However, if it observes no audit effort, the bank will switch to the bad management technology that implies lower expected returns on assets and, consequently, reduces the contract continuation value of the agency. We can thus state the agency maximization problem as follows:

$$\underset{u_t\in\{0,1\}}{\mathrm{Max}} \{A(u_t)K(x_t) + \psi(x_t)(R(x_t) - u_t\alpha_\psi(x_t)cr)\} = 0 \tag{14}$$

where $x_t \in [\underline{x}, \overline{x})$, $A(u_t)$ is given by (3), $K(x_T) = R_T$ and $u_t = 1$ when the agency chooses audit technology $\alpha_\psi(x)$.

Thus, the agency will use quality $\alpha_\psi(x)$, while the expected instantaneous loss of contract continuation value, caused by the bad management in the bank, will exceed the expected instantaneous cost savings:

$$\Delta\mu x K'(x) \geq \psi(x)\alpha_\psi(x)cr, \;\; x \in [\underline{x}, \overline{x}) \tag{15}$$

Taking into account this result, let us turn to the regulatory problem in the delegation framework. On the one hand, delegation allows the regulator to benefit from the greater audit efficiency of the agency, saving on random audit costs:

$$\Delta CA_\psi(x_0) = E_0\left[\int_0^{\tau_R} e^{-rt}(s_t - \alpha_\psi(x_t)\psi(x_t))crI_{x_t\in[\underline{x},\overline{x}]}dt\right], \tag{16}$$

where

$$s_t = \begin{cases} 1 & x_t \in [x_R, x_I^\star] \\ \alpha^\star\psi^\star(x_t) & x_t \in [x_I^\star, x_A] \end{cases}$$

and parameters $x_I^\star$, $\alpha^\star(x_t)$, $\psi^\star(x_t)$ are given by Proposition 2.

On the other hand, the regulator will have to bear the additional cost of compensating the agency. Note that outside the delegation region, the regulator will follow the supervision strategy that is optimal for the nondelegation framework. Then, for any $x_0 \geq x_A$, the regulatory problem is to maximize the gain from delegation, maintaining good management at the bank through the incentive contract with the agency:[19]

$$\underset{\alpha_\psi(x),\psi(x),R(x),x_T,R_T,[\underline{x},\overline{x})}{\mathrm{Max}} \{\Delta CA_\psi(x_0) - K_\psi(x_0)\} \geq 0$$

[19]Note that the regulator will never resort to delegation if $\Delta CA_\psi(x_0) < K_\psi(x_0)$, as in this case he can ensure preventive supervision by himself at lower cost.

$$\text{s.t.} \begin{cases} \Delta\mu x K'(x) \geq \psi(x)\alpha_\psi(x)cr, \ \forall x \in [\underline{x}, \overline{x}) & (ICA) \\ R(x) \geq \alpha_\psi(x)cr, \ \forall x \in [\underline{x}, \overline{x}) & (PCA_1) \\ R_T \geq 0 & (PCA_2) \end{cases}$$

where $\alpha_\psi(x)$ is given by (13), $[\underline{x}, \overline{x}) \in [x_R, x_A)$, $\Delta CA_\psi(x_0)$ is given by (16) and $K_\psi(x)$ is given by (12) for $\alpha(x) = \alpha_\psi(x)$.

To design the optimal supervision strategy for the above regulatory problem, we proceed as follows. First, for any arbitrary $[\underline{x}, \overline{x}) \in [x_R, x_A)$, $\psi(x)$ and corresponding $\alpha_\psi(x)$, we specify an incentive compensation scheme that ensures the minimum incentive-compatible contract continuation value. Then, we define the optimal audit parameters. Finally, we discuss the pattern of the optimal supervision strategy in the delegation framework.

## 5.2 Optimal contract with the agency

Let us fix any arbitrary delegation region $[\underline{x}, \overline{x}) \in [x_R, x_A)$. For any audit frequency $\psi(x)$, we take audit quality $\alpha_\psi(x)$, given by (13). Thus, the regulatory problem is to find the optimal compensation scheme $\{R(x), R_T\}$ and termination rule $x_T$ ensuring the minimum $K_\psi(x_0) \geq 0$, and simultaneously satisfying constraints $ICA$, $PCA_1$, $PCA_2$. The regulator therefore needs to find the minimum incentive-compatible $K_\psi(x_0) \geq 0$, which makes $ICA$ binding and satisfies $PCA_1$ at the lower bound of the delegation region:

$$K_\psi^*(x) = K_\psi(\underline{x}) + \frac{cr}{\Delta\mu}\left(\int_{\underline{x}}^{x} \frac{\psi(y)\alpha_\psi(y)}{y} dy\right), \ x \in [\underline{x}, \overline{x}) \tag{17}$$

Naturally, the minimum feasible $K_\psi^*(x)$ would be ensured by the minimum constant $K_\psi(\underline{x}) \geq 0$, which is chosen in such a way as to respect participation constraint $PCA_1$. Replacing the minimum incentive $K_\psi^*(x)$ in (14) with $u_t = 1$, we can easily get incentive remuneration $R_\psi(\underline{x})$ and check the participation constraint. Then, two cases are possible. If $PCA_1$ is satisfied for any arbitrary $K_\psi(\underline{x})$, it would be optimal to impose $K_\psi(\underline{x}) = 0$, which automatically gives the solution for termination rule and terminal payoff. Otherwise, the minimum feasible $K_\psi(\underline{x}) > 0$ results from $R_\psi(\underline{x}) = \alpha_\psi(\underline{x})cr$, and we need to determine the minimum incentive contract on $x \in [x_R, \underline{x})$ in order to find the optimal contract termination rule and terminal pay-off.

**Proposition 3** *For any $[\underline{x}, \overline{x}) \in [x_R, x_A)$, the optimal incentive contract with an independent audit agency implies:*

- *(i) audit parameters $\alpha^{\star\star} = \underset{\alpha \in T}{\operatorname{argmin}} \ \alpha/q(\alpha)$ and $\psi^{\star\star}(x) = \psi^B(x)/q(\alpha^{\star\star})$;*

- *(ii) per-audit remuneration $R_{\psi^{\star\star}}(x)$:*

$$R_{\psi^{\star\star}}(x) = \alpha^{\star\star}cr + \frac{rK^{*}_{\psi^{\star\star}}(x)}{\psi^{\star\star}(x)} - \frac{\alpha^{\star\star}cr}{\Delta\mu}\left(\mu_G - \frac{1}{2}\sigma^2 + \frac{1}{2}\sigma^2 x \frac{\partial\psi^{\star\star}(x)}{\partial x}\right)$$

- *(iii) termination rule $x^{\star\star}_T = \max\{x_R, x^*\}$, where $x^* \in [x_R, \underline{x}]$ is such that $K^{**}_{\psi^{\star\star}}(x^*) = 0$, and terminal pay-off $R^{\star\star}_T = K^{**}_{\psi^{\star\star}}(x^{\star\star}_T) \geq 0$, where:*

$$K^{**}_{\psi^{\star\star}}(x) = \frac{\psi^{\star\star}(\underline{x})\alpha^{\star\star}}{\beta_1 - \beta_2}\frac{cr}{\Delta\mu}\left[\left(\frac{x}{\underline{x}}\right)^{\beta_1} - \left(\frac{x}{\underline{x}}\right)^{\beta_2}\right] + \frac{K_{\psi}(\underline{x})}{\beta_1 - \beta_2}\left[\beta_1\left(\frac{x}{\underline{x}}\right)^{\beta_2} - \beta_2\left(\frac{x}{\underline{x}}\right)^{\beta_1}\right], \tag{18}$$

*for $x \in [x_R, \underline{x})$ and $K_{\psi}(\underline{x}) : R_{\psi^{\star\star}}(x) = \alpha^{\star\star}cr$.*

Thus, the optimal audit parameters for the agency are determined in the same manner as for the regulator, allowing for a higher technology frontier $q(\alpha)$. The minimum incentive remuneration $R_{\psi^{\star\star}}(x)$ implies two components: audit cost compensation, $\alpha^{\star\star}cr$, and moral hazard rent, which makes agency welfare contingent on bank financial health and thus creates sufficient incentives for good management in the bank.[20]

If the contract in not worthless at the moment of bank liquidation, i.e., $K^{**}_{\psi^{\star\star}}(x_R) > 0$, the regulator has to give the agency a positive terminal payoff $R^{\star\star}_T = K^{**}_{\psi^{\star\star}}(x_R)$ in order to compensate for the loss of potential profits from the contract if the bank had kept going. Otherwise, the contract termination occurs at $x^* \in [x_R, \underline{x}]$ such that $K^{**}_{\psi^{\star\star}}(x^*) = 0$, and the agency doesn't receive any terminal payment. In the particular case, when $K^{*}_{\psi^{\star\star}}(\underline{x}) = 0$, the contract termination rule consides with a lower bound of the delegation region, i.e., $x^{\star\star}_T = \underline{x}$. We show in Appendix B that this is always the case when $\mu \leq \sigma^2$:

**Lemma 3** *For $\mu \leq \sigma^2$, $x^{\star\star}_T = \underline{x}$ and $R^{\star\star}_T = 0$.*

Once we have the optimal incentive contract for any $[\underline{x}, \overline{x})$, the optimal design of supervision strategy will be determined by the $\underline{x}$ that ensures the maximal gain from delegation.[21] In fact, for any $\underline{x} \in [x_R, x_A)$, the optimal $\overline{x}$ will be given by the critical bank asset value, for which instantaneous costs of delegated random audit become equal to instantaneous costs of non-delegated supervision.

[20]The convexity of $\psi^B(x)$ does not allow us to identify the exact pattern of moral hazard rent. However, we find that moral hazard rent increases with bank asset value under sufficient condition $\sigma^2 \leq (2\mu + r)/3$.

[21]The optimal $\underline{x}$ can be found through numerical simulations. Note that $\underline{x} \geq x^{FB}_I$, where $x^{FB}_I : \alpha^{\star\star}\psi^{\star\star}(x) = 1$ denotes the optimal lower bound of the delegation region (and, simultaneously, the optimal inspection threshold) in the First Best case, where the audit efforts of the agency are freely observable by the regulator.

**Lemma 4** *The regulator will never resort to delegation in the left neighborhood of the audit threshold, i.e.,* $\overline{x} < x_A$.

The point is that, when bank asset value is in the left neighborhood of $x_A$, optimal audit frequency tends to zero. As audit events become too rare, remuneration for each audit event needs to be generous enough to provide the agency with sufficient incentive for the appropriate audit effort. Consequently, in the left neighborhood of $x_A$, it will be less costly for the regulator to ensure preventive supervision himself, rather than to compensate the agency for the effort. Then, there are two feasible alternatives:

- $\overline{x}$ is given by $\psi^{\star\star}(x)R_{\psi^{\star\star}}(x) = \alpha^{\star}\psi^{\star}(x)cr$: this is always the case if $\underline{x} \geq x_I^{\star}$, or if $\underline{x} < x_I^{\star}$ but $\psi^{\star\star}(x)R_{\psi^{\star\star}}(x) < cr$ for $\forall x < x_I^{\star}$;
- $\overline{x}$ is given by $\psi^{\star\star}(x)R_{\psi^{\star\star}}(x) = cr$: this is the case if $\underline{x} < x_I^{\star}$ and there is at least one $x < x_I^{\star}$ such that $\psi^{\star\star}(x)R_{\psi^{\star\star}}(x) > cr$.

We conclude this section by providing an illustration of the optimal incentive contract in a discrete setting with a single audit technology $\alpha^{\star\star}$ and stepwise-adjustable audit frequency.

**Example 2** *Optimal incentive contract in a discrete case.*

□ Consider the audit set-up with stepwise adjustable audit frequency, where delegation region $[\underline{x}, \overline{x})$ consists of $n$ exogenous intervals and the agency owns a single audit technology $\alpha^{\star\star}$. To homogenize notation, we denote $x_1 = \underline{x}$ and $x_{n+1} = \overline{x}$. Then, the minimum incentive compatible contract continuation value on $[\underline{x}, \overline{x})$ can be written as follows:

$$K^*_{\psi^{\star\star}}(x) = \frac{cr}{\Delta\mu}\frac{\alpha^{\star\star}}{q(\alpha^{\star\star})}\left(\sum_{k=1}^{i-1}\psi^B(x_k)\ln(x_{k+1}/x_k) + \psi^B(x_i)\ln(x/x_i) + \psi^B(x_1)\rho\right), \tag{19}$$

where $\rho = (\mu_G - 1/2\sigma^2)/r$ and $x \in [x_i, x_{i+1}), i = 1..(n-1)$.

Replacing $K^*_{\psi^{\star\star}}(x)$ in ODE (14) with $u_t = 1$, we obtain minimal incentive-compatible remuneration:

$$R_{\psi^{\star\star}}(x) = \alpha^{\star\star}cr\frac{(1/2\sigma^2 - \mu_B)}{\Delta\mu} + \frac{rK^*_{\psi^{\star\star}}(x)}{\psi^{\star\star}(x_i)}, \tag{20}$$

where $x \in [x_i, x_{i+1}), i = 1..n$ and $K^*_{\psi^{\star\star}}(x)$ is given by (19).

Thus, the minimum incentive remuneration in a discrete set-up consists of the fixed reward and the variable bonus, increasing with bank asset value. Note that in this particular case we have $K^*_{\psi^{\star\star}}(\underline{x}) > 0$ and, consequently, $x_T^{\star\star} < \underline{x}$.■

# 6 Conclusion

This paper outlines a preventive supervision strategy to combat moral hazard in bank asset management. Using an incentive-based approach, our design combines continuous intervention with random audits to reduce supervision costs. We show in this context that, under a single audit technology, minimum supervision costs can be ensured through the continuous adjustment of audit frequency to a bank's financial health. Moreover, the cost-saving effect of mixed supervision becomes even greater when the regulator can use a continuum of audit technologies, differing in quality and cost. We obtain proof that, given a large choice of audit technologies, it will be optimal to use a single audit technology throughout, the one with the minimum "cost/quality" ratio, continuously increasing audit frequency when the bank's asset value decreases.

We also explore a setting where the random audit can be delegated to an independent audit agency, able to ensure the same audit quality at lower cost than the regulator. We focus on the case where the audit effort of the agency is unobservable by the regulator, so that he needs to motivate the agency to maintain good management in the bank through an incentive compensation scheme with embedded moral hazard rent. As moral hazard rent makes it too costly to compensate the agency for effort when the bank's asset value is relatively high, it would be optimal to implement only a partial delegation of the random audits. In other words, delegation should not fully replace the regulatory audit. Partial delegation may be beneficial for the regulator, allowing total supervision costs to be reduced due to greater efficiency of the audit agency.

However, delegation raises the question of who should remunerate the independent audit agency: the audited bank or the regulator? In Swiss banking supervision practice, an audit firm involved in the supervisory process is remunerated by the audited bank. At first glance, this rule would appear to allow the regulator to reduce supervision spending. However, the financial dependence of the audit firm on the bank may negatively impact audit quality: it creates favorable conditions for bank pressure and, under competition in the audit market, may lead to greater indulgence by the audit firm towards its auditee. In the context of our model, any decision on whether to transfer the financial burden of the audit to the bank or not will be driven by the trade-off between incentive effect and cost of supervision. If the regulator provides the audit agency with audit instructions and makes the bank pay for each audit event, given that these costs will reduce the incentive effect of random audits on the bank, the regulator will need to perform more interventions in order to prevent bad management in the bank. This means higher intervention costs for the regulator. Thus, it might be cheaper for the regulator to pay for the audits himself and perform less interventions, rather than to charge the bank for audits but have to bear higher intervention costs.

# Appendix A. The evaluation of contingent claims

Let $J$ be a claim, contingent on the non-tradable asset which evolves according to (1). Let $\tau$ be its time to maturity and $\delta(x_t)$ be a continuous pay-off, conditional on the underlying asset value. In a risk-neutral world the current value of the claim is equal to the expected value of its future discounted pay-offs, conditional on current asset value $x$:

$$J(x) = E\left[\int_0^{\tau} e^{-rt}\delta(x_t)dt + e^{-r\tau}J_\tau(x_\tau)\right] \tag{A1}$$

According to standard techniques, a general solution of (A1) satisfies:

$$AJ(x) + \delta(x) = 0, \tag{A2}$$

where an operator $A$ is defined as:

$$AJ(x) = 1/2\sigma^2 x^2 J''(x) + \mu x J'(x) - rJ(x) \tag{A3}$$

## A.1. The bank's equity value

In the absence of supervision, the bank's equity value $E(x)$ is driven by:

| | |
|---|---|
| $AE_G(x) + bx - rD - \gamma r = 0$ | under good management technology |
| $AE_B(x) + bx - rD = 0$ | under bad management technology |

where $G$ and $B$ denote good and bad management technologies with $\mu = \mu_G$ and $\mu = \mu_B$ respectively.

Under random audits, $E_G(x)$ remains unchangeable. Conversely, $E_B(x)$ may incur a negative jump and thus follows:

$$AE_B(x) + bx - rD - \psi E(x) = 0 \tag{A4}$$

Under a mixed supervision strategy, the bank will use good management technology until its liquidation. Then, under a terminal condition $E(x_R) = 0$, the bank's equity value follows:

$$E_G(x) = \nu_G x - D - \gamma + (D + \gamma - \nu_G x_R)\,(x/x_R)^{\beta_2}\,, \tag{A5}$$

where $\nu_G = b/(r - \mu_G)$ and $\beta_2$ is a negative root of:

$$1/2\sigma^2\beta^2 + (\mu_G - 1/2\sigma^2)\beta = r \tag{A6}$$

## A.2. Supervision costs in the nondelegation case

For any given $\psi(x)$, $\alpha(x)$ and $x_I$, the total supervision costs $C(x)$ in the nondelegation framework are driven by the following ODE:

$$\begin{array}{ll} A\,C(x) = 0 & \text{when } x \geq x_A \\ A\,C(x) + \psi(x)\alpha(x)cr = 0 & \text{when } x \in [x_I, x_A) \\ A\,C(x) + cr = 0 & \text{when } x \in [x_R, x_I) \end{array}$$

where $C(x)$ is contingent on $x$ under good management technology ($\mu = \mu_G$), the operator $A$ is given by (A4) and $C(x_R) = 0$.

Consider the benchmark case where the regulator owns a single perfect audit quality $\alpha$ and $\psi = const$. Using a limit condition $\lim_{x\to+\infty} C(x) = 0$, a terminal condition $C(x_R) = 0$, value-matching and smooth-pasting conditions at $x_A$ and $x_I$, we get the following solution for $x \geq x_A$:

$$C(x) = k(\psi)x^{\beta_2}, \tag{A7}$$

where a cost coefficient $k(\psi)$ is given by:

$$k(\psi) = k - (1-\alpha\psi)\frac{c\left[\beta_1(x_A^{-\beta_2} - x_I^{-\beta_2}) - \beta_2 x_R^{\beta_1-\beta_2}(x_A^{-\beta_1} - x_I^{-\beta_1})\right]}{\beta_1 - \beta_2}, \tag{A8}$$

where $k = \frac{c}{\beta_1-\beta_2}(\beta_1 x_A^{-\beta_2} - \beta_2 x_R^{\beta_1-\beta_2} x_A^{-\beta_1}) - c x_R^{-\beta_2}$ is a cost coefficient of the pure continuous intervention strategy proposed in Rochet (2004), and $\beta_1$ is a positive root of (A6).

# Appendix B. Proofs

## Proof of Proposition 2

□ Using expression (9) and Lemma 1, we rewrite the regulatory problem as follows:

$$\underset{\alpha(x),\psi(x),x_I}{\text{Max}} \quad E_0\left[\int_0^{\tau_R} e^{-rt}cr(1-\alpha(x_t)\psi(x_t))I_{x_t\in[x_I,x_A)}dt\right]$$
$$\text{s.t. } \Delta\mu x E'_G(x) + \psi(x)p(\alpha(x))E_G(x) \geq \gamma r, \ \forall x \in [x_I, x_A)$$

where $x_0 \geq x_A$, $\alpha(x) \in T$ and $\psi(x) \leq 1/\alpha$.

The minimal incentive-compatible audit frequency is given by the binding incentive-compatibility constraint of the bank:

$$\psi(x) = \psi^B(x)/p(\alpha(x)), \tag{B1}$$

where $x \in [x_I, x_A)$, $\alpha \in T$ and $\psi^B(x)$ is given by (10).

Then, instantaneous random audit costs are proportional to:

$$\psi(x)\alpha = \psi^B(x)\alpha(x)/p(\alpha(x)) \tag{B2}$$

As $\psi^B(x)$ does not depend on audit quality, the minimal $\psi(x)\alpha$ will be ensured by a single audit technology, the one with the minimum ratio $\alpha/p(\alpha)$.

Let us consider the inspection threshold. For any arbitrary $\psi$ and $\alpha$, the minimum incentive compatible $x_I$ is given by the binding incentive-compatibility constraint. By Lemma 2, $x_I$ is increasing on $\psi$. Thus, the lowest feasible inspection threshold results from: $\psi(x_I) = 1/\alpha$. Using (B3), we can rewrite this equality as follows:

$$\psi^B(x_I) = p(\alpha(x_I))/\alpha(x_I) \tag{B3}$$

Therefore, a random audit technology with minimum $\alpha/p(\alpha)$ also ensures the lowest incentive-compatible inspection threshold. Then, the audit quality $\alpha^\star$ such that:

$$\alpha^\star = \underset{\alpha\in T}{\text{argmin}}\ \alpha/p(\alpha) \tag{B4}$$

provides a maximum gain from random audits and thus ensures minimum total supervision costs.■

## Proof of Proposition 3

### 3.1. An incentive contract continuation value

□ Let us fix some delegation region $[\underline{x}, \overline{x}) \in [x_R, x_A)$. For any $\psi(x)$, we consider an audit quality $\alpha_\psi(x)$ that makes the incentive constraint of the bank binding:

$$\Delta\mu x E'_G(x) + \psi(x) q(\alpha_\psi(x)) E_G(x) = \gamma r, \;\; x \in [\underline{x}, \overline{x}) \qquad \text{(B5)}$$

where $\psi^B(x)$ is given by (10).

Then, for any $x_0 \geq x_A$, the regulatory problem can be rewritten as follows:

$$\underset{R(x), R_T, x_T}{\text{Min}} \quad K_\psi(x_0) \geq 0$$

$$\text{s.t.} \begin{cases} \Delta\mu x K'(x) \geq \psi(x)\alpha_\psi(x) cr, \;\forall x \in [\underline{x}, \overline{x}) & (ICA) \\ R(x) \geq \alpha_\psi(x) cr, \;\forall x \in [\underline{x}, \overline{x}) & (PCA_1) \\ R_T \geq 0 & (PCA_2) \end{cases}$$

where $\alpha_\psi(x)$ is given by (B5).

For $x \in [\underline{x}, \overline{x}) \in [x_I, x_A)$ the minimal incentive compatible contract continuation value is given by the binding $ICA$:

$$K^*_\psi(x) = K_\psi(\underline{x}) + \frac{cr}{\Delta\mu}\left(\int_{\underline{x}}^{x} \frac{\psi(y)\alpha_\psi(y)}{y} dy\right), \;\; x \in [\underline{x}, \overline{x}) \qquad \text{(B6)}$$

where a constant $K_\psi(\underline{x}) \geq 0$ is defined below.

At the same time, $K^*_\psi(x)$ follows ODE:

$$A(1) K^*_\psi(x) + \psi(x)(R_\psi(x) - \alpha_\psi(x) cr) = 0 \qquad \text{(B7)}$$

Replacing $K^*_\psi(x)$ from (B6) into (B7), we get an incentive remuneration:

$$R_\psi(x) = \alpha_\psi(x) cr + \frac{r K^*_\psi(x)}{\psi(x)} - \frac{cr}{\Delta\mu}\left(\psi(x)\alpha_\psi(x)(\mu_G - \frac{1}{2}\sigma^2) + \frac{1}{2}\sigma^2 x \frac{\partial(\psi(x)\alpha_\psi(x))}{\partial x}\right) \qquad \text{(B8)}$$

We now need to find $K_\psi(\underline{x}) \geq 0$ that simultaneously minimizes $K^*_\psi(x)$ and ensures a participation constraint $R_\psi(x) \geq \alpha_\psi(x) cr$ for $\forall x \in [\underline{x}, \overline{x})$. Two cases are possible. If the term in parenthesis in (B8) is negative, the participation constraint will be respected throughout, so that the minimal $K^*_\psi(x)$ will be ensured by $K_\psi(\underline{x}) = 0$.[22] Otherwise, the minimum $K^*_\psi(x)$ will be ensured by

[22] Consequently, this will imply $R_\psi(\underline{x}) > \alpha_\psi(\underline{x}) cr$.

the minimal feasible $K_\psi(\underline{x}) > 0$ which results from $R_\psi(\underline{x}) = \alpha_\psi(\underline{x})cr$. Thus, we have:

$$K_\psi(\underline{x}) = \max \left\{0; \frac{cr}{\Delta\mu}\left(\psi(\underline{x})\alpha_\psi(\underline{x})(\mu_G - \frac{1}{2}\sigma^2) + \frac{1}{2}\sigma^2 \underline{x}\frac{\partial(\psi(x)\alpha_\psi(x))}{\partial x}|_{x=\underline{x}}\right)\right\} \tag{B9}$$

### 3.2. A terminal payoff and a termination rule

The minimal incentive-compatible terminal payoff will be given by the contract continuation value at the liquidation threshold, $R_T^{\star\star} = K_\psi^*(x_T^{\star\star})$, where $x_T^{\star\star}$ is the optimal termination rule. Indeed, any $R_T > R_T^{\star\star}$ incurs an excessive compensation over the whole delegation region, while $R_T < R_T^{\star\star}$ incurs a discontinuity of the contract at $\underline{x}$.

Naturally, when $K_\psi(\underline{x}) = 0$, we have $x_T^{\star\star} = \underline{x}$ and $R_T^{\star\star} = 0$.

Now let us consider the case when $K_\psi(\underline{x}) > 0$. Using the continuity of $K_\psi^*(x)$ and $K_\psi^{*\prime}(x)$ at $x = \underline{x}$, we can derive the contract continuation value for $x < \underline{x}$:

$$K_\psi^{**}(x) = \frac{\psi(\underline{x})\alpha_\psi(\underline{x})}{\beta_1 - \beta_2}\frac{cr}{\Delta\mu}\left(\underbrace{\left(\frac{x}{\underline{x}}\right)^{\beta_1} - \left(\frac{x}{\underline{x}}\right)^{\beta_2}}_{<0}\right) + \frac{K_\psi(\underline{x})}{\beta_1 - \beta_2}\left(\underbrace{\beta_1\left(\frac{x}{\underline{x}}\right)^{\beta_2} - \beta_2\left(\frac{x}{\underline{x}}\right)^{\beta_1}}_{>0}\right), \tag{B10}$$

where $K_\psi(\underline{x})$ is given by $R_\psi(\underline{x}) = \alpha_\psi(\underline{x})cr$.

Since $K_\psi(\underline{x}) > 0$, $K_\psi^{**\prime}(x) > 0$ for $x < \underline{x}$ and $\lim_{x\to 0} K_\psi^{**}(x) = -\infty$, there exists a unique $x^* \in [x_R, \underline{x})$ such that $K_\psi^{**}(x^*) = 0$. Thus, two cases are possible: (i) if $x^* < x_R$, we have $x_T^{\star\star} = x_R$ and $R_T^{\star\star} = K_\psi^{**}(x_R) > 0$; (ii) if $x^* > x_R$, we have $x_T^{\star\star} = x^*$ and $R_T^{\star\star} = 0$.

### 3.3. Optimal audit parameters

Now, allowing for the preceding results, we need to determine the optimal audit parameters $\psi(x)$ and $\alpha_\psi(x)$ that ensure:

$$\underset{\alpha_\psi(x),\psi(x)}{\text{Max}} \quad \{\Delta CA_\psi(x_0) - K_\psi^*(x_0)\} \geq 0, \tag{B11}$$

for any $x_0 \geq x_A$.

Since the pair $\psi(x)$ and $\alpha_\psi(x)$ satisfies the binding incentive constraint of the bank, we can express $\psi(x)$ as follows:

$$\psi(x) = \psi^B(x)/q(\alpha_\psi(x)), \tag{B12}$$

where $\psi^B(x)$ is given by (10). Then, $\Delta CA_\psi(x_0)$ can be rewritten as follows:

$$\Delta CA_\psi(x_0) = E_0\left[\int_0^{\tau_R} e^{-rt}\left(s_t - \psi^B(x_t)\frac{\alpha_\psi(x_t)}{q(\alpha_\psi(x_t))}\right) crI_{x_t\in[\underline{x},\overline{x}]}dt\right], \quad \text{(B13)}$$

where

$$s_t = \begin{cases} 1 & x_t \in [x_R, x_I^\star] \\ \alpha^\star\psi^\star(x_t) & x_t \in [x_I^\star, x_A] \end{cases}$$

and parameters $x_I^\star$, $\alpha^\star(x_t)$, $\psi^\star(x_t)$ are given in Proposition 2.

The minimal incentive $K^*_\psi(x_0)$ is:

$$K^*_\psi(x_0) = K_\psi(\overline{x})\left(\frac{x_0}{\overline{x}}\right)^{\beta_2} = \left(\frac{c}{\Delta\mu}\int_{\underline{x}}^{\overline{x}} \frac{\alpha_\psi(y)}{q(\alpha_\psi(y))}\frac{\psi^B(y)}{y}dy + K_\psi(\underline{x})\right)\left(\frac{x_0}{\overline{x}}\right)^{\beta_2}, \quad \text{(B14)}$$

where $K_\psi(\underline{x})$ is given by (B10) and $\beta_2$ is a negative root of (A6).

Note that, for $x > \underline{x}$, a constant $K_\psi(\underline{x})$ does not depend on audit parameters. Then, the solution of (B11) will be given by $\alpha^{\star\star} = \underset{\alpha\in T}{\operatorname{argmin}}\ \alpha/q(\alpha)$, as it simultaneously maximizes $\Delta CA_\psi(x_0)$ and minimizes the integrand in the expression of $K^*_\psi(x_0)$. Consequently, the optimal audit frequency is given by: $\psi^{\star\star}(x) = \psi^B(x)/q(\alpha^{\star\star})$. ■

## Proof of Lemma 3

□ Let us show that $\overline{x} < x_A$. Replacing $\alpha^{\star\star}$ and $\psi^{\star\star}(x)$ into (B6) and (B8), we obtain:

$$R_{\psi^{\star\star}}(x) = \alpha^{\star\star}cr + \frac{rK^*_{\psi^{\star\star}}(x)}{\psi^B(x)} - \frac{\alpha^{\star\star}cr}{\Delta\mu}\left(\mu_G - 1/2\sigma^2 + 1/2\sigma^2\frac{\partial\psi^B(x)}{\partial x}\frac{x}{\psi^B(x)}\right) \quad \text{(B15)}$$

Taking the first derivative of $\psi^B(x)$ on $x$, we get:

$$\frac{\partial\psi^B(x)}{\partial x} = -\frac{\Delta\mu(E'_G(x) + xE''_G(x))}{E_G(x)} - \psi^B(x)\frac{E'_G(x)}{E_G(x)} \quad \text{(B16)}$$

Since $\psi^B(x_A) = 0$, we obtain $\lim_{x\to x_A-} R_{\psi^{\star\star}}(x) = +\infty$. Therefore, there always exists a non-empty region $[\overline{x}, x_A)$ where $\alpha^\star\psi^\star(x) < R_{\psi^{\star\star}}(x)\psi^{\star\star}(x)$. Thus, we have $\overline{x} < x_A$. ■

## Proof of Lemma 4

□ Let us show that, for $\mu \leq \sigma^2$, the minimal feasible $K_{\psi^{\star\star}}(\underline{x}) = 0$. Let consider the sign of the term in parenthesis of expression (B8), allowing for the optimal audit parameters $\alpha^{\star\star}$, $\psi^{\star\star}(x)$ and any arbitrary $x \in [x_R, x_A)$:

$$\frac{c}{\Delta\mu}\frac{\alpha^{\star\star}}{q(\alpha^{\star\star})}\left(\psi^B(x)(\mu_G - \frac{1}{2}\sigma^2) + \frac{1}{2}\sigma^2 x \frac{\partial\psi^B(x)}{\partial x}\right) \tag{B17}$$

This will be equivalent to consider the sign of function $f(x)$ such that:

$$f(x) = x\frac{\partial\psi^B(x)}{\partial x} + \frac{(\mu_G - 1/2\sigma^2)}{1/2\sigma^2}\psi^B(x) \tag{B18}$$

Using (B16), we can rewrite $f(x)$ as follows:

$$f(x) = -\frac{\Delta\mu x(E'_G(x) + xE''_G(x))}{E_G(x)} - \psi^B(x)\left(\frac{xE'_G(x)}{E_G(x)} - \frac{(\mu_G - 1/2\sigma^2)}{1/2\sigma^2}\right) \tag{B19}$$

Note that $E_G(x)$ is convex. Then, for $x_R$ and any $x > x_R$ we can state:

$$E_G(x) \leq E_G(x_R) + E'_G(x)(x - x_R) \leq E_G(x_R) + xE'_G(x) = xE'_G(x) \tag{B20}$$

Since $xE'_G(x)/E_G(x) \geq 1$, for $\mu_G \leq \sigma^2$ we have $f(x) < 0$, so the expression (B17) is negatively signed for any $x \in [x_R, x_A)$. According to (B9), we have $K_{\psi^{\star\star}}(\underline{x}) = 0$. Then, $x_T^{\star\star} = \underline{x}$ and $R_T^{\star\star} = 0$. ■

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