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Aggregate and Bank-specific Information Disclosure in Bank Stress Tests

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Abstract

This paper studies how a bank regulator's aggregate and bank-specific information dis-closure policy affects social welfare. We apply global games to studying an economy where depositors, with strategic complementarities among them, face uncertainties about both aggregate and bank-specific information of a bank. Then we examine how disclosure policy of a bank regulator on the bank's aggregate and bank-specific information affects welfare. With the assumption that bank depositors rely on the bank regulator to collect aggregate bank performance information but have precise private information about bank-specific in-formation, we find that more precise aggregate information disclosed by the bank regulator improves welfare when bank fundamentals are either extremely strong or weak, but tends to reduce welfare when the fundamentals are in the intermediate range where coordina-tion plays a key role. In contrast, more precise bank-specific information disclosed by the regulator tends to increase welfare, even when the fundamentals are in the intermediate range.

JEL classification: D8; E58; G28

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1 Introduction

Bank information disclosure policy is at the centre of banking regulation. In the past, this policy focused mainly on banks' self-disclosure. Bank regulators generally kept their information about banks collected through supervisory activities undisclosed to the public. However, things have changed recently. Since 2008, both the US Federal Reserve and the European Central Bank have introduced bank stress tests as a regular banking regulation tool. An innovative but controversial feature of the tests is that bank regulators will disclose their test results to the public. Many interesting questions arise about the bank regulator's disclosure policy over stress test results. For example, should a bank regulator disclose its stress test results at all? Is more disclosure always better? Is more precise disclosure always better?[1]

In practice, bank regulators often choose to disclose aggregate banking sector performance but avoid disclosing bank-specific information after a stress test. This motivates us to study a specific question: How does a bank regulator's disclosure of aggregate banking sector performance and bank-specific performance affect bank depositors' decisions and social welfare differently?

We establish global games to examine this question. In our model, a continuum of bank depositors needs to decide whether or not to run a bank. The depositors face two types of uncertainty: First, they are uncertain about bank fundamentals that include both aggregate bank and bank-specific performance. Second, they face strategic uncertainty about other depositors' actions. The latter originates from the assumption that the bank is subject to rollover risk by borrowing short-term debts to finance its long-term assets. As a result, we study a typical Diamond-Dybvig environment where banks are subject to self-fulfilling bank runs caused by coordination failure due to strategic complementarities among depositors. Then we introduce a bank regulator with information about aggregate bank performance and/or bank-specific performance. Specifically, we confine to a realistic case where the regulator has more precise information about aggregate bank performance, but less precise information about bank-specific information than bank depositors. In the current version, we examine the case where bank depositors have no private information about aggregate bank performance and rely entirely on the bank regulator to collect

[1]See Goldstein and Sapra (2013) for a detailed survey.

this information. We then examine how the precision of the regulator's two types of information affect depositors' behaviour and welfare.

Our models produce the following major results. We find that the relationship between the precision of aggregate bank information and welfare depends on the strength of bank fundamentals. When bank fundamentals are either strong or weak, more precise aggregate and bank-specific information tends to improve welfare. However, when bank fundamentals are in the intermediate range where coordination matters, more precise aggregate information can worsen welfare by inducing more severe coordination failure. Specifically, we find that more precise aggregate information tends to worsen welfare, while more precise bank-specific information tends to improve welfare.

The key to understanding our results is the interaction between the two types of uncertainty at different levels of bank fundamentals. When the fundamentals are either strong or weak, depositors' optimal strategy is determined by the fundamentals, and other depositors' actions are irrelevant. More precise aggregate and bank-specific information reduces the first type of uncertainty in the absence of the second type of uncertainty. As a result, welfare increases unambiguously with information precision. However, when the fundamentals are in the intermediate range, depositors' optimal strategy is determined not only by the fundamentals, but also by other depositors' actions. More precise aggregate and bank-specific information reduces the first type of uncertainty, but may cause more severe coordination failure due to the second type of uncertainty. As a result, welfare may increase or decrease with information precision. The different welfare effects of aggregate and bank-specific information when the fundamentals are in the intermediate range originate from our assumption that bank depositors lack private information about aggregate bank information but have precise private information about bank-specific information. Due to this assumption, we find that more precise aggregate information tends to cause more severe coordination failure, while more precise bank-specific information tends to alleviate coordination failure.[2]

This paper contributes to an emerging literature on bank information disclosure policy of bank regulators that is motivated by the introduction of bank stress tests during

[2] We will offer a more detailed analysis about the interaction between the two types of uncertainty once technical details of our models are introduced.

the global financial crisis.[3] This paper is closely related to Moreno and Takalo (2016), who also study bank information disclosure in a global game setup. They find that more transparency (i.e. more precise information of bank depositors about bank asset quality) will lead to more bank runs, because bank runs have a negative externality on the payoffs of creditors who choose not to run the bank. A key result in their paper is that maximum transparency is not socially optimal. Bouvard, Chaigneau, and de Motta (2015) examine the strategic interaction between the bank regulator and depositors over the bank regulator's information disclosure. Their key finding is that during the crisis, when the average bank asset quality is low, where both strong and weak banks are subject to bank runs, a regulator will pursue a transparent policy of revealing the type of each bank to creditors: an action which will at least save strong banks from bank runs. However, during normal times when the average bank asset quality is high, the regulator will prefer an opaque policy such that both strong and weak banks will avoid bank runs with their types unrevealed to creditors. They find that when the bank regulator has better information than the market, it has an incentive to hide bank-specific information in the times of low average bank quality, inducing inefficiency.

Our paper differs from these two papers, and more generally most of the existing literature by assuming possible efficient bank runs. In these two papers, any asset liquidation (or bank run) is assumed to be socially inefficient. This assumption makes sense in a crisis scenario where even the bankruptcy of distressed banks is socially inefficient, which was the case during the global financial crisis when the bank stress test was first introduced. However, with financial stability having been restored, bank stress tests, as a regular prudential policy tool, now face a different market environment. In normal times, bankruptcies of distressed banks are a natural part of market discipline. Asset liquidation of these banks is socially efficient. In this paper, we examine the welfare effect of information disclosure of a bank regulator in such a situation. In our model, asset liquidation is not necessarily socially inefficient. As a result, a bank run could be welfare improving because it prevents a distressed bank from continuing inefficient operation. In our model, a bank run is socially efficient when the bank's fundamentals are weak, but is socially inefficient when the bank's fundamentals are strong. Although our models produce the

[3]Goldstein and Sapra (2013) conduct an excellent survey on the existing literature that helps us understand bank regulators' disclosure policy over stress test results.

similar result that more precise information may not be welfare improving as most of the existing literature does, the economic mechanism behind our results differs. The most existing literature reaches this result because with the assumption that all the bank runs are inefficient, better information about distressed banks' fundamentals induces more bank runs and consequently reduces welfare. In our models, better information about distressed banks' fundamentals that induces more bank runs is welfare improving. However, better information may cause more severe *coordination failure* among bank depositors when bank fundamentals are in the intermediate range, which reduces welfare.

This paper is also closely related to the literature on global games that are used for our analysis. Global games were first introduced by Carlsson and van Damme (1993) and then applied by Morris and Shin (1998) to the study of currency attacks. They are now widely applied in various economic issues such as bank runs and economies with investment complementarities.[4] Our model is an extension to Morris and Shin (2001). We introduce two types of bank information to the bank run model introduced by them, and examine how the precision of these two types of information disclosed by a bank regulator will affect welfare. This paper also contributes to the literature on the role of public information in the presence of strategic complementarities.[5] In particular, it studies the role of public information in a specific case of bank regulators' disclosure policy when strategic complementarities exist among bank depositors.

The rest of the paper is organised as follows. Section 2 establishes a model where only aggregate information about banks is disclosed by a bank regulator and examines policy implications of aggregate information disclosure. Section 3 establishes a model where bank-specific information is disclosed by a bank regulator and examines associated policy implications. Section 4 concludes.

[4]See, e.g., Goldstein, Itay, and Ady Pauzner (2005), Morris and Shin (1998, 2003), and Li (2012, 2013) among many others.

[5]See, e.g., Morris and Shin (2002) and Angeletos and Pavan (2004).

2 A model with aggregate information disclosed

2.1 The environment

Consider a Diamond-Dybvig bank run model with three dates denoted by 0, 1 and 2. There is a continuum of depositors of mass $1 + \lambda$. At date 0, all the depositors are identical and unaware of their type. At date 1, a liquidity shock hits the depositors. As a result, they are divided into two types: (1) Proportion λ of them become early depositors who gain utility only from date 1 consumption, and (2) proportion one of them become late depositors who gain utility only from date 2 consumption. The utility function of a depositor is natural logarithm, and the ex-ante expected utility of a representative depositor is given by

$$EU = \frac{\lambda}{1+\lambda} ln(c_1) + \frac{1}{1+\lambda} ln(c_2) \tag{1}$$

Consider a bank which holds a long-term asset. The asset is fully financed by short-term debts that have to be rolled over at date 1. Depositors could withdraw either at date 1 or at date 2. Following Morris and Shin (2001), who introduce a global game to the Diamond-Dybvig bank run model, we assume that if a depositor withdraws at date 1, the liquidation technology is such that he will receive $e^0 = 1$ unit of the good. If he withdraws at date 2, he will receive e^{r-tl} units of the good, where r is given by

$$r = \theta + \eta \tag{2}$$

Here θ is a common component that captures systemic factors that affect all the banks, and η is a bank-specific component that captures factors that affect an individual bank. Additionally, θ and η are independent of each other. Moreover, l is the proportion of late depositors withdrawing at date 1, and $t > 0$ is a constant capturing how costly liquidation is if the asset is liquidated prematurely at date 1. Note that the introduction of the negative term $-tl$ in the long-term asset return rate captures strategic complementarities among late depositors. More late depositors withdrawing at date 1 lead to lower return rates for the rest of late depositors withdrawing at date 2. Thus, a bank's asset return depends on two components: (1) bank fundamentals captured by $r = \theta + \eta$, and (2) coordination among late depositors that is captured by $-tl$. Besides bank deposits, depositors have access to a storage technology that transforms one unit of date 1 goods into one unit of date 2 goods.

Now we introduce the information structure. We assume that depositors have imperfect information about the aggregate information of the banking sector, θ. Specifically, they have an improper uniform prior belief over the real line about θ. Each of them observes a public signal from the bank regulator,

$$y = \theta + \varepsilon_y \tag{3}$$

where ε_y is normally distributed with mean 0 and precision α.

Depositors also have imperfect information about bank-specific information, η_i. Specifically, each depositor receives a private signal about it,

$$x_i = \eta + \varepsilon_{x,i} \tag{4}$$

where $\varepsilon_{x,i}$ is normally distributed with mean 0 and precision β. Additionally, $\varepsilon_{x,i}$ is i.i.d. among all the depositors.

Thus, following Bayes' rule, depositors update their belief about r as follows. Conditional on two signals, y and x_i, they believe that r is normally distributed with mean

$$E(r|y, x_i) = y + x_i \tag{5}$$

and variance $\frac{1}{\alpha} + \frac{1}{\beta}$.

2.2 The equilibrium

This is a typical global game with a unique equilibrium that is characterized by a switching strategy x^*. Each late depositor will run the bank if and only if his private signal, x_i, is below x^*. Otherwise, he will stay until date 2.

To prove this result, note that for an individual late depositor with a signal x_i, his expected utility from withdrawing at date 2 is given by

$$E(r|y, x_i) - tE(l|y, x_i) = y + x_i - tE(l|y, x_i) \tag{6}$$

Thus, the key here is to find $E(l|y, x_i)$. Suppose that we confine to a symmetric switching strategy equilibrium x^*. That is, all the late depositors follow a switching strategy of withdrawing if and only if their private signal $x_i < x^*$. For a late depositor with a private signal x_i, provided that all the other late depositors follow the equilibrium strategy, he expects that l is given by:

$$E(l|y,x_i) = Prob(x_j < x^*|y,x_i) \tag{7}$$

where x_j is the private signal received by another late depositor. Recall that

$$x_j = \eta + \varepsilon_{x,j} \tag{8}$$

Conditional on his private signal x_i, the depositor believes that η is normally distributed with mean x_i and variance $1/\beta$. In turn, he believes that x_j is normally distributed with mean x_i and variance $2/\beta$. Thus, we have

$$E(l|y,x_i) = Prob(x_j < x^*|y,x_i) = \Phi\left(\sqrt{\frac{\beta}{2}}(x^* - x_i)\right) \tag{9}$$

where $\Phi(.)$ is the CDF of a standard normal distribution.

Thus, we find that a depositor with private signal x_i has

$$E(r|y,x_i) - tE(l|y,x_i) = y + x_i - t\Phi\left(\sqrt{\frac{\beta}{2}}(x^* - x_i)\right) \tag{10}$$

For a depositor with signal x^*, he must be indifferent between withdrawing at date 1 and date 2. Thus, we have

$$E(r|y,x^*) - tE(l|y,x^*) = y + x^* - t\Phi\left(\sqrt{\frac{\beta}{2}}(0)\right) = 0 \tag{11}$$

which gives us $x^* = \frac{1}{2}t - y$.

We can prove that this switching strategy is optimal for all the late depositors. To see this, note that for a late depositor with a private signal x_i, his expected utility from withdrawing at date 2, which is given by Eq.(10), is strictly increasing in x_i. Thus, for all the late depositors with $x_i < x^*$, $E(r|y,x_i) - tE(l|y,x_i) < 0$. As a result, it is optimal for them to withdraw at date 1. While for all the late depositors with $x_i > x^*$, $E(r|y,x_i) - tE(l|y,x_i) > 0$. As a result, it is optimal for them to withdraw at date 2. Morris and Shin (2001) provide a proof showing that this symmetric switching strategy is the unique equilibrium surviving the iterated elimination of strictly dominated strategy.

2.3 Welfare analysis

We now examine how the public signal, y, will affect the equilibrium and welfare. We assume that all the depositors weigh equally for a social planner such that the aggregate utility is given by

$$W = (\lambda + l)u(1) + (1 - l) \times u(e^{\theta+\eta-tl}) = (1 - l)(\theta + \eta - tl) \tag{12}$$

We use this aggregate utility function to measure social welfare. The first-best solution in a friction-free world with perfect information and without coordination failure is as follows: When $\theta + \eta > 0$, no late depositors withdraw at date 1, and the aggregate utility is $\theta + \eta$. Whereas when $\theta + \eta < 0$, all the late depositors withdraw at date 1, and the aggregate utility is simply 0. Additionally, with perfect information, when $\theta+\eta > t$, no run is the dominant strategy and the first-best allocation is attained. While when $\theta + \eta < 0$, bank run is the dominant strategy and the first-best allocation is also attained. When $0 < \theta + \eta < t$, we have a typical coordination game with two Pareto-ranked equilibria. In our global game setup, due to the payoff perturbation we introduce to the game, there is a unique equilibrium as described above.

The frictions of imperfect information and coordination failure are present in this model, implying that the first-best allocation cannot be attained. In this model, uncertainty is twofold: (1) Depositors are uncertain about both aggregate and bank-specific information of the bank, θ, and η. (2) Depositors are also uncertain about other depositors' actions, which matters due to strategic complementarities among them. It will be interesting to examine how these two types of uncertainty interact with each other, inducing different welfare effects of the bank regulator's information disclosure.

Given the realisation of θ and η, the expected aggregate utility is given by

$$EW = \int_{-\infty}^{\infty} (1 - l(y))(\theta + \eta - tl(y))\sqrt{\alpha}\phi(\sqrt{\alpha}(y - \theta))dy \tag{13}$$

where $\phi(.)$ is the density function of a standard normal distribution.

Note that given the realisation of η,

$$l(y) = Prob(x < x^*) = Prob(x < \frac{1}{2}t - y) = \Phi\left(\frac{\frac{1}{2}t - y - \eta}{\sqrt{\frac{1}{\beta}}}\right) = \Phi\left(\sqrt{\beta}\left(\frac{1}{2}t - y - \eta\right)\right) \tag{14}$$

Now we examine how the precision of the bank regulator's signal for aggregate information, α, affects welfare. It is difficult to find a clear-cut result about the sign of the first-order derivative of EW w.r.t α.[6] To gain some insight, we now consider a special case where $\beta \to \infty$. In this case, late depositors have perfect information about η. Thus, when $y < \frac{1}{2}t - \eta$, or $\eta < \frac{1}{2}t - y$, all the late depositors will receive a private signal $x = \eta < \frac{1}{2}t - y = x^*$. As a result, $l = 1$. On the other hand, when $y > \frac{1}{2}t - \eta$, or $\eta > \frac{1}{2}t - y$, all the late depositors will receive a private signal $x = \eta > \frac{1}{2}t - y = x^*$. As a result, $l = 0$. Thus, we can write the welfare function as follows:

$$EW = \int_{\frac{1}{2}t-\eta}^{\infty} (\theta + \eta)\sqrt{\alpha}\phi(\sqrt{\alpha}(y - \theta))dy = (\theta + \eta)\left(1 - \Phi\left(\sqrt{\alpha}\left(\frac{1}{2}t - \eta - \theta\right)\right)\right) \quad (15)$$

This is because y is normally distributed with mean θ and variance $\frac{1}{\alpha}$. When $y < \frac{1}{2}t - \eta$, all the late depositors will withdraw early, and the welfare at each realised level of y is $(1 + \lambda) \times 0 = 0$. When $y > \frac{1}{2}t - \eta$, all the late depositors will withdraw in period 2, and the welfare at each realised level of y is $\lambda \times 0 + 1 \times (\theta + \eta) = \theta + \eta$.

We find that

$$\frac{\partial EW}{\partial \alpha} = -\frac{1}{2}\alpha^{-0.5}\left(\frac{1}{2}t - \eta - \theta\right)\phi\left(\sqrt{\alpha}\left(\frac{1}{2}t - \eta - \theta\right)\right)(\theta + \eta) \quad (16)$$

The sign of the first-order derivative depends crucially on the signs of $\frac{1}{2}t - \eta - \theta$ and $\theta + \eta$. When $0 < \theta + \eta < \frac{1}{2}t$, the sign of the first-order derivative is negative, implying that a larger α decreases welfare. When $\theta + \eta < 0 < \frac{1}{2}t$ and when $\theta + \eta > \frac{1}{2}t > 0$, the sign of the first-order derivative is positive, implying that a larger α increases welfare.

The cases of $\theta + \eta < 0 < \frac{1}{2}t$ and $\theta + \eta > \frac{1}{2}t > 0$ are not surprising because they produce the conventional result that more precise information improves welfare. This is because when bank fundamentals are in these ranges, depositors' strategy is determined only by the fundamentals, and other depositors' actions do not matter. Thus, better information reduces the first type of uncertainty in the absence of the second type of uncertainty, inducing more depositors to choose the socially optimal strategy and improving welfare. The case of $0 < \theta + \eta < \frac{1}{2}t$ is interesting because it produces an unconventional result that more precise information in fact worsens welfare. The key reason for this result is coordination failure, or the presence of the second type of uncertainty. When bank

[6] See the Appendix for the derivation of this first-order derivative.

fundamentals are in this intermediate range, other depositors' actions matter. Depositors' strategy is determined not only by the fundamentals, but also by other depositors' actions. In a friction-free world with perfect information and no coordination failure, the first-best solution should be late depositors coordinating toward a no bank run strategy ($l = 0$). However, a higher α actually leads to more severe coordination failure (a higher average proportion of late depositors who mistakenly run the the bank). To see how this happens, note that when $\theta + \eta < \frac{1}{2}t$, $\theta < \frac{1}{2}t - \eta$. Because y is normally distributed with mean θ and variance $\frac{1}{\alpha}$, a higher α implies that values for y are more concentrated around a value below $\frac{1}{2}t - \eta$, that is, y is more likely to be below $\frac{1}{2}t - \eta$, implying that it is more likely that all the late depositors withdraw early ($l = 1$). This could be told by a higher value for $\Phi\left(\sqrt{\alpha}\left(\frac{1}{2}t - \eta - \theta\right)\right)$ when α is higher given that $\frac{1}{2}t - \eta - \theta > 0$, or $\theta < \frac{1}{2}t - \eta$. In this case, although better information reduces the first type of uncertainty, it causes more severe coordination failure in the presence of the second type of uncertainty, inducing lower welfare.

Thus, our model produces the result that more precise public information is not always welfare-improving, which is similar to that of existing literature. However, the mechanism behind this result in our model differs greatly from the one in the existing literature. Most existing literature assumes that bank runs are inefficient and less bank runs are always welfare improving, even when bank fundamentals are weak. As a result, more precise information may reduce welfare, because it induces more bank runs once bank depositors are better informed about weak bank fundamentals. Our model assumes that bank runs are efficient so long as $\theta + \eta < 0$, that is, when bank fundamentals are weak. Thus, in our model, more precise information is welfare-improving even if it induces more bank runs when the fundamentals are weak. More precise information could be welfare-worsening in our model because it may induce more severe coordination failure, when the fundamentals are in the intermediate range.

We now use numerical examples to examine the welfare effect of α in the general case without assuming that $\beta \to \infty$. Here we give five numerical examples with $\theta = 0$, and $\eta = 0.2$, 1.5, -0.5, 0.8, and -0.2, respectively. Besides, we set $t = 1$, $\beta = 5$, and let α vary from 0.1 to 10 to see how the welfare changes in α in five different cases of $\theta + \eta = 0.2$, 1.5, -0.5, 0.8 and -0.2. For all the examples, we also show how the average proportion of late depositors who withdraw early, the ex-ante expected value of l, varies in α. Figure 1 gives the results.

Our numerical examples about the general case produce results consistent with our analytical results in the special case where $\beta \to \infty$. Specifically, we find that: (1) When $\theta + \eta$ is in an intermediate range (between 0 and t), the welfare tends to decrease in α. But the welfare could also have a non-monotonic relationship with α in this range, especially when $\theta + \eta$ is close to the lower and upper bounds of the intermediate range. (2) When $\theta + \eta$ is either very strong or weak, the welfare tends to increase in α.

The intuition behind these results is similar to the one in the special case where $\beta \to \infty$. As mentioned before, late depositors face two types of uncertainty: the uncertainty about bank fundamentals and the strategic uncertainty about other late depositors' actions. More precise information about bank fundamentals is welfare-improving because it reduces the first type of uncertainty and induces depositors to correctly choose socially optimal strategies that match the fundamentals. But more precise information may cause more severe coordination failure due to the second type of uncertainty, which is welfare-worsening. The second effect could be significant when the fundamentals are in the intermediate range, implying that more precise information could reduce welfare at the intermediate level of the fundamentals.

Unlike the case of $\beta \to \infty$ where the proportion of the late depositors withdrawing early, l, is either 0 or 1, it may vary from 0 to 1 as α increases in the general case. A further examination of the relationship between l and welfare provides some insight on how α affects welfare through affecting l. To examine the relationship between l and welfare, note that the realised welfare is given by

$$W = (1 - l)(\theta + \eta - tl) \tag{17}$$

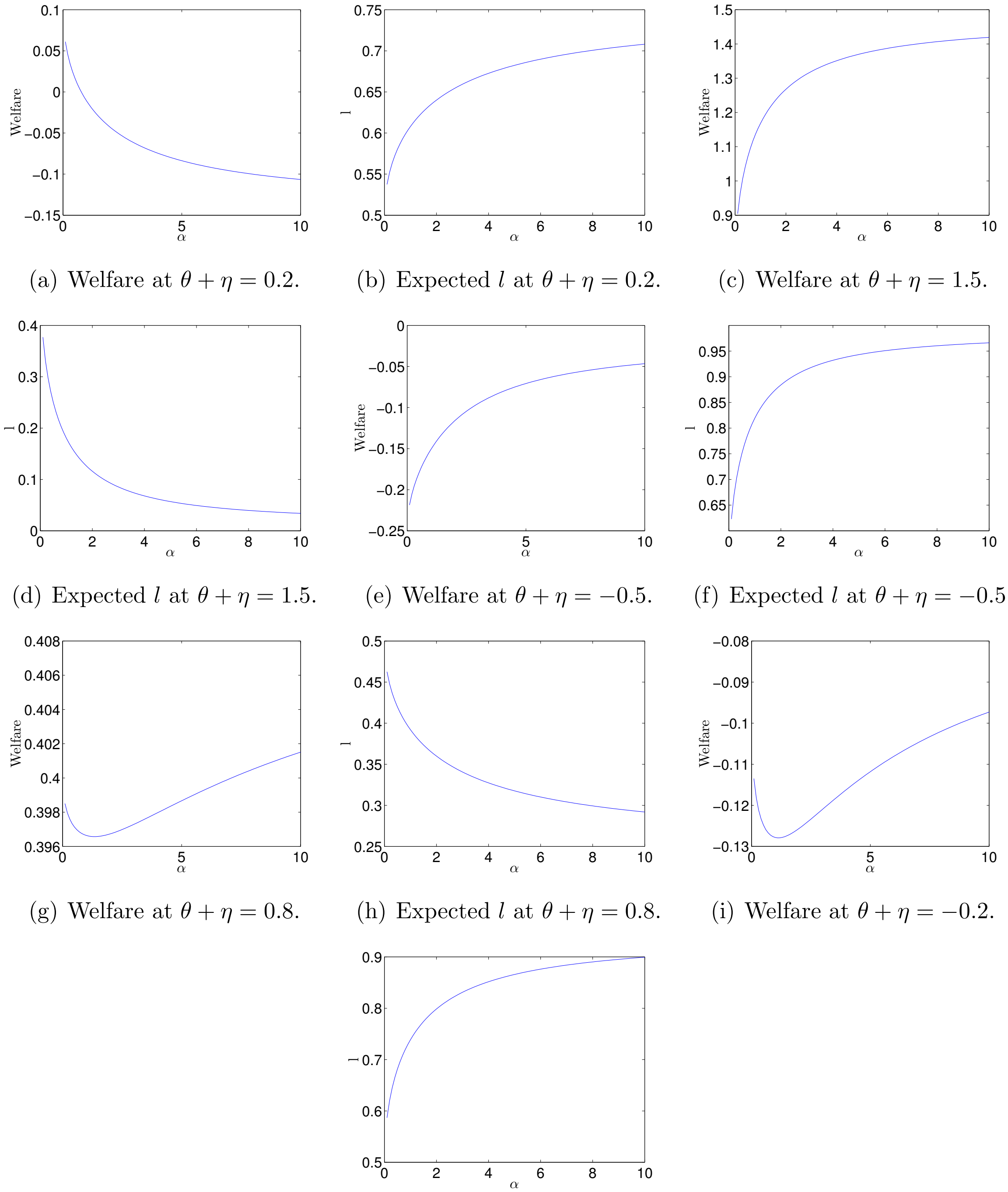
The first-order derivative of W w.r.t l gives us

$$\frac{\partial W}{\partial l} = 2tl - \theta - \eta - t \tag{18}$$

The second-order derivative of W w.r.t l gives us

$$\frac{\partial^2 W}{\partial l^2} = 2t \tag{19}$$

Thus, we find that W is a convex function in l with the minimum value at $l^* = \frac{t+\theta+\eta}{2t}$. When $l > l^*$, the welfare is increasing in l, while when $l < l^*$, the welfare is decreasing



(a) Welfare at $\theta + \eta = 0.2$.

(b) Expected l at $\theta + \eta = 0.2$.

(c) Welfare at $\theta + \eta = 1.5$.

(d) Expected l at $\theta + \eta = 1.5$.

(e) Welfare at $\theta + \eta = -0.5$.

(f) Expected l at $\theta + \eta = -0.5$.

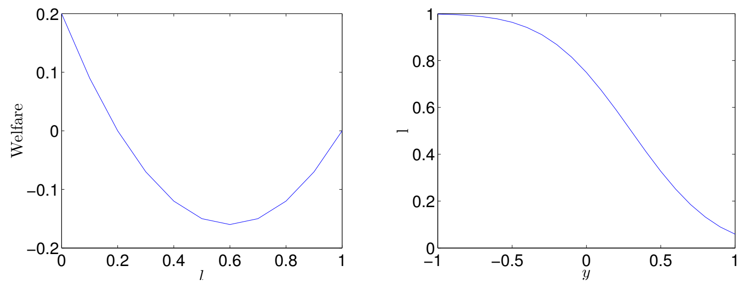
(g) Welfare at $\theta + \eta = 0.8$.

(h) Expected l at $\theta + \eta = 0.8$.

(i) Welfare at $\theta + \eta = -0.2$.

(j) Expected l at $\theta + \eta = -0.2$.

Figure 1: Welfare and α.



(a) Welfare and l at $\theta + \eta = 0.2$.   (b) y and l at $\theta + \eta = 0.2$.

Figure 2: Welfare, l and y.

in l. Because $0 \leq l \leq 1$, we find that when the fundamentals are strong $(\theta + \eta > t)$, l is always below l^*, implying that the welfare is always decreasing in l. Similarly, when the fundamentals are weak $(\theta + \eta < -t)$, l is always above l^*, implying that the welfare is always increasing in l. However, when $-t < \theta + \eta < t$, the welfare takes the shape of a typical convex function, which is higher when l takes extremely high or low values and is lower when l takes intermediate values around l^*. Figure 2(a) gives an example.

The intuition behind the convex welfare function is as follows: When l starts from 0, the welfare is decreasing in l, the proportion of the late depositors withdrawing early, as long as the rate of return on the risky asset is higher than e^0, or $\theta + \eta - tl > 0$. However, as l becomes larger and the rate of return on the risky asset is lower than e^0, or $\theta + \eta - tl < 0$, an increase in l has two opposite effects on welfare: On one hand, an increase in l reduces the proportion of late depositors that suffer a negative return from holding the risky asset and increases the number of late depositors that receive a zero return from holding the safe asset, which is welfare-improving. On the other hand, an increase in l lowers the return of the risky assets and induces a larger loss for the late depositors who hold the risky assets, which is welfare-worsening. When l is small, the second effect is dominant, inducing a negative relationship between l and welfare. Once l is sufficiently large, the first effect dominates, inducing a positive relationship between l and welfare.

The convexity of the welfare function explains why a higher α could reduce welfare when the fundamentals are in the intermediate range in the general case. Recall that

$$l(y) = Prob(x < x^*) = Prob(x < \frac{1}{2}t - y) = \Phi\left(\frac{\frac{1}{2}t - y - \eta}{\sqrt{\frac{1}{\beta}}}\right) = \Phi\left(\sqrt{\beta}\left(\frac{1}{2}t - y - \eta\right)\right)$$

Figure 2 (b) illustrates the relationship between y and l. A higher α implies the values of y are more concentrated around the true value of the aggregate information, θ. Consequently, l is more likely to take the value of $\Phi\left(\sqrt{\beta}\left(\frac{1}{2}t-\theta-\eta\right)\right)$. Recall that the welfare reaches its lowest value at $l^{*}=\frac{t+\theta+\eta}{2t}$. Thus, a higher α tends to lower the welfare when $\Phi\left(\sqrt{\beta}\left(\frac{1}{2}t-\theta-\eta\right)\right)$ is close to l^{*}. In our numerical example where $\theta=0$, $\eta=0.2$, and $t=1$, y is normally distributed around 0. A higher α implies that the values of y fall more often around 0 where $\Phi\left(\sqrt{\beta}\left(\frac{1}{2}t-\theta-\eta\right)\right)=0.7488$, which is close to $l^{*}=0.6$ at which the welfare reaches its minimum value in this numerical example. Thus, a higher α induces a larger incidence of low welfare, lowering the average welfare. Actually, in our numerical example, $\Phi\left(\sqrt{\beta}\left(\frac{1}{2}t-\theta-\eta\right)\right)=l^{*}$ when $\eta=0.317$. Numerical exercises show that when η is in the neighbourhood of this value, a higher α indeed reduces the welfare.

3 A model with bank-specific information disclosed

3.1 The model and equilibrium outcomes

Now we assume that the bank regulator will disclose a public signal about a bank's bank-specific information. Specifically, assume that now the bank regulator will disclose a public signal, denoted by z, about the bank's bank-specific information:

$$z=\eta+\varepsilon_{z} \tag{20}$$

where ε_{z} is normally distributed with mean zero and precision γ. For simplicity, we assume that depositors have perfect information about θ.

With the introduction of z, depositors will change their beliefs over η. Specifically, for a depositor with a private signal of x_i about η, his belief over η is normally distributed with mean

$$E(\eta|x_i,z)=\frac{\beta x_i+\gamma z}{\beta+\gamma} \tag{21}$$

and precision $\beta+\gamma$. We let $\rho_i\equiv\frac{\beta x_i+\gamma z}{\beta+\gamma}$.

Again, we can prove that there is a unique symmetric switching strategy equilibrium that survives the iterated elimination of strictly dominated strategies. In this equilibrium, a late depositor withdraws at date 1 if and only if his private signal is below a threshold level of x^*. To derive x^* intuitively, consider a late depositor's expected payoff from withdrawing at date 1, provided that all the late depositors follow this equilibrium strategy, which is given by

$$Eln(e^{\theta+\eta-tl}|x_i, z) = E(\theta + \eta - tl|x_i, z) = \theta + \frac{\beta x_i + \gamma z}{\beta + \gamma} - tE(l|x_i, z) \tag{22}$$

Again, the key here is to find his expected value for l, which is given by

$$E(l|x_i, z) = Prob(x_j < x^*|x_i, z) \tag{23}$$

Conditional on x_i and z, late depositor x_i believes that η is normally distributed with mean ρ_i and precision $\beta + \gamma$. Additionally, recall that

$$\eta = x_j + \varepsilon_{x,j} \tag{24}$$

implying that late depositor x_i believes that x_j is normally distributed with mean ρ_i and variance $\frac{1}{\beta} + \frac{1}{\beta+\gamma} = \frac{2\beta+\gamma}{\beta(\beta+\gamma)}$. Thus we have

$$E(l|x_i, z) = Prob(x_j < x^*|x_i, z) = \Phi\left(\sqrt{\frac{\beta(\beta+\gamma)}{2\beta+\gamma}}(x^* - \rho_i)\right) \tag{25}$$

Late depositor x^* must be indifferent between withdrawing at date 1 and date 2, implying that

$$Eln(e^{\theta+\eta-tl}|x^*, z) = \theta + \rho^* - tE(l|x^*, z) = \theta + \rho^* - t\Phi\left(\sqrt{\frac{\beta(\beta+\gamma)}{2\beta+\gamma}}(x^* - \rho^*)\right) = 0 \tag{26}$$

Note that

$$x^* = \frac{(\beta+\gamma)\rho^* - \gamma z}{\beta} = \rho^* + \frac{\gamma}{\beta}(\rho^* - z) \tag{27}$$

Thus we have

$$\Phi\left(\sqrt{\frac{\beta(\beta+\gamma)}{2\beta+\gamma}}(x^* - \rho^*)\right) = \Phi\left(\sqrt{\frac{\beta(\beta+\gamma)}{2\beta+\gamma}}\frac{\gamma}{\beta}(\rho^* - z)\right) = \Phi\left(\sqrt{\frac{\gamma^2(\beta+\gamma)}{\beta(2\beta+\gamma)}}(\rho^* - z)\right) \tag{28}$$

Thus the indifference condition for late depositor $\rho^*(x^*)$ is

$$\theta + \rho^* - t\Phi\left(\sqrt{\frac{\gamma^2(\beta+\gamma)}{\beta(2\beta+\gamma)}}(\rho^* - z)\right) = 0 \tag{29}$$

Morris and Shin (2001) show that so long as the private signal is sufficiently more precise than the public signal such that complementarities among late depositors are not so strong, the LHS of Eq.(29) is strictly increasing in ρ^*, which ensures a unique solution to ρ^* and in turn to x^*. Specifically, note that the maximum value for the density function of a standard normal distribution is $\sqrt{\frac{1}{2\pi}}$, implying the maximum value for the first-order derivative of $\Phi\left(\sqrt{\frac{\gamma^2(\beta+\gamma)}{\beta(2\beta+\gamma)}}(\rho^* - z)\right)$ w.r.t ρ^* is $\sqrt{\frac{\gamma^2(\beta+\gamma)}{\beta(2\beta+\gamma)2\pi}}$. Thus, so long as β is sufficiently higher than γ such that $t\sqrt{\frac{\gamma^2(\beta+\gamma)}{\beta(2\beta+\gamma)2\pi}} < 1$, the first-order derivative of the LHS of Eq.(29) w.r.t ρ^* is strictly positive, ensuring a unique solution to ρ^*.

3.2 Welfare analysis

Now we examine how the precision of the bank regulator's signal about η will affect welfare. The ex-ante expected welfare function is given by:

$$W = \int_{-\infty}^{\infty} (1 - l(z))(\theta + \eta - tl(z))\sqrt{\gamma}\phi(\sqrt{\gamma}(z - \eta))dz \tag{30}$$

where $\phi(.)$ is the density function of a standard normal distribution. Here

$$l(z) = Prob(x < x^*(z)) = \Phi(\sqrt{\beta}(x^*(z) - \eta)) \tag{31}$$

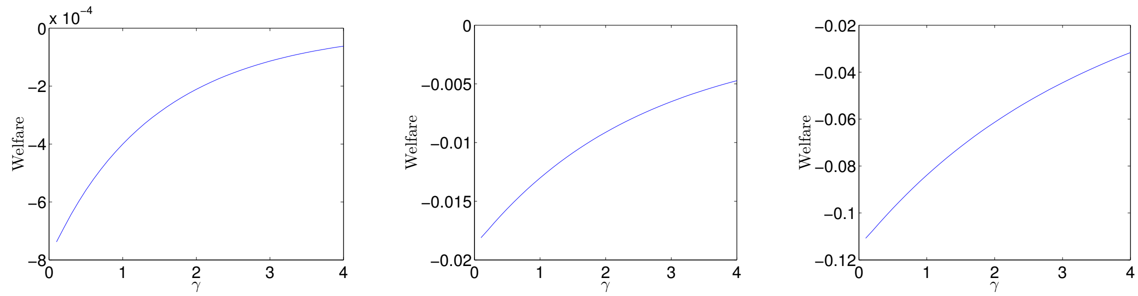
where

$$x^* = \frac{(\beta + \gamma)\rho^* - \gamma z}{\beta} = \rho^* + \frac{\gamma}{\beta}(\rho^* - z) \tag{32}$$

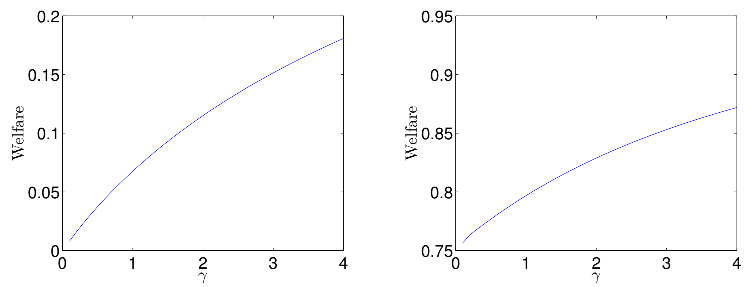
with ρ^* given by Eq.(29).

Again, we examine how the precision of the bank regulator's signal, γ, affects the welfare. Due to the complex nature of the problem, we find that the first-order derivative of the welfare function w.r.t γ is messy without an unambiguous sign.[7] Here we provide some numerical examples to examine its property. We set $\beta = 5$, $\theta = 0$, and $t = 1$. Additionally, we let γ vary from 1 to 4, and let η vary from -1 to 1. Figure 3 reveals the results. It shows that more precise public information about bank-specific information tends to increase welfare. In fact, in our numerical example with relatively precise private information ($\beta = 5$), an increase in γ unambiguously increases welfare, even when the fundamentals are in the intermediate range. More numerical examples show that unless β is extremely low (e.g., $\beta = 0.1$), this result always holds.

[7] See the derivation of the first-order derivation in the Appendix.



(a) Welfare and γ at $\theta + \eta = -1$. (b) Welfare and γ at $\theta + \eta = -0.5$. (c) Welfare and γ at $\theta + \eta = 0$.



(d) Welfare and γ at $\theta + \eta = 0.5$. (e) Welfare and γ at $\theta + \eta = 1$.

Figure 3: Welfare and γ.

This result differs from the one we find about the aggregate information. Recall that in the case of the aggregate information, more precise public information improves welfare only when the fundamentals are either extremely high or low. When the fundamentals are in the intermediate range, more precise public information in fact reduces welfare. Next, we examine why these two types of information affect welfare differently.

First, unlike the aggregate information case, we find that now γ affects late depositors' equilibrium switching strategy, $\rho^*(x^*)$. To rigorously examine how γ affects ρ^*, we can rewrite Eq.(29) as follows:

$$\theta + \rho^* = t\Phi\left(\sqrt{\frac{\gamma^2(\beta+\gamma)}{\beta(2\beta+\gamma)}}(\rho^* - z)\right) \tag{33}$$

The first-order derivative of the RHS w.r.t γ gives us

$$\frac{\partial RHS}{\partial \gamma} = t\phi\left(\sqrt{\frac{\gamma^2(\beta+\gamma)}{\beta(2\beta+\gamma)}}(\rho^* - z)\right)(\rho^* - z)\frac{\partial\sqrt{\frac{\gamma^2(\beta+\gamma)}{\beta(2\beta+\gamma)}}}{\partial \gamma} \tag{34}$$

where

$$\frac{\partial\sqrt{\frac{\gamma^2(\beta+\gamma)}{\beta(2\beta+\gamma)}}}{\partial\gamma} = \sqrt{\frac{\beta+\gamma}{\beta(2\beta+\gamma)}} + \gamma\frac{1}{2}(\frac{\beta+\gamma}{\beta(2\beta+\gamma)})^{-\frac{1}{2}}\frac{1}{(2\beta+\gamma)^2} > 0$$

Thus, when $\rho^* < z$, the sign of the first-order derivative is negative, and the RHS decreases in γ. When $\rho^* > z$, the sign of the first-order derivative is positive, and the RHS increases in γ. It implies that if $\rho^* < z$, then ρ^* will decrease in γ, while if $\rho^* > z$, then ρ^* will increase in γ.[8] Note that when $\rho^* = z$, they must be equal to $\frac{1}{2}t - \theta$. Because ρ^* is strictly decreasing in z, we find that when $z < \frac{1}{2}t - \theta$, $\rho^* > z$ and increases in γ. While $z > \frac{1}{2}t - \theta$, $\rho^* < z$ and decreases in γ.

Now we connect ρ^* with x^*. Recall that

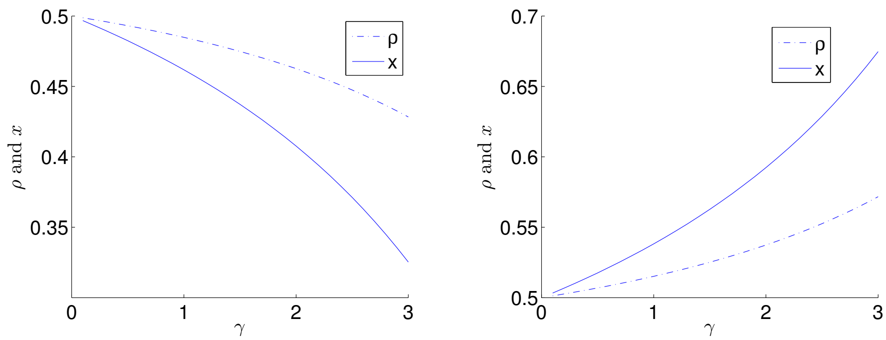
$$x^* = \frac{(\beta+\gamma)\rho^* - \gamma z}{\beta} = \rho^* + \frac{\gamma}{\beta}(\rho^* - z) \tag{35}$$

It is straightforward to see that when $\rho^* < z$, x^* decreases in γ. Thus we conclude that when $\rho^* < z$, a higher γ induces a lower ρ^* that further induces an even lower x^*. On the other hand, when $\rho^* > z$, a higher γ induces a higher ρ^* that further induces an even higher x^*.

The message we take away from the above analysis is that when the public signal is optimistic ($z > \frac{1}{2}t - \theta$), a higher precision of the signal induces a lower ρ^* and x^*, that is, a higher γ reduces early withdrawal of late depositors. However, when the public signal is pessimistic ($z < \frac{1}{2}t - \theta$), a higher precision induces a higher ρ^* and x^*, that is, a higher γ increases early withdrawal of late depositors.

Now we give some numerical examples to illustrate the above results. Specifically, we set $t = 1$, $\beta = 5$, and $\theta = 0$. Additionally, we let γ vary from 0.1 to 3. We examine two cases where $z = 0.6 > \frac{1}{2}t - \theta = 0.5$ and $z = 0.4 < \frac{1}{2}t - \theta = 0.5$. Figure 4 gives the results. It clearly shows that when $z > \frac{1}{2}t - \theta$, a higher γ induces a lower ρ^* and further a lower x^*. As γ increases, the negative gap between x^* and ρ^* becomes larger. While when $z < \frac{1}{2}t - \theta$, a higher γ induces a higher ρ^* and further a higher x^*. As γ increases, the positive gap between x^* and ρ^* becomes larger.

[8] This is because ρ^* is the solution to Eq.(29). Also the LHS of Eq.(29) is increasing in ρ^*. Thus, when $\rho^* < z$, an increase in γ induces a higher LHS of Eq.(29) and consequently a lower ρ^* to re-balance Eq.(29).



(a) How x^* and ρ^* vary in γ at $z = 0.6$. (b) How x^* and ρ^* vary in γ at $z = 0.4$.

Figure 4: How x^* and ρ^* vary in γ.

Next, we examine how γ affects the welfare through affecting x^*. Note that x^* affects the welfare through affecting l, because $l(x^*) = Prob(x < x^*) = \Phi(\sqrt{\beta}(x^* - \eta))$.

Our previous analysis shows the realised welfare is a convex function of l with the minimum value at $l^* = \frac{t+\theta+\eta}{2t}$. When $l > l^*$, the welfare is increasing in l, while when $l < l^*$, the welfare is decreasing in l. Because $0 \le l \le 1$, we find that when the fundamentals are strong ($\theta + \eta > t$), l is always below l^*, implying that the welfare is always decreasing in l. Similarly, when the fundamentals are weak ($\theta + \eta < -t$), l is always above l^*, implying that the welfare is always increasing in l. However, when $-t < \theta + \eta < t$, the welfare takes the shape of a typical convex function, which is higher when taking extreme high or low values and is lower when taking the intermediate values around l^*. Recall that γ affects x^* as follows: When $z < \frac{1}{2}t - \theta$, a higher γ induces a higher x^* and consequently a higher l. When $z > \frac{1}{2}t - \theta$, a higher γ induces a lower x^* and consequently a lower l. That is, a higher γ tends to induce either an extremely high or an extremely low value for l, which tends to induce a higher welfare level when bank fundamentals, $\theta + \eta$, are in the intermediate level. When bank fundamentals are extremely strong, η is much greater than $\frac{1}{2}t - \theta$. Because z is normally distributed with mean η, a larger γ ensures that z is greater than $\frac{1}{2}t - \theta$ with a larger probability, in which case a larger γ also induces a lower x^*, a lower l, and higher welfare. On the other hand, when bank fundamentals are extremely weak, η is much lower than $\frac{1}{2}t - \theta$. Because z is normally distributed with mean η, a larger γ ensures that z is lower than $\frac{1}{2}t - \theta$ with a larger probability, in which case a larger γ also induces a higher x^*, a higher l, and higher welfare.

Intuitively, it is not surprising to find that when the fundamentals are extremely weak or strong, a higher γ induces higher welfare. As mentioned before, in the absence of the second type of uncertainty, better information reduces the first type of uncertainty and facilitates late depositors to choose the socially optimal decision. In contrast to the case of the aggregate bank information, we find that a more precise public signal for bank-specific information can also improve welfare even when the fundamentals are in the intermediate range where the second type of uncertainty is present. Our analytical analysis shows that the key reason for this result is that more precise public information on bank-specific information facilitates late depositors to coordinate over one specific action. As a result, the proportion of the late depositors who withdraw early will take more extremely values that are close either to zero or to one. Because the welfare function is convex in the proportion of the late depositors who withdraw early, it tends to improve welfare.

3.3 Aggregate information versus bank-specific information

Now we summarise how aggregate information and bank-specific information affect late depositors' decisions and welfare.

First, we find that the precision of aggregate information does not affect depositors' equilibrium switching strategy, x^*; while the precision of bank-specific information does. This difference originates from our assumption that bank depositors have no private information about banks' aggregate information, but heterogenous private information about bank-specific information. As a result, the precision of aggregate information does not affect bank depositors' beliefs about the expected rate of return on risky assets and consequently their equilibrium switching strategy.

We find that this difference leads to vastly different welfare implications for the precision of aggregate information and bank-specific information when bank fundamentals are in the intermediate range where coordination matters. Specifically, we find that more precise aggregate banking information tends to reduce welfare, when the fundamentals induce an intermediate level of l that leads to the lowest welfare. In this case, more precise aggregate information means l is more likely to take this welfare-minimizing value, lowering the welfare. Meanwhile, we find that more precise bank-specific information tends to improve welfare. This is because more precise bank-specific information induces more late depositors either to withdraw early when the fundamentals are low or to withdraw in period 2 when the fundamentals are high. As a result, l is more likely to take extremely values that are close to either 0 or 1, which is welfare improving because the welfare function is convex in l.

Second, we find that a higher precision in both the aggregate and bank-specific information is welfare-improving when the fundamentals are either strong or weak. The intuition is straightforward. When the fundamentals are either strong or weak, depositors' strategy is determined only by the fundamentals and other depositors' actions do not matter. Thus, more precise information reduces the first type of uncertainty in the absence of the second type of uncertainty, inducing higher welfare.

A key takeaway message from our models is that welfare effects of the bank regulator's information disclosure depend crucially on the interaction of two types of uncertainty: (1) the uncertainty about bank fundamentals and (2) the strategic uncertainty about other depositors' actions. In turn, the interaction of these two types of uncertainty depends crucially on the strength of bank fundamentals as follows:

When bank fundamentals are strong, that is, when $\theta + \eta > t$, the socially optimal solution is that no late depositors withdraw at date 1, that is, $l = 0$. This socially optimal strategy can be attained when the first type of uncertainty does not exist, that is, when depositors have perfect information about $\theta + \eta$. This is because without the first type of uncertainty, the second type of uncertainty disappears as well: When late depositors know that $\theta + \eta > t$ for sure, withdrawing at date 2 is the dominant strategy for them, regardless of actions taken by other late depositors. When the first type of uncertainty does exist as in our model, more precise information on bank fundamentals will induce less late depositors to withdraw at date 1, that is, l is decreasing in the precision of the information on bank fundamentals. Thus, more precise information on bank fundamentals brings the economy closer to the socially optimal solution. In this case, less first type of uncertainty induces less coordination failure, leading to a monotonic positive relationship between the precision of information on bank fundamentals and welfare.

Similarly, when bank fundamentals are weak, that is, when $\theta + \eta < 0$, the socially optimal solution is that all the late depositors withdraw at date 1, that is, $l = 1$. Again, this socially optimal strategy can be attained when the first type of uncertainty does not exist. This is because without the first type of uncertainty, the second type of uncertainty disappears as well: When late depositors know that $\theta + \eta < 0$ for sure, withdrawing at date 1 is the dominant strategy for them, regardless of actions taken by other late depositors. When the first type of uncertainty does exist as in our model, more precise information on bank fundamentals will induce more late depositors to withdraw at date 1, that is, l is increasing in the precision of the information on bank fundamentals. Thus, more precise information on bank fundamentals brings the economy closer to the socially optimal solution. Again, less first type of uncertainty induces less coordination failure, inducing a monotonic positive relationship between the precision of information on bank fundamentals and welfare.

However, when bank fundamentals are in the intermediate range, that is, when $0 < \theta + \eta < t$, things become much more complicated. The socially optimal solution without any uncertainty will be that all the late depositors withdraw at date 2 ($l = 0$). However, this socially optimal solution may not be attained even without the first type of uncertainty, that is, even when late depositors know $\theta + \eta$ for sure, due to the second type of uncertainty. All the late depositors may choose to withdraw at date 1, simply because they believe that other late depositors will do so, which is a self-fulfilling Pareto-inferior Nash equilibrium in a coordination game with perfect information. Once we introduce the first type uncertainty as in our model, the interaction between the first and second types of uncertainty becomes even more complicated. Unlike the previous two cases where there is a monotonic relationship between l and welfare, the relationship between l and welfare is convex: Starting from $l = 0$, welfare decreases with l first until it reaches the minimum value at an intermediate value of l. Afterward, welfare increases with l until $l = 1$. The relationship between information precision and l is also complicated and non-monotonic. Due to the convex relationship between l and welfare, we find that if more precise information induces l to approach the intermediate value that yields the minimum welfare, then more precise information will worsen welfare. If more precise information induces l to take either extremely low (close to 0) or high (close to 1) values, then it will improve welfare. Depending on the specific information structure, we find that both cases could happen, that is, more precise information could increase or decrease welfare when the fundamentals are in the intermediate range.

4 Conclusions

This paper studies bank information disclosure policy in a global game setup where (1) strategic complementarities exist among bank depositors and (2) bank depositors have imperfect aggregate and bank-specific information. We examine how precision of both aggregate and bank-specific information disclosed by a bank regulator will affect welfare. We find that when bank fundamentals are either strong or weak, a higher precision of both aggregate and bank-specific information disclosed by a bank regulator will improve welfare. However, when the bank fundamentals are in an intermediate range where coordination matters, more precise aggregate information tends to reduce welfare, while more precise bank-specific information tends to improve welfare, provided that bank depositors lack private information about aggregate bank performance, but have precise private information about bank-specific performance. The key reason why more precise information could reduce welfare when the fundamentals are in the intermediate range is that although more precise information reduces the uncertainty about bank fundamentals, it may cause more severe coordination failure.

Appendix

A Derivation of the first-order derivative of EW w.r.t α

Analytically, we find that

$$\begin{aligned}\frac{\partial EW}{\partial \alpha} &= \int_{-\infty}^{\infty}(1-l(y))(\theta+\eta-tl(y)) \\ &\quad \left[\frac{1}{2}\alpha^{-1/2}\phi(\sqrt{\alpha}(y-\theta))+\sqrt{\alpha}(y-\theta)\frac{1}{2}\alpha^{-1/2}\phi'(\sqrt{\alpha}(y-\theta))\right]dy \\ &= \int_{-\infty}^{\infty}(1-l(y))(\theta+\eta-tl(y))\frac{1}{2}\alpha^{-1/2}\Big[\phi(\sqrt{\alpha}(y-\theta))+\sqrt{\alpha}(y-\theta)\phi'(\sqrt{\alpha}(y-\theta))\Big]dy\end{aligned} \tag{36}$$

B Derivation of the first-order derivative of the welfare function w.r.t γ

$$\begin{aligned}\frac{\partial W}{\partial \gamma} = \int_{-\infty}^{\infty}\Bigg\{&\left[-\frac{\partial l(z,x^*)}{\partial\gamma}(\theta+\eta-tl(z))\sqrt{\gamma}\phi(\sqrt{\gamma}(z-\eta))\right] \\ &+\left[-t\frac{\partial l(z,x^*)}{\partial\gamma}(1-l(z))\sqrt{\gamma}\phi(\sqrt{\gamma}(z-\eta))\right] \\ &+\left[\frac{1}{2}\gamma^{-\frac{1}{2}}(1-l(z))(\theta+\eta-tl(z))\phi(\sqrt{\gamma}(z-\eta))\right] \\ &+\left[(1-l(z))(\theta+\eta-tl(z))\sqrt{\gamma}\frac{1}{2}\gamma^{-\frac{1}{2}}\phi'(\sqrt{\gamma}(z-\eta))\right]\Bigg\}dz\end{aligned} \tag{37}$$

Here

$$\frac{\partial l(z,x^*)}{\partial\gamma}=\frac{\partial l(z,x^*)}{\partial\rho^*}\frac{\partial\rho^*}{\partial\gamma} \tag{38}$$

Here $\frac{\partial\rho^*}{\partial\gamma}$ is implicitly given by Eq.(29). Using the implicit function theorem, we have

$$\frac{\partial\rho^*}{\partial\gamma}=-\frac{\frac{\partial LHS}{\partial\gamma}}{\frac{\partial LHS}{\partial\rho}} \tag{39}$$

We have proved that as long as β is sufficiently higher than γ, $\frac{\partial LHS}{\partial \rho} > 0$, which is the case we confine to. Additionally, we have

$$\frac{\partial LHS}{\partial \gamma} = -t\phi\left(\sqrt{\frac{\gamma^2(\beta+\gamma)}{\beta(2\beta+\gamma)}}(\rho^* - z)\right)(\rho^* - z)\frac{\partial\sqrt{\frac{\gamma^2(\beta+\gamma)}{\beta(2\beta+\gamma)}}}{\partial \gamma} \tag{40}$$

We can prove that $\frac{\partial\sqrt{\frac{\gamma^2(\beta+\gamma)}{\beta(2\beta+\gamma)}}}{\partial \gamma} > 0$ as follows:

$$\begin{aligned} \frac{\partial\sqrt{\frac{\gamma^2(\beta+\gamma)}{\beta(2\beta+\gamma)}}}{\partial \gamma} &= \frac{[(\beta+\gamma)^{\frac{1}{2}} + \gamma\frac{1}{2}(\beta+\gamma)^{\frac{1}{2}}]\beta^{0.5}(2\beta+\gamma)^{0.5} - \gamma(\beta+\gamma)^{0.5}\beta^{0.5}\frac{1}{2}(2\beta+\gamma)^{-0.5}}{\beta(2\beta+\gamma)} \qquad (41) \\ &= \frac{\beta^{0.5}}{\beta(2\beta+\gamma)}\left\{(2\beta+\gamma)^{0.5}\left[(\beta+\gamma)^{0.5} + \frac{1}{2}\gamma(\beta+\gamma)^{-0.5} - \gamma(\beta+\gamma)^{0.5}\frac{1}{2}\frac{1}{2\beta+\gamma}\right]\right\} \\ &= \frac{\beta^{0.5}(2\beta+\gamma)^{0.5}}{\beta(2\beta+\gamma)}\left\{(\beta+\gamma)^{0.5}(1 - \frac{\gamma}{2(2\beta+\gamma)}) + \frac{1}{2}\gamma(\beta+\gamma)^{-0.5}\right\} > 0 \end{aligned}$$

Thus, the sign of $\frac{\partial LHS}{\partial \gamma}$ depends on the sign of $\rho^* - z$. When it is positive, $\frac{\partial LHS}{\partial \gamma} < 0$. While when it is negative, $\frac{\partial LHS}{\partial \gamma} > 0$. The $\frac{\partial l}{\partial \rho^*} > 0$.

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