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Luctor et emergo.

To my parents.

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Lausanne, September 13, 2021 S.J.P.L. Vissers

Abstract

This thesis examines how banks choose their optimal capital structure and cash reserves in the presence of regulatory measures.

The first chapter, titled "*Bank Capital Structure and Tail Risk*", presents a bank capital structure model in which bank assets are subject to both diffusion and tail risk. Of these two types of risk, tail risk causes uninsured deposits to be risky, as the bank's asset value can unexpectedly fall below the value of deposits in case of default. The model shows that tail risk, rather than diffusion risk, is the main driver of the risk on deposits when the bank is unregulated and of the endogenous deposit insurance premium when the bank is regulated. Keeping total volatility constant, the model shows that a high tail risk component leads to higher credit spreads, default risk, and magnitude of bank losses in default than a high diffusion risk component.

The second chapter, titled "*Bank Regulation and Market Discipline in the Presence of Risk-Taking Incentives*", presents a bank capital structure model in which equity holders can increase asset risk once debt is in place. I study the effects of capital requirements and subsidized deposit insurance on the bank's privately optimal funding and operational risk level. The model predicts that there are synergetic effects of regulation and market discipline. When the regulator sets the capital charge and deposit insurance premium payments sufficiently high for a risky portfolio, the bank commits to the low-risk asset portfolio by setting a lower leverage ratio and substituting market debt for deposits. This market discipline effect disappears when the regulatory costs become too high.

The third chapter is joint work with Mads Nielsen (Université de Lausanne) and is titled "*Dividend Restrictions and Asymmetric Information*". We develop a dynamic model of a bank whose management has superior information about the impact of a pending shock to the bank's cash holdings and can signal the bank's type through its dividend policy. Banks that will be adversely affected by the shock have incentives to pool with unaffected banks to increase their market value. To avoid being mimicked, the unaffected banks can *credibly* signal via a more aggressive payout strategy. Dividend payout restrictions have the potential to prevent a separating equilibrium from forming. This leads to the bad type adopting a more aggressive payout policy with a higher risk of default but mitigates the distortion of the good type's policy. We identify a number of scenarios where this trade-off presents an opportunity for regulatory intervention and some where it does not.

Keywords: banking; financial regulation; capital structure; liquidity management; insolvency

risk; tail risk; risk-shifting; market discipline; asymmetric information; dividend signaling.

Résumé

Cette thèse examine comment les banques choisissent leur structure de capital et leurs réserves de liquidités en présence de mesures réglementaires.

Le premier chapitre, intitulé "*Bank Capital Structure and Tail Risk*", présente un modèle qui vise à étudier la structure du capital d'une banque dont les actifs sont soumis à deux types de risque : risque de *diffusion* et risque *extrême*. Parmi ces deux types de risque, le modèle montre que c'est le risque extrême, plutôt que le risque de diffusion, qui est le principal vecteur (i) de risque sur les dépôts lorsque la banque n'est pas réglementée ; et (ii) de la prime d'assurance sur les dépôts lorsque la banque est réglementée. Cela s'explique par le fait que le risque extrême rend les actifs non assurés risqués, la valeur des actifs de la banque pouvant de manière inattendue tomber en dessous de la valeur des dépôts, et ainsi entrainer le défaut de la banque. Le modèle montre également qu'à volatilité totale constante, comparé au risque de diffusion, un risque extrême élevé génère des écarts de taux de crédit plus importants, un plus fort risque de défaut, et des pertes en cas de défaut plus importantes.

Le deuxième chapitre, intitulé "*Bank Regulation and Market Discipline in the Presence of Risk-Taking Incentives*", présente un modèle qui vise à étudier la structure du capital d'une banque dont les actionnaires peuvent augmenter le risque des actifs après avoir contracté de la dette. J'utilise ce modèle pour étudier l'impact de deux types de règlementation - les exigences en matière de fonds propres et la garantie des dépôts par l'Etat - sur le financement privé optimal des banques et leur niveau de risque opérationnel. Le modèle prédit qu'il existe des synergies entre les règlementations et la discipline de marché : Lorsque le régulateur fixe le niveau des fonds propres et le montant des primes d'assurance sur les dépôts à un niveau suffisamment élevé, la banque s'engage dans un portefeuille d'actifs à faible risque, et adopte un ratio de levier plus faible en remplaçant la dette de marché par des dépôts. Cependant, cet effet de discipline de marché disparaît lorsque les coûts réglementaires deviennent trop élevés.

Le troisième chapitre est un travail conjoint avec Mads Nielsen (Université de Lausanne) et est intitulé "*Dividend Restrictions and Asymmetric Information*". Nous développons un modèle dynamique d'une banque dont la direction dispose d'une information privée sur la réalisation possible d'un choc négatif sur ses liquidités, et qui peut signaler son *type* - *affectée* ou *non affectée* - via sa politique de dividendes. Les banques affectées par le choc sont incitées à imiter les banques non affectées pour augmenter leur valeur de marché. Afin d'éviter cela, les banques non affectées peuvent envoyer un signal crédible en adoptant une stratégie de distribution de dividendes plus agressive. Par conséquent, restreindre le versement de dividendes peut empêcher la formation d'un équilibre séparateur, conduisant la banque affectée à adopter une politique de distribution plus agressive avec un risque de défaut plus élevé, tout en atténuant la distorsion générée par la politique de la banque non affectée. Nous identifions un certain nombre de scénarios pour lesquels ce compromis présente une opportunité d'intervention réglementaire et d'autres non.

Mots-clés : secteur bancaire; régulation financière; structure du capital; gestion des liquidités; risque d'insolvabilité; risque extrême; transfert de rique; discipline de marché; asymétrie d'information; signalisation par le dividende.

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Introduction

In the aftermath of the financial crisis of 2007-2009, economists and regulators became acutely aware of the central role that banks play in the financial system and the spill-over effects that bank defaults can have on the real economy. Bank regulation has been tightened, with a particular emphasis on requiring banks to hold more equity capital. The idea of higher capital requirements is that well-capitalized banks will be able to withstand major losses on their assets without defaulting on their depositors and creditors. Next to capital regulation, payout restrictions have become an increasingly important part of the macro-prudential toolbox of regulatory authorities. Restrictions on dividend payouts and share buy-backs are aimed at maintaining adequate levels of bank capital. By increasing the loss absorption capacity of banks, regulators seek to foster the stability of the financial system and increase the resilience of banks in economic downturns allowing them to sustain the real economy.

The optimal design of banking regulation is a complex topic and a subject of ongoing debate. This thesis contributes to this discussion by studying the effects of several regulatory measures on bank stability resulting from capital structure, risk management, and liquidity management policies.

Many economists have emphasized the role of tail risk in the most recent financial crisis. Exposure to tail risk causes losses only rarely, but when those materialize, they significantly impact bank capital. An example of a tail risk exposure strategy is the underwriting of contingent liabilities on systemic risk that are callable at times of widespread distress. Acharya et al. (2009) provide an extensive exposition on how systemically important banks built up excessive tail risks on their balance sheets, ultimately resulting in a severe financial crisis that was soon transferred to the real economy and required government bailouts of unprecedented proportions.

The objective of the first chapter is to analyze the impact of tail risk on a bank's privately optimal capital and liability structure and the corresponding effects of banking regulation in the form of deposit insurance and capital requirements. Building on the work of Sundaresan and Wang (2017), I formulate a structural continuous-time model of a bank whose assets are exposed to both diffusion and tail risk. The diffusion risk component represents small and frequent changes in the asset value, whereas the tail risk component represents significant and infrequent negative jumps. These drops can be thought of as large trading losses, widespread defaults across the loan portfolio, or regulatory fines.

The model predicts that tail risk, rather than diffusion risk, is the main driver of instability in the banking sector. Keeping total volatility constant, a bank that is subject to mostly tail risk has higher credit spreads, default risk, and losses in the event of bank failure compared to a bank that is exposed to mostly diffusion risk. Furthermore, I identify a non-monotonic relationship between tail risk exposure and optimal leverage. Capital regulation can somewhat limit the risk of default. However, it can have an adverse effect on the bank's losses in default due to the higher leverage position of regulated banks coming from the higher market valuation of insured deposits and subsidized insurance premium payments. These results show that if the regulator wants to assess the likelihood and impact of bank insolvency properly, it should distinguish between tail risk and diffusion risk, as the latter has a much larger impact on bank stability.

There is a broad consensus among economists that the widespread scale of bank bailouts in the financial crisis of 2007-2009 induced by mispriced government guarantees allowed banks to take excessive risks. Examples of such government guarantees are deposit insurance and implicit too-big-to-fail subsidies. A central concern of post-crisis banking regulation is avoidance of excessive risk-taking behavior of inadequately capitalized banks. Regulators have responded to the recent financial crisis by reforming the regulatory framework and enhancing supervision, aiming to curb risk-taking incentives and improve the resilience of banks. In specific, a key objective of the Basel III regulatory framework is to improve the banks' calculations of risk-weighted assets, thereby limiting the potential for regulatory arbitrage. Furthermore, the Dodd-Frank Act implemented in 2011 introduced the Volcker Rule, which limits the risk-taking possibilities of banks directly by prohibiting them from proprietary trading. The same Act aimed to limit the significant deposit insurance premium subsidies observed in the period before the financial crisis. In specific, it required the Federal Deposit Insurance Corporation (FDIC) to redefine the deposit insurance assessment rate and revise the risk-based assessment system for all large insured depository institutions.

A complementary way for banking authorities to oversee banks is to let markets discipline financial institutions. The process of market discipline in the banking industry refers to uninsured debt holders monitoring and limiting the risk levels of banks by requiring higher risk premiums and withdrawing funds. Transparency is key for the market discipline channel to be effective. Pillar 3 of the Basel regulatory framework aims to promote market discipline by improving transparency in the complex banking industry through disclosure requirements.

Whereas many economists have underlined the importance of capital regulation and market discipline, far less is written in the literature about the interaction between the two. In the second chapter of this thesis, I explore the synergetic effects of market discipline and regulatory measures in the form of capital regulation and (mispriced) deposit insurance. I extend the model of Sundaresan and Wang (2017) by giving equity holders the possibility to reallocate investments into riskier projects once debt is issued, thereby extracting wealth from bondholders. When the bank chooses higher investment risk, this translates into a stricter capital requirement and a higher deposit insurance premium.

I distinguish three regions for the bank's investment and financing risk decisions as a function of the high-risk capital requirement and deposit insurance premium payment. When the costs associated with increased investment risk are sufficiently low, equity holders increase risk after debt has been issued. In the second region, the regulatory costs of shifting to a high-risk portfolio are sufficiently high to deter equity holders from selecting the riskier assets. However, the corresponding optimal capital structure is different from the benchmark case of a bank that cannot shift to riskier assets and guarantees that equity holders commit to the low-risk assets. In particular, the bank sets a lower leverage ratio and substitutes market debt for regulatory cost-sensitive deposits to commit to low-risk. Only when regulatory costs associated with increased investment risk become sufficiently high, equity holders do not need to select a capital structure that deviates from the benchmark case of a bank that is restricted in its investment decisions.

Hence, when regulatory costs are increased beyond the point at which they are high enough to prevent the bank from taking high investment risk, the market discipline effect becomes weaker. This corresponds to more funding risk in terms of a higher leverage ratio and increased bank losses in the event of default. This analysis demonstrates the synergetic effects of bank regulation and market discipline and suggests that the regulator should incorporate the bank's endogenous response to regulatory measures. Without doing so, the regulator underestimates the impact of regulation on the bank's investment and financing risk decisions.

In the third chapter of this thesis, I study the effects of payout restrictions, which have become a more prevalent tool for regulators. For example, Basel III introduced the counter-cyclical capital buffer and the capital conservation buffer that, when triggered, restrain banks from dividend payouts and share buy-backs. More recently, in response to the Covid-19 outbreak, the Federal Reserve and the European Central Bank imposed strict limitations on banks' distributions to shareholders to enhance bank resilience and support bank lending. However, empirical literature shows that banks use dividends as a signaling device to investors, given the opaque nature of the banking industry. The corresponding strategic behavior complicates the consequences of regulatory intervention. The trade-off between the informational value of dividend payouts and bank stability is the central topic of the third chapter co-written with Mads Nielsen.

We develop a dynamic model of a bank that controls its cash reserves by paying out dividends. Bank management has superior information about the impact of a future shock on the bank's cash reserve. One could interpret this as some banks in the economy having to accept some tail risk to bring their average earnings to a competitive level. The shock itself represents a significant trading loss, a regulatory fine, or a margin call. For simplicity, we distinguish between a good type that is unaffected by the shock and a bad type that loses a fixed amount of its cash reserves upon arrival of the shock. Absent informational asymmetries or regulatory restrictions, the good type pays out dividends at a lower cash level than the bad type, or, put differently, the good bank hoards less cash than the bad bank. In the presence of information asymmetry, the good type has an incentive to signal its type to the market by paying out more dividends and thereby get a higher market valuation. This strategic behavior results in either a separating or a pooling equilibrium. In the separating equilibrium, the good bank pays out dividends more aggressively compared to the symmetric information benchmark, whereas the bad bank adopts its first-best strategy. In the pooling equilibrium, the good type pays dividends at a higher cash level than in the separating equilibrium, making it less prone to default. In contrast, the bad bank pays out at a lower cash level in the pooling equilibrium than in the separating equilibrium, thereby becoming riskier.

Dividend restrictions have the potential to break the separating equilibrium, thereby decreasing the default risk of the good banks but increasing the default risk of the bad banks. The effect on the stability and valuation of the aggregate banking sector depends on fundamental economic factors of the shock's scope and size, and on the weight that investors put on the market valuation of the bank. We identify a number of scenarios for which payout restrictions are beneficial and some for which they are not. In particular, we show that regulation has more potential to be beneficial when the liquidity shock is large but concentrated than when it is small but widespread. Furthermore, a high degree to which investors put weight on the market valuation of the bank improves the outlook of regulation.

1 Bank Capital Structure and Tail Risk

1.1 Introduction

The financial crisis of 2008 has shown that tail risk is a key driver of default risk in banks. Acharya et al. (2009) provide an overview of how many large and complex financial institutions were under-capitalized and took excessive tail risks. In the wake of the financial crisis, avoidance of risks that banks can impose on the economy became a major concern of prudential regulation. As a result, banking regulation has been tightened, with a particular emphasis on requiring banks to hold more equity capital.

Many financial economists have emphasized the central role of tail risk in the recent financial crisis. However, to the best of my knowledge, there exists no model that analyzes the privately optimal bank capital structure and the effects of banking regulation in the form of deposit insurance and capital requirements in the presence of tail risk. The objective of this paper is to start filling this gap. To do so, I extend the work of Sundaresan and Wang (2017) and formulate a model of a bank that owns a portfolio of assets that is exposed to both diffusion risk and tail risk. The diffusion risk component represents small and frequent changes in the bank's asset value. The tail risk component represents large and infrequent negative jumps in the bank's asset value. These drops should be thought of as large losses resulting from, for example, large defaults across the bank's loan portfolio, trading losses, or fines to authorities.

The bank finances itself through a privately optimal combination of deposits, subordinated market debt, and equity. The main frictions that the bank is subject to are taxation, default costs, as well as regulatory requirements, and implicit subsidies. Furthermore, as banks have the unique feature of providing direct liquidity to depositors, it is assumed that the bank can deduct a liquidity premium from the deposit interest rate, following Gorton and Pennacchi (1990) and DeAngelo and Stulz (2015). However, the issuance of deposits comes with the risk of a costly bank run. Depositors run in this model when the bank's asset value (net of bankruptcy costs) hits or falls below the face value of deposits.

I first analyze a setting in which the bank is unregulated, and deposits are uninsured. Deposits are risky as a result of the downward jumps in the asset value dynamics. The privately optimal capital structure maximizes the bank's total value over the coupons paid on deposits and subordinated market debt. In this setting, the bank balances the liquidity premium and tax benefits from holding deposits with the risk of a costly bank run. Subordinated market debt comes with tax benefits too, but has no impact on the bank run risk.

After solving for the privately optimal capital structure of the unregulated bank, I introduce regulation and deposit insurance.[1] As a result, deposits become risk-free, and depositors no longer have an incentive to initiate a bank run. As deposit insurance comes with strict regulation, I assume that the regulator imposes capital requirements on the bank and that the regulator has the right to close the bank when it is under-capitalized. In this setup, the bank balances the benefits of issuing deposits with the risk of regulatory bank closure. The bank pays an endogenously determined premium for the deposit insurance. I allow for deposit insurance mispricing, resulting in a subsidy for the bank; see Duffie et al. (2003).

Introducing tail risk in a structural model of bank capital structure generates a number of key insights. First, tail risk rather than diffusion risk is the driver of the deposit credit spread of an unregulated bank and of the deposit insurance premium of a regulated bank. In the unregulated case, the presence of tail risk implies that the bank's asset value can unexpectedly fall below the value of deposits. This potential loss for depositors results in a positive price for deposit insurance. Surprisingly, there is a negative relation between the deposit credit spread and diffusion risk. When the bank's asset value dynamics are dominated by diffusion risk, it is likely that the default boundary is reached by diffusion, allowing depositors to run exactly at the point at which they can retrieve their full deposit value. In the regulated case, deposits are rendered safe, but equity holders pay an insurance premium, potentially subsidized by the regulator. Similar to the deposit credit spread, the deposit insurance premium is increasing in tail risk. The relation between the insurance premium and diffusion risk is ambiguous. On the one hand, more diffusion risk increases the probability of hitting the default boundary by diffusion rather than by a jump, which reduces the expected loss in default. On the other hand, when the regulator closes the bank at a threshold lower than the one at which depositors are fully reimbursed, the regulator's expected obligation to depositors in default is strictly positive. In this case, an increase of diffusion risk leads to a higher default probability and deposit insurance premium.

Second, the analysis shows that the relation between tail risk exposure and optimal leverage is non-monotonic, whereas the relation between diffusion risk and leverage is strictly negative. The high leverage ratios observed in the banking industry are generally associated with low bank asset volatility and implicit and explicit subsidies. However, the model suggests that high tail risk exposure can be hiding behind a high leverage ratio. When the size of the negative asset value jumps is very large, the bank issues more debt and accepts a high default boundary,

[1] Deposit insurance was introduced to the banking system with the aim of preventing bank runs. In the United States, deposit insurance is provided by the Federal Deposit Insurance Corporation (FDIC). The FDIC fund, which guarantees up to $250,000 of deposits, stood at $119.4 billion as of March 31, 2021, see Federal Deposit Insurance Corporation (2021).

as the actual asset value in default is likely to be significantly lower. Note that this effect is not in play for the regular diffusion risk component.

Third, the credit spreads, actuarially fair deposit insurance premium, probability of default, and magnitude of bank losses in default are higher for a bank that is primarily subject to tail risk than for a bank with the same total volatility, but that is predominantly subject to diffusion risk. These results suggest that if the regulator wants to perform a proper risk analysis of a bank, it is important to make a distinction between diffusion risk and tail risk, as the latter has a larger impact on the stability of the bank. Furthermore, the bank substitutes market debts for deposits, while the leverage ratio does not move much.

Fourth, the model predicts that bank regulation in the form of capital requirements and (mispriced) deposit insurance leads to a lower likelihood of default at the cost of higher bank losses in default. These losses in default can be limited by imposing stricter capital requirements. The effect of capital regulation on leverage is typically limited. Compared to an unregulated bank, a regulated bank enjoys deposit insurance subsidy benefits and higher liquidity premium benefits through the risk-free valuation of deposits, which increases the bank's incentives to issue deposits. On the other hand, the risk of being closed by the regulator reduces the bank's incentives to issue deposits and market debt. The overall effect of bank regulation depends on the bank's risk exposure. For low risk levels, the deposit insurance subsidy and increased liquidity premium benefits dominate the increased bankruptcy costs, and the bank leverages up. By contrast, if the bank is subject to high risk levels, the cost of being closed by the regulator outweighs the benefits of debt, and the bank will reduce its debt position.

The model presented in this paper builds on the continuous-time corporate finance models analyzing optimal capital structure. The early contributions of Merton (1974), Cox and Black (1976) and Leland (1994) assume that the bank's asset value follows a diffusion process. The paper of Kou and Wang (2003) finds closed-form solutions for the first passage time to flat boundaries for an exponential jump-diffusion process. Chen and Kou (2009) apply this jump-diffusion process to the model of Leland and Toft (1996) and find that the introduction of jumps and endogenous default has a significant impact on credit spreads and optimal capital structure decisions. In specific, they show that the presence of tail risk leads to much lower optimal leverage ratios. This is in line with the observation that many growth firms with high investment risk have rather low levels of debt.

In the banking literature, Merton (1977) and Merton (1978) use a diffusion model to study the behavior of commercial banks and determine the fair cost of deposit insurance in the presence of costly audits by the regulator. Some limitations of these models are the exogeneity of the default barrier and of both the asset value dynamics process and the capital structure, the latter which implies that there is no link between the asset and liability side of the bank. The models presented by Mella-Barral and Perraudin (1997), Bhattacharya et al. (2002), Decamps et al. (2004) extend this model by incorporating endogenous default triggered by the shareholders.

However, these papers do not address the interaction between the asset and liability structure and its implications on insolvency risk.

Froot and Stein (1998) present a two-period model to analyze the capital structure of a value-maximizing bank. They argue that it is optimal for banks to hold some capital as a buffer for illiquid risks that cannot be hedged away. Allen et al. (2015) develop a one-period general equilibrium model to study bank capital structure where deposits are a cheaper source of financing than equity because of market segmentation. Neither of those models considers subordinated market debt or the presence of bank runs.

Perotti et al. (2011) study the link between tail risk and capital regulation in a two-period model. The liability side of the bank is fixed, but the bank can choose the riskiness of its assets and its exposure to tail risk events. The authors show that a bank may wish to hold higher capital levels in the presence of tail risk, which goes against the traditional result that higher capital levels reduce risk-taking incentives.

The paper of Sundaresan and Wang (2017) extends the work of Leland (1994) by studying the optimal capital structure of banks in the presence of deposit insurance and capital requirements and serves as a building block to this paper. They show that a value-maximizing bank balances the benefits and costs of deposits and subordinated market debt so that the regulatory closure and endogenous default boundary coincide. Furthermore, their model shows that the business of taking deposits leads to higher optimal leverage. A drawback of this model is the fact that the bank's asset value follows a diffusion process. Consequently, the endogenously determined deposit insurance premium is only positive when the regulatory default threshold is lower than the threshold at which the after bankruptcy costs asset value was sufficient to repay depositors. The introduction of jumps in this paper results in a strictly positive price for deposit insurance.

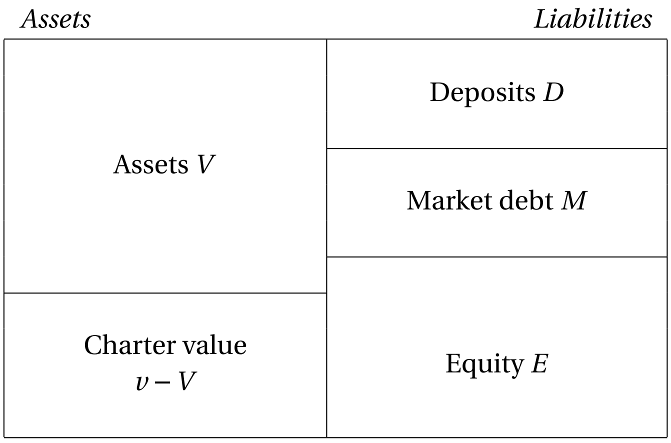
Hugonnier and Morellec (2017) present a dynamic model of banking to assess the effects of liquidity and leverage requirements on a bank's financing decisions and insolvency risk. In their model, the bank's portfolio is subject to negative jumps capturing tail risk that could lead to bank insolvency. However, there are no bank runs in this model. Gornall and Strebulaev (2018) develop a model to jointly determine the capital structure decisions of banks and their borrowers. They argue that the high leverage ratios of banks can be explained through the low asset volatility of banks. However, this paper ignores tail risk and bank runs.

The remainder of this paper is as follows. Section 1.2 presents the model assumptions and the characteristics of the bank's assets and liabilities. Section 1.3 analyzes the bank valuation and the optimal capital and liability structure of an unregulated bank. Then, Section 1.4 studies the effects of regulation, i.e., deposit insurance and capital requirements, on the bank's capital and liability structure. Section 1.5 presents the numerical analysis and comparative statics. Section 1.6 concludes.

1.2 Model

Time is continuous, and all agents are risk-neutral. I study a single bank that is held by shareholders who have limited liability and maximize shareholder value. I start the analysis by considering the policy choices of an unregulated bank. I then introduce bank regulation and examine its effects on bank capital structure and credit risk. Figure 1.1 represents the bank's balance sheet in this model.

Figure 1.1: Bank's balance sheet. This figure is a graphic representation of the balance sheet of the bank. The bank value equals $v = D + M + E$. The charter value is the difference between bank value v and physical asset value V.



1.2.1 Assets

The bank owns a portfolio of risky assets valued at V_t generating a continuous stream of cash flows δV_t that is perfectly observable by all agents. It is assumed that under the risk-neutral measure $\mathbb{Q}$, the asset value evolves according to the following jump-diffusion process:

$$\frac{dV_t}{V_t} = (r - \delta)dt + \underbrace{\sigma dW_t}_{\text{diffusion risk}} + \underbrace{d\left(\sum_{i=1}^{N_t}(Z_i - 1)\right)}_{\text{tail risk}} + \lambda\xi dt, \quad V_0 = V. \tag{1.1}$$

where $(r, \delta, \sigma, \lambda, \xi)$ are constant parameters. In these dynamics, r is the risk-free rate of interest and δ the cash flow rate of the bank. $(W_t)_{t\geq 0}$ is a standard Brownian motion under the risk-neutral measure $\mathbb{Q}$ and σ is a constant diffusion parameter. $(N_t)_{t\geq 0}$ is a Poisson process with intensity λ, so that over each time interval of length dt there is a probability λdt that a downward jump arrives. The Z_i's are i.i.d. random variables such that $Y_i := \ln(Z_i)$ follows an exponential density with (constant) intensity parameter $\eta > 0$ on the negative domain, so that its probability distribution function is given by $f(y) = \eta e^{\eta y}$, for $y \leq 0$. Lastly, ξ is defined as the mean percentage downward jump size:

$$\xi := \mathbb{E}[1 - Z] = \mathbb{E}\left[1 - e^{Y}\right] = \frac{1}{\eta + 1}.$$

This means that every time a tail risk event arrives, the asset value drops on average by a fraction ξ. The term $\lambda\xi$ compensates the drift of the bank's asset value for the negative tail risk, such that the expected return on assets equals the risk-free rate under the risk-neutral probability measure. The Brownian motion term is referred to as the continuous or diffusion risk component, and its increments represent small and frequent shocks to the bank's asset value. The Poisson process term is referred to as the discontinuous or tail risk component, and its increments represent large and infrequent negative shocks to the bank's asset value. These downward drops should be thought of as large losses, for example, caused by significant defaults across the bank's loan portfolio, large trading losses, or fines to authorities.[2,3]

1.2.2 Liabilities

The bank's capital structure consists of a privately optimal combination of deposits, subordinated market debt, and equity. The bank's liabilities are valued as contingent claims on the asset value dynamics described by Eq. (1.1). Below, the characteristics of the three types of financing are discussed.

The bank issues perpetual deposits with face value D at $t = 0$ and pays an endogenously determined coupon C_D to depositors per unit of time until default. Depositors have seniority in the event of bankruptcy. Coupon payments are deductible from taxes, where the corporate tax rate is denoted by $\theta \in (0,1)$. A liquidity premium $\pi \in (0, r)$ is deducted from the interest rate on deposits, as in Sundaresan and Wang (2017). Note that the liquidity premium increases the bank value $v = v(V)$, as the bank issues funds at a lower rate than the discount rate r. In the unregulated case, deposits are uninsured and, as a result of the downward asset value jumps, risky. Therefore, the deposit interest rate equals the risk-free rate r plus a fair credit spread s_D minus the liquidity premium π, resulting in the coupon on deposits $C_D = (r - \pi + s_D)D$. In the regulated case, deposits are insured against bank failure and can be considered safe, so that deposit credit spread $s_D = 0$. It is assumed that depositors can perfectly observe the bank's asset value and have the possibility to run. A bank run triggers default, which is costly. Notably, I consider that a fraction $\alpha > 0$ of assets and a fixed amount $K > 0$ is lost in default.[4]

[2] An example of a significant loss on the loan portfolio is the $2.8 billion loss of Lehman Brothers in the second quarter of 2008 that was caused in part by a $3.7 billion write-down on its portfolio of mortgage-related assets and leveraged loans. An example of a large trading loss is the $7 billion loss at JP Morgan in 2012 on a series of derivative transactions involving credit default swaps, which is also referred to as the *London Whale* trading scandal. An example of a significant fine to authorities is the $16.65 billion paid by Bank of America to the US authorities in 2014 for knowingly selling risky mortgages to investors.

[3] For clarity of exposition, the model assumes that the bank is only subject to downward jumps. The model can be easily generalized to the case in which the bank is subject to both positive and negative jumps with different intensities and mean jump sizes.

[4] Examples of proportional bankruptcy costs are losses from selling distressed assets, whereas filing, legal, and

Thus, when the bank defaults at time t, the total bankruptcy costs equal $\min\{V_t, \alpha V_t + K\}$. Depositors wait to run until the asset value net of bankruptcy costs is at or below the deposit face value corrected for bankruptcy costs. That is, the run level is given by $V_R = (D+K)/(1-\alpha)$. Because the bank's assets are subject to negative jumps, depositors will receive less than the face value D when the asset value jumps below V_R. In the absence of tail risk, deposits are risk-free. I denote by $\tau_R := \inf\{t : V_t \leq V_R\}$ the first time that the asset value hits or drops below the run threshold.

In addition to deposits, the bank can issue market debt. Let M and C_M denote the endogenously determined face value of market debt and the corresponding coupon, respectively. It is assumed that market debt is subordinated to deposits and market debt holders cannot run. Hence, when the bank defaults, depositors get their money first, and the remainder, if positive, goes to market debt holders. Because the lower priority protects deposits in default, long-term subordinated market debt can be considered Tier 2 capital.

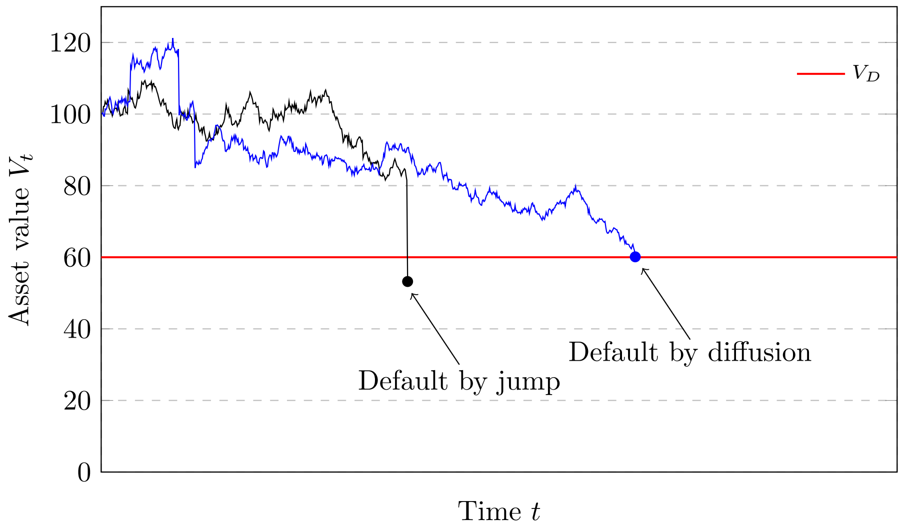
Equity holders receive all the residual value of the bank after paying the contractual obligations to depositors and market debt holders. That is, they have a claim on the difference between bank value and total debt value, $\upsilon - D - M$. Equivalently, the total dividend paid to equity holders is the difference between the asset cash flow and the total after-tax coupon payments: $\delta V - (1-\theta)(C_D + C_M)$.

At $t = 0$, the bank's shareholders choose the capital structure (C_D, C_M) that maximizes the total market value of the combined debt $(D + M)$ and equity E, which sums up to υ. Once debt is in place, equity holders have the possibility to default on their debt obligations. Following Leland (1994) and Sundaresan and Wang (2017), the bank defaults when the equity value becomes negative. Endogenous default will occur when the asset value reaches or jumps below the boundary V_B, which will be determined endogenously. Let $\tau_B := \inf\{t : V_t \leq V_B\}$ be the first time that the asset value drops below the endogenous default boundary.

The bank defaults at τ_R or τ_B, whichever happens first, so that the default time becomes $\tau = \min\{\tau_R, \tau_B\}$. Equivalently, the bank defaults as soon as the asset value reaches or drops below $V_D = \max\{V_R, V_B\}$, where $\tau := \inf\{t : V_t \leq V_D\}$. It is assumed that the initial asset value is higher than the default threshold, $V > V_D$, so that default does not occur at time zero. The tail risk component in the asset value dynamics implies that the asset value can either diffuse to the default boundary, in which case $V_\tau = V_D$, or jump below the default boundary, in which case $V_\tau < V_D$. Figure 1.2 illustrates two sample paths, of which one diffuses to the default boundary, and the other one jumps below it.

accounting fees can be considered fixed bankruptcy costs.

Figure 1.2: Default by diffusion and jump. The figure plots two sample paths of the bank's asset value dynamics V_t. Suppose $V_D = V_R$. The blue path displays the case where the asset value diffuse to the default boundary V_D, so that depositors get back all their money stored in the bank. The black path is the case where some tail risk event occurs, causing the asset value to drop below the default threshold V_D, so that depositors lose part of their money.



1.3 Unregulated bank

1.3.1 Bank valuation

I start by solving for the values of the securities issued by an unregulated bank and use these results in Section 1.3.2 to derive the bank's privately optimal capital and liability structure. First, define the following quantities:

$$p_D := \mathbb{E}\left[e^{-r\tau}\right], \quad \tilde{p}_D := V_D^{-1}\mathbb{E}\left[V_\tau e^{-r\tau}\right].$$

The quantity p_D represents the default state price, i.e., the present value of \$1 paid out in the event of default, and $\tilde{p}_D$ is the expected present value of assets in default as a fraction of the default boundary V_D. In the absence of tail risk $\tilde{p}_D = p_D$, since the asset value in default coincides with the default boundary, i.e., $V_\tau = V_D$. However, when the assets are subject to tail risk, the asset value at default V_τ can jump below default boundary V_D, which is the so-called *undershoot problem*, resulting in $\tilde{p}_D < p_D$. The derivations of p_D and $\tilde{p}_D$ can be found in Appendix A.1.1. Let $V_K := K/(1-\alpha)$ be the threshold asset value below which the bank has no remaining value in default. The following proposition presents the capital and liability structure and the corresponding default boundaries of the unregulated bank. The coefficients c_i and d_i, and exponents γ_i for $i \in \{1,2\}$ are defined in Appendix A.1.1.

Proposition 1.1. *Given a liability structure* (C_D, C_M), *the default boundary is given by* $V_D =$

$\max\{V_B, V_R\}$, *where*

$$V_B = \frac{(1-\theta)(C_D + C_M)}{r} \frac{d_1\gamma_1 + d_2\gamma_2}{1 + c_1\gamma_1 + c_2\gamma_2},$$
$$V_R = \frac{D+K}{1-\alpha}.$$

The deposit, market debt, equity, and bank value solve the following equations:

$$D = \frac{C_D(1-p_D) - rK(p_D - \tilde{p}_D)\left[(V_R/V_D)^\eta - (V_K/V_D)^\eta\right]}{(r-\pi)(1-p_D) + r(p_D - \tilde{p}_D)(V_R/V_D)^\eta}, \tag{1.2}$$

$$M = \frac{C_M}{r}\left(1-p_D\right) + (1-\alpha)V_D\tilde{p}_D - (D+K)\left[p_D - (p_D - \tilde{p}_D)\left(\frac{V_R}{V_D}\right)^\eta\right], \tag{1.3}$$

$$E = V - \frac{(1-\theta)(C_D + C_M)}{r}\left(1-p_D\right) - V_D\tilde{p}_D,$$

$$\begin{aligned} v &= D + M + E \\ &= V + \frac{\pi D + \theta(C_D + C_M)}{r}\left(1-p_D\right) - \alpha V_D\tilde{p}_D - K\left[p_D - (p_D - \tilde{p}_D)\left(\frac{V_K}{V_D}\right)^\eta\right]. \end{aligned}$$

Proof. See Appendix A.1.3. □

Eq. (1.2) gives the market value of deposits of an unregulated bank subject to tail risk. In the absence of tail risk, $p_D = \tilde{p}_D$, and the value of deposits simplifies to the risk-free deposit value $C_D/(r-\pi)$. In the presence of tail risk, $p_D > \tilde{p}_D$, which reduces the value of deposits below the risk-free value. As the asset value can drop below the run threshold V_R, deposits are risky, and the corresponding credit spread $s_D = C_D/D - (r-\pi)$ is strictly positive. In general, the expression of D is not in closed-form because of its dependence on V_R, which is a function of D. When $K = 0$, one can analytically show that Eq. (1.2) has two solutions for D, see Appendix A.1.3. In the presence of tail risk, the non-trivial solution $\tilde{D}_1$ is strictly smaller than the risk-free deposit value $C_D/(r-\pi)$. The other solution, $\tilde{D}_2 = (1-\alpha)V$, is the trivial solution where depositors withdraw immediately at $t = 0$ and can be discarded. For strictly positive values of K, numerical methods confirm the existence of a unique, non-trivial solution for D.

Eq. (1.3) gives the market value of the subordinated market debt. The first term on the right-hand side is the expected present value of the coupon payments C_M until default. The remaining terms represent the expected asset value in default that goes to subordinated market debt holders after bankruptcy costs are deducted and depositors are repaid, i.e., $\mathbb{E}\left[\max\{(1-\alpha)V_\tau - D - K, 0\}e^{-r\tau}\right]$. Note that the proceeds to market debt holders in default are zero when the bank defaults because of a bank run ($V_D = V_R \geq V_B$). By contrast, when the bank defaults because of the choice of the equity holders ($V_D = V_B \geq V_R$), market debt holders receive a positive fraction of the remaining bank value in expectation.

The market value of equity E is simply the unlevered bank value, minus the after-tax coupon payments to depositors and market debt holders until default, and minus the bank value in default. The endogenous default boundary is found by solving for the smooth pasting condition:[5]

$$\left.\frac{\partial E(V;V_B)}{\partial V}\right|_{V=V_B} = 0. \tag{1.4}$$

The bank's total market value v is the sum of the deposit, market debt, and equity market values. Equivalently, it equals the sum of unlevered bank value, expected liquidity premium on deposits, and tax benefits until default, minus expected bankruptcy costs.

1.3.2 Optimal capital and liability structure

The bank's privately optimal capital and liability structure $\left(C_D^*, C_M^*\right)$ maximizes bank value over (C_D, C_M):

$$\left(C_D^*, C_M^*\right) = \arg\max_{(C_D, C_M)} v.$$

At the optimal capital structure (C_D^*, C_M^*), the costs and benefits of deposits and subordinated market debt are perfectly balanced. Both types of debt create tax benefits and increase the endogenous default threshold optimally chosen by equity holders. The distinctive advantage of deposits over market debt is the liquidity premium π earned by the bank. The disadvantage of issuing deposits is the increased threshold for depositor initiated bank runs V_R, whereas issuing market debt leaves the bank run threshold V_R unaltered. In the optimum, the trade-off between the costs and benefits of both types of debt results in the two default boundaries to coincide, that is, $V_R^* = V_B^*$. In order for the optimal liability structure (C_D^*, C_M^*) to be unique, it is necessary that $\pi, \theta > 0$. When liquidity premium $\pi = 0$, the bank prefers to issue market debt over deposits because issuing market debt does not increase the run threshold V_R. If tax rate $\theta = 0$, the bank has no incentive to issue market debt.

To see that the optimum is obtained for $V_R^* = V_B^*$, consider the following two scenarios. When $V_R > V_B$, the bank can create value through additional tax savings by issuing additional market debt without altering the default boundary and expected bankruptcy costs. Therefore, this is a suboptimal scenario. A capital structure with $V_B > V_R$ is not optimal either, as the bank can replace some of its market debt with more profitable deposits without increasing the default boundary. The following corollary formalizes the equality of the optimal default boundaries.

Corollary 1.1. *Suppose* $0 < \pi < r$ *and* $0 < \theta < 1$. *At the optimal capital structure* (C_D^*, C_M^*) *of the unregulated bank,* $V_D^* = V_B^* = V_R^*$, *and the deposit value, market debt value, and their respective*

[5] Kyprianou and Surya (2007) formally showed that the presence of the Gaussian term in the dynamics of the asset value ($\sigma > 0$) ensures the optimality of the endogenous default boundary resulting from the smooth pasting condition.

credit spreads become:

$$D^* = \frac{C_D^*(1-p_D^*) - rK(p_D^* - \tilde{p}_D^*)\,[D^*/(D^*+K)]^\eta}{r(1-\tilde{p}_D^*) - \pi(1-p_D^*)}, \qquad M^* = \frac{C_M^*}{r}\left(1-p_D^*\right),$$
$$s_D^* = r\frac{p_D^* - \tilde{p}_D^*}{1-p_D^*}\left[1 + \frac{K}{D^*}\left(\frac{D^*}{D^*+K}\right)^\eta\right], \qquad s_M^* = r\frac{p_D^*}{1-p_D^*},$$

where $p_D^* := d_1(V_D^*/V)^{\gamma_1} + d_2\left(V_D^*/V\right)^{\gamma_2}$ *and* $\tilde{p}_D^* := c_1\left(V_D^*/V\right)^{\gamma_1} + c_2\left(V_D^*/V\right)^{\gamma_2}$.

Proof. See Appendix A.1.4. □

The difference $p_D^* - \tilde{p}_D^*$ can be considered a measure of the riskiness of deposits caused by tail risk. The larger this difference is, the higher the deposit credit spread s_D^* is and the lower the value of deposits D^*. Figure 1.3 displays the effects of the different risk parameters (ξ, λ, σ) on the optimal default state price p_D^* and on the optimal expected asset value in default divided by the default boundary $\tilde{p}_D^*$. The figure shows that the quantities $\tilde{p}_D^*$ and p_D^* are increasing in all risk parameters.[6] The difference $p_D^* - \tilde{p}_D^*$ is increasing in tail risk, but is decreasing in diffusion risk. When there is more tail risk, the expected gap between the asset value in default and the default boundary increases. However, an increase in diffusion volatility σ increases the probability of the default boundary being hit by diffusion rather than by a tail event, which reduces the expected gap between the asset value in default and the default boundary.

Upon eliminating the tail risk component by either letting jump arrival rate $\lambda \to 0$ or inverse jump size $\eta \to \infty$, the exponent $\gamma_2 \to \eta$, so that the coefficients $(c_1, d_1) \to (1,1)$ and $(c_2, d_2) \to (0,0)$. As a result, the term $p_D^* - \tilde{p}_D^* \to 0$, and the deposits become safe: $D^* \to C_D/(r-\pi)$ and $s_D^* \to 0$. By contrast, the market debt credit spread s_M^* remains strictly positive when jump risk is eliminated. Appendix A.1.2 presents the valuation of the securities at the optimal capital structure in the absence of tail risk, as based on Sundaresan and Wang (2017).

The fixed bankruptcy cost K reduces deposit value D^* and equivalently increases the credit spread on deposits s_D^*. The effects are bigger when the tail risk is more pronounced, i.e., when $p_D^* - \tilde{p}_D^*$ is large and η is small. At the optimal capital structure, the subordinated debt holders do not receive anything in default. This makes that the value of the subordinated market debt equals the present value of coupon payments until default only.

1.4 Regulated bank

1.4.1 Bank valuation

This section extends the model by introducing deposit insurance and capital requirements, following Sundaresan and Wang (2017). With full coverage deposit insurance, deposits are

[6] The qualitative results do not change for a fixed rather than optimal capital structure.

rendered safe, and depositors no longer have an incentive to initiate a bank run. Equity holders pay an endogenously determined insurance premium I to the FDIC in exchange for the deposit insurance. This increases the bank's total flow cost on deposits to $I + C_D$ and decreases the total dividend to equity holders to $\delta V - (1-\theta)(C_D + C_M) - I$.[7]

It is often argued that the deposit insurance premium paid by banks is lower than the actuarially fair premium, see Duffie et al. (2003). To allow for the possibility of subsidized deposit insurance, the actual insurance premium paid by the bank equals $I = \omega I^o$, where I^o is the fair insurance premium and $\omega \in [0,1]$ is the fraction of the fair premium paid. When $\omega = 1$, the insurance premium paid by the bank is equal to the fairly priced premium. The implications of subsidized deposit insurance on the bank's capital structure can be studied by setting $\omega < 1$.

With FDIC insurance, the bank can be closed by its charter authority when considered critically under-capitalized. The bank's total capital is the sum of Tier 1 and Tier 2 capital, which in this model equals the sum of the tangible equity value $V - D - M$ and the subordinated market debt M, and sums up to $V - D$. The regulator closes the bank when total capital drops below a fraction $e \in (0,1)$ of total asset value, that is $eV_A = V_A - D$, or alternatively, $V_A = D/(1-e) = \kappa D$, where $\kappa := 1/(1-e)$. When the bank's asset value hits either the regulatory default threshold V_A or the endogenous default threshold V_B, whichever comes first, the bank defaults, and the regulator takes over control of the bank. The regulator repays depositors from the bank's remaining assets in default and, in case that is insufficient, covers the difference from the FDIC insurance fund. The following proposition derives the value of the bank and its liabilities for any given liability structure (C_D, C_M, I). In the absence of bank runs, interpret $V_R = (D+K)/(1-\alpha)$ as the asset value at which depositors are fully reimbursed in case of default by diffusion. Let $\mathbb{1}_{\{\cdot\}}$ denote the zero-one indicator function.

Proposition 1.2. *For a given liability structure* (C_D, C_M, I), *the default boundary equals* $V_D = \max\{V_A, V_B\}$, *where:*

$$V_A = \frac{\kappa C_D}{r-\pi},$$
$$V_B = \frac{(1-\theta)(C_D + C_M) + I}{r} \frac{d_1\gamma_1 + d_2\gamma_2}{1 + c_1\gamma_1 + c_2\gamma_2}.$$

The deposit, market debt, equity, and bank value are given by:

$$D = \frac{C_D}{r-\pi},$$
$$M = \frac{C_M}{r}\left(1 - p_D\right) + \mathbb{1}_{\{V_D > V_R\}}\left((1-\alpha)V_D\tilde{p}_D - (D+K)\left[p_D - (p_D - \tilde{p}_D)\left(\frac{V_R}{V_D}\right)^{\eta}\right]\right),$$

[7] Unlike Sundaresan and Wang (2017), I assume that the banks cannot deduce their insurance premium payments from their taxes. This is in line with a US tax bill introduced on November 2, 2017, stating that banks with more than \$50 billion in consolidated assets can no longer deduct federal deposit insurance premiums payments from their taxable income. Banks with less than \$50 billion can partially deduct deposit insurance premiums payments from taxes, whereas banks with less than \$10 billion can apply a full deduction. For the complete document of this US tax bill, see http://src.bna.com/tV7.

$$\begin{aligned} E &= V - \frac{(1-\theta)(C_D + C_M) + I}{r}\left(1 - p_D\right) - V_D \tilde{p}_D, \\ v &= D + M + E \\ &= V + \frac{\pi D + \theta(C_D + C_M) + (1-\omega) I^o}{r}\left(1 - p_D\right) - \alpha V_D \tilde{p}_D - K\left[p_D - (p_D - \tilde{p}_D)\left(\frac{V_K}{V_D}\right)^{\eta}\right]. \end{aligned}$$

Proof. See Appendix A.1.5. □

Compared to the unregulated case, deposit value D is now risk-free and equal to its perpetual value. As depositors no longer have an incentive to run for their money, run threshold V_R becomes irrelevant for the default threshold V_D. Instead, the regulator closes the bank when the asset value reaches regulatory default threshold V_A. Subordinated market debt value M is derived in the same way as in the unregulated case. The introduction of the deposit insurance premium can be found in the equity valuation and the resulting endogenous default boundary. Compared to the unregulated case, total bank value v now also contains the present value of the deposit insurance subsidy benefits. That is, the total bank value is the unlevered asset value, plus the liquidity premium, tax, and deposit insurance benefits until default (second term), minus the expected value of bankruptcy costs (last two terms).

For the deposit insurance to be fairly priced, the payments received by the regulator must be equal to the expected payments to depositors in default. The fair insurance premium I^o solves the following equation:

$$\mathbb{E}\left[\int_0^{\tau} I^o e^{-rt} dt\right] = \mathbb{E}\left[\max\{D - V_\tau + \min\{V_\tau, \alpha V_\tau + K\}, 0\} e^{-r\tau}\right]. \tag{1.5}$$

The term on the left-hand side represents the present value of insurance premium payments received by the regulator until default. The term on the right-hand side reflects the present value of the regulator's obligations in default. Note that the insurance premium cannot be negative. The following proposition presents the endogenously determined fair insurance premium I^o.

Proposition 1.3. *The actuarially fair deposit insurance premium is given by:*

$$I^o = \begin{cases} r\frac{p_D}{1-p_D} D, & \text{for } V_D \le V_K, \\ r\frac{1}{1-p_D}\left[(D+K)p_D - (1-\alpha)V_D\tilde{p}_D - K(p_D - \tilde{p}_D)\left(\frac{V_K}{V_D}\right)^{\eta}\right], & \text{for } V_K < V_D \le V_R, \\ r\frac{p_D - \tilde{p}_D}{1-p_D}\left[(D+K)\left(\frac{V_R}{V_D}\right)^{\eta} - K\left(\frac{V_K}{V_D}\right)^{\eta}\right], & \text{for } V_D > V_R. \end{cases}$$

Proof. See Appendix A.1.6. □

When $V_D = V_B$, there is no closed-form solution for I^o because of its dependence on V_B, which is a function of I^o itself. In this case, one must rely on numerical techniques to jointly solve for I^o and V_B. When $V_D = V_A \leq V_R$, the regulator closes the bank at an asset value level below the level at which depositors would have run were there no deposit insurance. When $V_D = V_A > V_R$, the regulator closes the bank before the asset value at which depositors would have run. Note that when $V_D = V_R$, the fair insurance premium over the deposit face value I^o/D corresponds exactly to the deposit credit spread s_D from the unregulated case.

Whether the insurance premium per deposits I/D is higher or lower than the deposit credit spread s_D from the unregulated case for a given capital structure (C_D, C_M), depends on the parameters κ, α, K, and ω. If the regulatory closure boundary is smaller than the threshold at which depositors are fully reimbursed, $V_A < V_R$, the expected loss on deposits is larger than in the unregulated case, which pushes up the fair deposit insurance premium. The contrary is true for the case $V_A > V_R$. However, the bank benefits from the deposit insurance premium subsidies $(1-\omega)$, which reduces the cost of deposits in the regulated case. Note that while debt coupon payments are deductible from corporate taxes, it is assumed that the deposit insurance premium is not, which reduces the benefits of issuing deposits in the regulated case. The combination of these three effects determines whether the cost of deposits is higher in the unregulated or regulated case.

1.4.2 Optimal capital structure

Like the unregulated case, the privately optimal capital structure is determined by maximizing bank value v over (C_D, C_M).

Corollary 1.2. *Suppose $0 < \pi < r$ and $0 < \theta < 1$. At the optimal capital structure (C_D^*, C_M^*) of the regulated bank, $V_D^* = V_B^* \geq V_A^*$. The optimal deposit value is given by:*

$$D^* = \frac{C_D^*}{r-\pi}.$$

Consider the case of equality $V_B^* = V_A^*$ and distinguish two cases. When the default threshold is weakly smaller than the asset value of full reimbursement to depositors, $V_D^* \leq V_R^*$, the market debt value, fair insurance premium over deposits, and market debt credit spread simplify to:

$$\begin{aligned} M^* &= \frac{C_M^*}{r}(1-p_D^*), \\ I^o/D^* &= \frac{r}{1-p_D^*}\left[\frac{D^*+K}{D^*}p_D^* - (1-\alpha)\tilde{p}_D^* - \frac{K}{D^*}(p_D^* - \tilde{p}_D^*)\left(\frac{K}{\kappa(1-\alpha)D^*}\right)^{\eta}\right], \\ s_M^* &= r\frac{p_D^*}{1-p_D^*}. \end{aligned}$$

When the default threshold is strictly larger than the asset value of full reimbursement to depositors, $V_D^* > V_R^*$, the market debt value, fair insurance premium over deposits, and market *debt credit spread become:*

$$
\begin{aligned}
M^* &= \frac{C_M^*}{r}\left(1-p_D^*\right)+\kappa(1-\alpha)\tilde{p}_D^* D^* - (D^*+K)\left[p_D^* - (p_D^*-\tilde{p}_D^*)\left(\frac{1+K/D^*}{\kappa(1-\alpha)}\right)^{\eta}\right],\\
I^o/D^* &= \frac{r}{[\kappa(1-\alpha)]^{\eta}}\frac{p_D^*-\tilde{p}_D^*}{1-p_D^*}\left[\left(\frac{D^*+K}{D^*}\right)^{\eta+1}-\left(\frac{K}{D^*}\right)^{\eta+1}\right],\\
s_M^* &= \frac{rC_M^*}{C_M^*(1-p_D^*)+r\kappa(1-\alpha)D^*\tilde{p}_D^* - r(D^*+K)\left[p_D^*-(p_D^*-\tilde{p}_D^*)\left(\frac{1+K/D^*}{\kappa(1-\alpha)}\right)^{\eta}\right]} - r.
\end{aligned}
$$

Proof. See Appendix A.1.7. □

Whereas in the unregulated case, it always holds that $V_R^* = V_B^*$, the equivalent case does not always apply in the regulated case. In other words, there are parameter settings for which V_A^* and V_B^* do not coincide. To see this, consider the following. The scenario $V_A > V_B$ is always suboptimal, as the bank can increase its value by issuing additional market debt to generate additional tax benefits without increasing the default boundary. It is possible for the scenario $V_B > V_A$ to be optimal when the deposit insurance premium I is very high, thereby making deposits expensive relative to subordinated market debt. This scenario might happen when the regulator sets the capital requirement κ very low, as a small κ corresponds to higher expected obligations of the regulator in case of insolvency, leading to a higher I^o. Alternatively, a low subsidy on deposits $(1-\omega)$ reduces the benefits of issuing deposits relative to market debt. These effects are more pronounced when the bank's assets are very risky (low η, high λ, and σ). However, in the numerical analysis of this paper, the equality $V_A^* = V_B^*$ holds for all parameter values under consideration.

If the regulator sets κ such that $V_D^* \leq V_R^*$, the bank value in default goes to the regulator, and subordinated market debt holders do not receive anything. When the regulator sets κ such that $V_D^* > V_R^*$, market debt holders expect some of the bank's assets after the depositors have been repaid. The positive proceeds in default to the market debt holders are reflected by a lower market debt credit spread s_M^*.

1.5 Numerical analysis

I use numerical optimization methods to examine the predictions of the model for the bank's default risk, capital structure, and liability structure.

1.5.1 Calibration of model parameters

Table 1.1 reports the exogenous parameter values for the asset dynamics, the financial frictions and the regulatory policies. First, the current bank asset value V is set to 100. The risk-free rate r is set to 3% and payout rate δ is set to 2%. The risk parameters, σ, η and λ are based on the calibration of Chen et al. (2017). The risk parameters can be interpreted as follows: when $\lambda = 0.2$ and $\eta = 9$, on average once every 5 years a jump costs the bank 10% of its asset value.

The three main frictions that banks face when making their capital structure decision are bankruptcy costs, corporate taxes, and the liquidity premium on deposits. Fractional default costs are set to $\alpha = 20\%$ and fixed bankruptcy costs to $K = 10$, based on the estimates of James (1991). The statutory corporate income tax rate in the United States goes up to 35%. The marginal tax rate θ for banks is set to 20%, which is in line with the estimates of Heckemeyer and De Mooij (2013). The liquidity premium π represents the bank's earnings from the liquidity premium on deposits. If the banking industry were a fully competitive market, this income would be pushed to 0. However, because entrance to the banking sector is generally regulated, the banks can earn rent from providing account services. Following the estimates of Sundaresan and Wang (2017) among the largest commercial banks, the liquidity premium π is set to 0.5%.

The parameters ω and κ are linked to the deposit insurance and capital requirements, respectively. Deposit insurance pricing ω is set to 0.8. Under Basel III, the minimum capital adequacy ratio, which is defined as the sum of Tier 1 and Tier 2 capital divided by the risk-weighted asset value, is set to 8%. In addition, Basel III introduced the capital conservation buffer, which requires financial institutions to hold an additional buffer of 2.5% to withstand future periods of stress. This brings the total amount of capital a bank must hold to 10.5% of risk-weighted assets. As a baseline value, I set $\kappa = 1.1$.

1.5.2 Endogenous variables

The (privately) optimal capital and liability structure of the bank can be characterized by a set of endogenously determined variables. The first set of variables I focus on are the total bank value v and its decomposition into equity value E, deposit value D, and market debt value M. Furthermore, I define the bank's book leverage ratio L_b as the total debt value over the book value of assets, $L_b := (D+M)/V$.[8] The bank's market leverage ratio L_m is defined as the total debt value over the total market value of assets, $L_m := (D+M)/v$. The debt composition of the bank is characterized by deposits-to-debt ratio $D/(D+M)$. To analyze the risk on deposits and market debt, I analyze the credit spreads $s_D = C_D/D - (r-\pi)$ and $s_M = C_M/M - r$, respectively. In the regulated case, $s_D = 0$ and I will study the insurance premium to deposits I/D instead.

I report the endogenous default boundary V_B, the run threshold V_R (in the case of an unregulated bank) and the regulatory closure threshold V_A (in the case of a regulated bank). Furthermore, I consider the composition of the charter value $v - V$ into tax benefits $(\theta/r)(C_D + C_M)(1 - p_D)$, liquidity premium benefits $(\pi D/r)(1-p_D)$, bankruptcy costs $\mathbb{E}\left[\min\{\alpha V_\tau + K, V_\tau\} e^{-r\tau}\right]$, and in case of deposit insurance, subsidy benefits $(\omega I^o/r)(1-p_D)$.

[8] Note that in banking regulation, the leverage ratio is often defined as Tier 1 capital to book value of assets. In this model, this would correspond to $1 - L_b$.

One of the main concerns of the regulator is the effect of regulation on the bank's default probabilities and losses in default. In order to do so, one needs to find the probability of default $\mathrm{PD}_T := \mathbb{P}(\tau < T)$, which is the probability that the bank defaults within some time horizon $T \geq 0$. There exists no closed-form solution for this probability, but there is one for its Laplace transform:

$$\int_0^\infty e^{-r\tau}\mathbb{P}(\tau < T)\,dT = \frac{1}{r}\mathbb{E}\left(e^{-r\tau}\right).$$

Next, the losses in default equal the sum of the market valuations of deposits and market debt, minus the remaining asset value in default, and is as such defined by

$$\mathcal{L}_\tau = (D + M - ((1-\alpha)V_\tau - K)^+)^+.$$

To quantify the expected losses in default, consider the following probability:

$$\mathbb{P}\left(\tau < T, \mathcal{L}_\tau \geq y\right),$$

which is the joint probability that the bank defaults before time $T \geq 0$ and that losses to creditors exceed some amount $y \geq 0$. The closed-form solution for this probability is given by:

$$\int_0^\infty e^{-rT}\mathbb{P}(\tau < T, \mathcal{L}_\tau \geq y)\,dT = \frac{1}{r}\mathbb{E}\left[e^{-r\tau}\mathbb{1}_{\{\mathcal{L}_\tau \geq y\}}\right],$$

from which the T-year value-at-risk at a q% level can be derived:

$$\mathrm{VaR}_T(q) = \inf\{x \geq 0 : \mathbb{P}(\mathcal{L}_\tau \geq x \mid \tau < T) \leq q\}.$$

In the numerical applications, the 1-year 1% value-at-risk values are reported. The Gaver-Stehfest algorithm, see Stehfest (1970), is used to numerically approximate this probability and the default probability, of which a description can be found in Appendix A.1.8.

Table 1.2 displays the capital and liability structures of an unregulated and regulated bank for the baseline parameter settings from Table 1.1. There is a shift from market debt to deposits when the bank becomes regulated. As insured deposits have a higher face value than uninsured deposits for the same coupon C_D, the bank can create more liquidity premium benefits by issuing more deposits. Also, the issuance of more deposits will come with more subsidy benefits when the deposit insurance premium is subsidized ($\omega < 1$). On the other hand, the regulatory default threshold κD is increasing in deposits, which reduces the bank's incentive to issue deposits. Furthermore, note that for these parameter settings, the regulated bank has a higher leverage ratio than the unregulated bank. This can be explained by the higher liquidity premium and deposit insurance subsidy benefits that a regulated bank faces. Lastly, the 1-year default probability decreases when the bank becomes regulated. However, the 1% value-at-risk increases as well, being a result of the higher total debt position.

1.5.3 Comparative statics

In this section, I study the effects of the tail risk parameters $\xi = 1/(\eta+1)$ and λ, and diffusion risk σ, in the presence and absence of regulation on the endogenous variables discussed above. All other exogenous parameters are set to the values in Table 1.1.

Effects of risk parameters on credit spreads

Figure 1.4 displays the effects of the risk parameters on deposit credit spread s_D and market debt credit spread s_M. Deposit credit spread s_D is strictly increasing in tail risk parameters ξ and λ. This result is not surprising, as tail risk leads to a bigger discrepancy between the default threshold and the asset value in default, thereby lowering the proceeds in defaults to depositors. What might be a less intuitive result is that the relation between σ and s_D is strictly negative, implying that deposits become safer as diffusion risk increases. There are two effects at play when increasing σ. On the one hand, diffusion risk reduces the expected time to default, which has a positive effect on s_D. On the other hand, more volatility also increases the likelihood of reaching the default boundary by diffusion rather than by a tail risk event. Therefore, depositors are more likely to run exactly at the asset value at which they retrieve the full deposit value D. This reduces depositors' expected loss in default, resulting in a lower deposit credit spread. In the numerical analysis, this second effect dominates.

One can also these two effects at play in the expression of s_D^* in Corollary 1.1. Assume for simplicity that $K=0$, so that $s_D^* = r(p_D^* - \tilde{p}_D^*)/(1-p_D^*)$. When diffusion risk increases, both p_D^* and $\tilde{p}_D^*$ rise, but the difference becomes smaller, see Figure 1.3(c). This translates to the dominating negative effect σ has on s_D^*. Meanwhile, the increase in p_D^* reduces the denominator, thereby having a positive effect on s_D. This corresponds to the first effect.

In Figure 1.4, market debt credit spread s_M is strictly increasing in all risk parameters, including σ. In the unregulated case and in the regulated case provided that $V_D \leq V_R$, subordinated market debt holders do not retrieve any assets in default and the credit spread is given by $s_M^* = r p_D^*/(1-p_D^*)$, see Corollary 1.1 and 1.2. As such, an increase of any type of risk leads to a higher default state price p_D^* and credit spread s_M^*. In the scenario of a regulated bank where $V_D > V_R$, market debt holders receive, in expectation, a positive amount of proceeds in default. In this scenario, diffusion risk σ starts having a positive effect on the expected proceeds in default. However, this effect does not become dominant in the considered numerical scenarios.

Furthermore, Figure 1.4 shows that s_M decreases when the bank becomes subject to (stricter) capital requirements. Hence, the introduction of deposit insurance and capital requirements not only takes away the risk on deposits but also (slightly) reduces the risk of market debt.

Effects of risk parameters on deposit insurance premium

In the regulated case, deposits are insured, and the corresponding credit spread is 0. Instead, the bank pays (subsidized) insurance premiums to the regulator. Figure 1.5 displays the effects of the different risk parameters on the insurance premium to deposits ratio I/D for regulatory requirement levels $\kappa = 1.1$ and $\kappa = 1.25$, and for fixed bankruptcy cost $K = 10$ and $K = 0$. Figures 1.5(a) and 1.5(b) show that there is a positive link between tail risk parameters ξ and λ and deposit insurance premium I/D for all combinations of κ and K. Similar to the effect of tail risk on deposit credit spread s_D, tail risk increases the probability of the asset value in default being below the default boundary, thereby increasing the expected present value of the regulator's obligations to depositors in default, leading to a higher premium.

Figure 1.5(c) shows that the effect of diffusion risk σ on I/D can be either positive or negative, depending on κ and K. An increase in σ both reduces the expected time to default and the expected gap between the default threshold and the expected asset value in default. When the regulatory default threshold is below the threshold at which depositors would have been fully reimbursed, i.e., $\kappa D < (D+K)/(1-\alpha)$, an increase in σ generally leads to a higher deposit insurance premium. Figure 1.5(c) confirms that when κ is small and/or K is large, the relation between σ and I/D is positive. However, when κ is large and K is small, this relation reverses. Thus, the overall effect of increasing σ on the deposit insurance premium depends on the regulatory closure level κ and the fixed bankruptcy cost K.

Effects of risk parameters on leverage and debt composition

Figure 1.6 shows the relation between the risk parameters and the bank's optimal leverage ratio and debt composition for an unregulated bank, a regulated bank that is subject to capital requirement $\kappa = 1.1$, and a regulated bank with stricter capital requirement $\kappa = 1.25$. Figures 1.6(a)-1.6(c) show that the leverage ratio L_b is generally decreasing in risk, with the exception of very large values of ξ. When the bank's assets become riskier, the default state price increases. This reduces the benefits of debt, since tax, liquidity premium, and, if applicable, deposit insurance subsidy benefits are enjoyed over a shorter period. At the same time, it generally increases the costs of issuing debt through increased expected bankruptcy costs. As a result, bank value, deposit value, market debt value, and the leverage ratio are decreasing in risk.

However, as Figure 1.6(a) shows, this effect reverses for large values of average downward jump size ξ. In other words, significant tail risk exposure can be hiding behind a high leverage ratio. Note that large tail risk exposure not only increases the default state price but also reduces the expected asset value in default V_τ. In untabulated results, one can observe that the relation between default boundary V_D and average downward jump size ξ is U-shaped. When the negative jumps are very large, the bank's owners optimally decide to issue more debt, as the corresponding increase of default threshold V_D has a negligible effect on the state price of default. A second explanation for the non-monotonic pattern between tail risk and leverage is the fact that a large tail risk component lowers asset value in default V_τ and dampens the fractional bankruptcy cost component $\alpha\mathbb{E}(V_\tau e^{-r\tau})$. As a result, the bank wishes to lever up again. Note that this effect would be much stronger in the absence of the fixed bankruptcy cost component K.

For most risk parameter values into consideration, the bank slightly increases its leverage position when it becomes regulated. This is a result of the higher valuation of deposits and deposit insurance subsidies. Only for large values of ξ and σ, this relation reverses, which can be a result of the deposit insurance premiums being so high that the bank decides to abstain from issuing more deposits. One can observe that book leverage decreases in capital requirement κ. That is, when κ is increased, the default boundary becomes more sensitive to changes in deposits. As a result, the bank will issue fewer deposits.

The deposits-to-debt ratio is non-monotonic in tail risk parameter ξ. Consider the case of the unregulated bank. At first, when tail risk goes up, the bank wants to lower the costs of default and sets the capital structure such that it has a lower default threshold V_D. In order to do so, it replaces deposits with market debt. Note that a 1-to-1 substitution from C_D to C_M does not affect V_B in the unregulated case. By contrast, the bank lowering C_D results in a lower run threshold V_R. Ultimately, the bank rebalances its capital structure to balance the two thresholds. In an untabulated graph, V_D is initially decreasing in ξ. However, at some point, tail risk ξ becomes so big that the bank is willing to set its capital structure in such a way that it increases V_D. Similar to the effect of ξ on L_b, beyond some level of ξ, a further increase of tail risk does not increase the expected fractional bankruptcy costs much more. The higher default threshold V_D results in the bank substituting market debt back with deposits. Overall, this leads to a non-monotonic relation between tail risk and debt composition. Note that this relation is strictly negative for the other risk parameters, as σ and λ (for the current level of ξ) do not have the same effect on expected bankruptcy costs as ξ has.

Diffusion versus tail risk

To study the partial effects of diffusion risk σ^2 and tail risk $\sigma^2_{jump}(\eta,\lambda)$, I keep total volatility σ^2_{total} constant and look at the effects of varying the emphasis from diffusion risk to tail risk. The total variance of the assets following the dynamics in Eq. (1.1) is given by:

$$\sigma^2_{tot} = \sigma^2 + \sigma^2_{jump}(\eta,\lambda) = \sigma^2 + \frac{1}{t}Var\left[\sum_{i=1}^{N(t)}(Z_i - 1)\right] = \sigma^2 + \frac{2\lambda}{(\eta+2)(\eta+1)}.$$

Panel A of Table 1.3 displays the effects of varying diffusion risk σ and mean downward jump size ξ so that total risk is kept constant. I study three scenarios, where the ratio of tail risk to total risk is 0%, 40%, and 80%. Again, the banks into consideration are an unregulated bank, a regulated bank with $\kappa = 1.1$, and a regulated bank with $\kappa = 1.25$.

Moving from a scenario with only diffusion risk to a scenario with 80% tail risk reduces total bank value and equity value. Furthermore, a stronger tail risk component of total volatility leads to increased credit spreads and deposit insurance premiums, which confirms the earlier result that tail risk is the main driver of credit risk. When the tail risk component goes up, the market debt credit spread increases more in absolute terms than the deposit credit spread. In the case of an unregulated bank and $K = 0$, remember that $s_M^* - s_D^* = \tilde{p}_D^*/(1 - p_D^*)$. The results imply that this quantity is more sensitive to changes in tail risk than diffusion risk. Hence, for a given capital structure (C_D, C_M), the bank can collect relatively more funds from deposits than from market debt for increased levels of tail risk. As such, the bank substitutes market debt for deposits, resulting in a higher value of D and $D/(D+M)$. The book leverage ratio of the regulated bank is decreasing in the fraction of tail risk. Lastly, the 1-year default probability and 1% value-at-risk are significantly increasing when shifting from diffusion to tail risk. This shows again that tail risk, rather than diffusion risk, is the driver of default risk and the magnitude of bank losses in default.

Arrival versus impact tail risk

Panel B of Table 1.3 shows the effect of varying the jump arrival rate λ and the jump mean size ξ such that total tail risk is kept constant. Subpanel B1 represents a scenario where jumps occur rather frequently (on average once every 2.5 years) but with a relatively small average size of 7%. In Subpanel B2, jumps are expected to occur every five years with a jump size of 10%, and in Subpanel B3, this is every ten years with a jump size of 14%.

Small and frequent jumps result in lower expected losses to depositors than large and infrequent jumps. One can observe that the credit spreads s_D and s_M, and the insurance premium per deposits I/D are higher for a scenario with infrequent but big jumps than for a scenario with frequent small jumps. This observation is in line with the limiting case when there is only diffusion risk, and the resulting deposit credit spread equals zero. Furthermore, the market value of deposits and the deposits-to-debt ratio are higher for a bank subject to infrequent and big jumps. This can be explained by the fact that the deposit insurance premium and its subsidy benefits are mostly driven by tail risk, thereby creating incentives to increase deposits.

Effect of regulation

Table 1.3 also shows the effects of stricter capital requirements on the bank's capital structure characteristics. Stricter capital requirements reduce the bank's incentive to issue deposits. As a result, the bank issues fewer deposits and more market debt so that the deposit-to-debt ratio goes down. Furthermore, the 1-year default probability decreases when the bank becomes regulated and decreases even further when the capital requirement is increased. However, the 1% value-at-risk is higher for a regulated than for an unregulated bank. This is a result of the higher valuation of deposits and the corresponding higher leverage ratio observed at regulated banks. When the capital requirement is tightened, this lowers the value-at-risk and leverage position.

1.6 Conclusion

This paper presents a banking capital structure model where the assets are exposed to both diffusion and tail risk. The results show that tail risk, rather than diffusion risk, is the main driver of the credit spread of deposits in the unregulated case and of the deposit insurance premium in the regulated case. Furthermore, the model predicts that there exists a non-monotonic relation between tail risk and the privately optimal leverage ratio and between tail risk and the deposit-to-debt ratio. This suggests that a high leverage ratio can go hand-in-hand with a tail risk exposure. The analysis shows that quantities expressing the safety of the bank, such as credit spreads, default risk, value-at-risk, are high when a large fraction of total risk is composed of tail risk. Capital regulation can somewhat limit the risk of default, but it could have a counterproductive impact on the value-at-risk. These results suggest that if the regulator wants to perform a proper risk analysis of a bank, it is important to make a distinction between diffusion risk and tail risk, as the latter has a larger impact on the safety of the bank.

In this model, I have assumed that market debt is perpetual and that market debt holders do not initiate bank runs. However, one of the striking features of the recent financial crisis was the sudden market freeze for the rollover of short-term uninsured debt. The introduction of short-term market debt and the risk of bank runs could serve as an interesting extension of this model.

Tables and Figures of Chapter 1

Table 1.1: Baseline parameters values.

	Notation	Value
Initial asset value	V	100
Interest rate	r	3%
Cash flow rate	δ	2%
Diffusion volatility	σ	5%
Downward jump size	η	9
Jump arrival intensity	λ	0.2
Proportional bankruptcy costs	α	20%
Fixed bankruptcy cost	K	10
Tax rate	θ	20%
Liquidity premium	π	0.5%
Pricing deposit insurance	ω	80%
Regulatory closure	κ	1.1

Table 1.2: Privately optimal capital and liability structure characteristics of an unregulated and regulated bank. Parameter values are set according to Table 1.1.

	Notation	Unregulated bank	Regulated bank
Total value	v	118.10	120.47
Equity value	E	28.86	29.10
Deposit value	D	38.24	54.61
Market debt value	M	51.00	36.76
Book leverage ratio (%)	L_b	89.24	91.37
Market leverage ratio (%)	L_m	75.56	75.85
Deposits-to-debt ratio (%)	$D/(D+M)$	42.85	59.77
Run threshold	V_R	60.29	-
Regulatory closure	V_A	-	60.07
Endog. default threshold	V_B	60.29	60.07
Tax benefits		15.75	15.14
Liquidity premium benefits		5.44	7.79
Subsidy benefits		-	0.57
Bankruptcy loss		3.09	3.05
Deposit credit spread (bp)	s_D	4.58	-
Ins. premium-to-deposits (bp)	I/D	-	14.74
Market debt credit spread (bp)	s_M	51.13	50.43
1Y default probability (bp)		2.20	2.13
1Y 1% value-at-risk		70.30	72.60

Table 1.3: Comparison of effects risk parameters. Panel A shows the effects of increasing tail risk while keeping total volatility constant on the privately optimal capital structure characteristics of an unregulated bank, a mildly regulated bank subject to capital requirement $\kappa = 1.1$ and a strictly regulated bank subject to capital requirement $\kappa = 1.25$. Panel B shows the effects of varying the jump arrival rate and mean downward jump size such that the total risk is kept constant. The other parameters are according to Table 1.1.

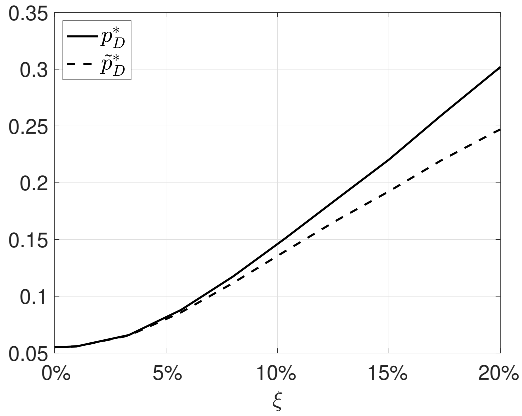
	v	E	D	M	$\frac{D}{D+M}$	L_b	L_m	V_D	s_D	I/D	s_M	PD_{1y}	VaR_{1y}
					%	%	%		bp	bp	bp	bp	
Panel A: Tail risk versus diffusion risk													
$A1 : \sigma^2_{jump}/\sigma^2_{tot} = 0 \quad (\sigma = 0.15, \xi = 0)$													
Unregulated	111.06	39.64	22.64	48.79	31.69	71.42	64.31	40.79	0.00	-	96.24	0.00	38.79
Regulated, $\kappa = 1.1$	112.72	41.31	36.35	35.05	50.91	71.40	63.35	39.99	-	29.18	92.34	0.00	39.41
Regulated, $\kappa = 1.25$	112.21	41.28	31.88	39.05	44.95	70.94	63.22	39.85	-	23.00	91.69	0.00	39.05
$A2 : \sigma^2_{jump}/\sigma^2_{tot} = 0.4 \quad (\sigma = 0.12, \xi = 0.16)$													
Unregulated	110.01	39.34	23.91	46.76	33.83	70.67	64.24	42.38	14.75	-	122.99	4.16	66.70
Regulated, $\kappa = 1.1$	111.74	40.16	37.89	33.69	52.93	71.58	64.06	41.68	-	43.77	119.39	3.82	67.80
Regulated, $\kappa = 1.25$	111.20	40.55	33.08	37.57	46.82	70.65	63.53	41.35	-	36.43	117.73	3.66	67.00
$A3 : \sigma^2_{jump}/\sigma^2_{tot} = 0.8 \quad (\sigma = 0.07, \xi = 0.24)$													
Unregulated	108.61	38.51	26.63	43.47	37.98	70.10	64.54	45.78	49.33	-	172.34	39.55	70.10
Regulated, $\kappa = 1.1$	110.20	39.35	40.90	29.95	57.72	70.85	64.29	44.99	-	73.62	168.09	37.42	70.85
Regulated, $\kappa = 1.25$	109.68	39.96	35.53	34.19	50.97	69.72	63.57	44.42	-	64.62	165.07	35.93	69.72

continuation of Table 1.3

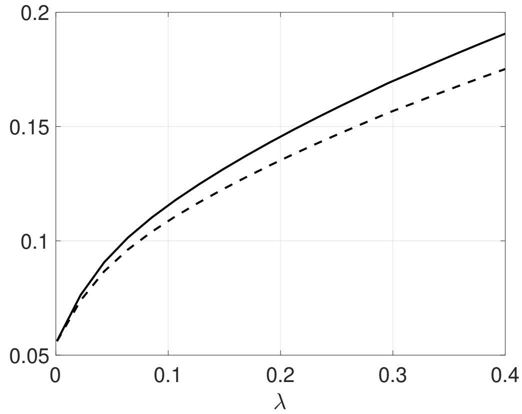
	v	E	D	M	$\frac{D}{D+M}$	L_b	L_m	V_D	s_D	I/D	s_M	PD_{1y}	VaR_{1y}
					%	%	%		bp	bp	bp	bp	
Panel B: Jump arrival rate versus jump size													
$B1: \lambda = 0.4, \xi = 0.07$													
Unregulated	118.55	28.81	37.97	51.77	42.31	89.74	75.70	59.96	2.74	-	45.87	0.34	65.80
Regulated, $\kappa = 1.1$	120.94	29.12	54.25	37.58	59.07	91.83	75.92	59.67	-	12.44	44.97	0.31	68.10
Regulated, $\kappa = 1.25$	120.00	29.37	47.55	43.08	52.46	90.63	75.52	59.43	-	9.11	44.25	0.30	67.00
$B2: \lambda = 0.2, \xi = 0.1$													
Unregulated	118.10	28.86	38.24	51.00	42.85	89.25	75.57	60.30	4.58	-	51.15	2.20	70.30
Regulated, $\kappa = 1.1$	120.47	29.16	54.56	36.75	59.75	91.31	75.80	60.01	-	14.70	50.25	2.11	72.60
Regulated, $\kappa = 1.25$	119.53	29.48	47.76	42.29	53.04	90.05	75.34	59.70	-	11.05	49.30	2.01	71.40
$B3: \lambda = 0.1, \xi = 0.14$													
Unregulated	122.03	15.89	51.78	54.36	48.79	106.14	86.98	77.22	36.56	-	75.43	47.22	106.14
Regulated, $\kappa = 1.1$	124.48	15.96	70.13	38.38	64.63	108.52	87.18	77.15	-	37.35	75.22	47.17	108.52
Regulated, $\kappa = 1.25$	123.36	16.10	61.61	45.65	57.44	107.26	86.95	77.01	-	34.17	74.86	47.10	107.26

Figure 1.3: Effects of the mean jump size $\xi = 1/(1+\eta)$, jump arrival rate λ and diffusion volatility σ on the quantities p_D^* and $\tilde{p}_D^*$ for the optimal capital structure (C_D^*, C_M^*) of an unregulated bank. The other parameters are according to Table 1.1.

(a) Effect of ξ on p_D^* and $\tilde{p}_D^*$



(b) Effect of λ on p_D^* and $\tilde{p}_D^*$



(c) Effect of σ on p_D^* and $\tilde{p}_D^*$

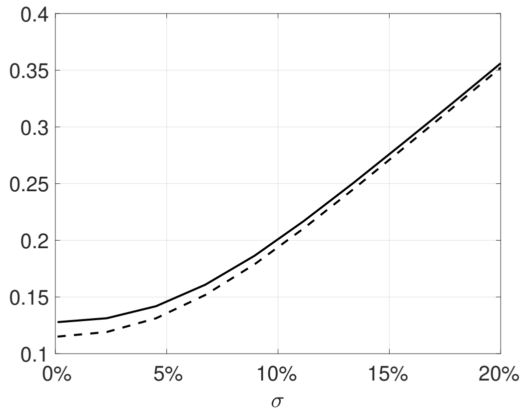


Figure 1.4: Effects of risk parameters (ξ, λ, σ) on credit spreads s_D and s_M corresponding to the bank's privately optimal capital structure. The solid black lines represent deposit credit spread s_D and the green solid lines represent market debt credit spread s_M of an unregulated bank. The dashed and dotted green lines represent s_M of a regulated bank subject to capital requirement $\kappa = 1.1$ and $\kappa = 1.25$, respectively. The other parameters are according to Table 1.1. All values are in basis points.

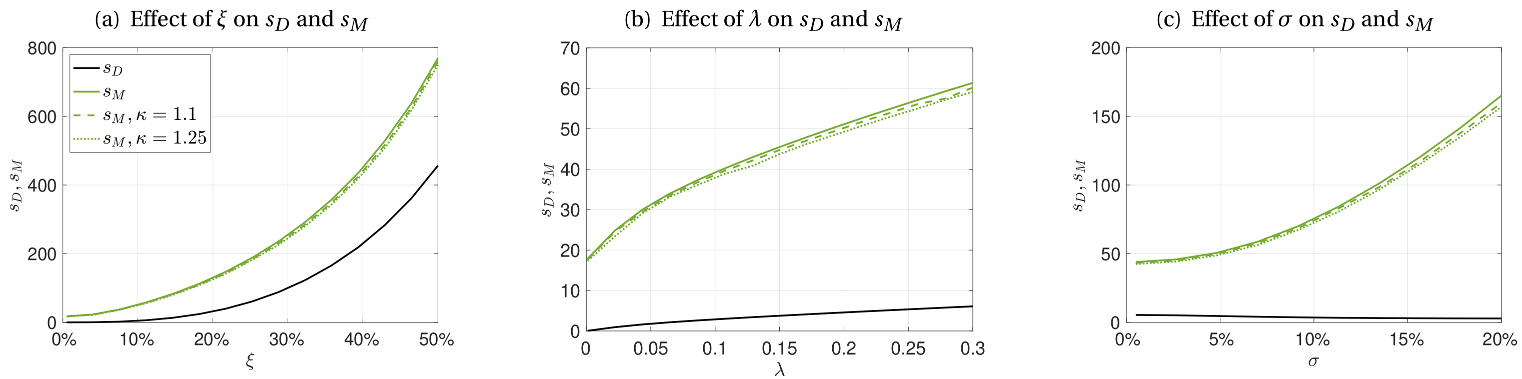
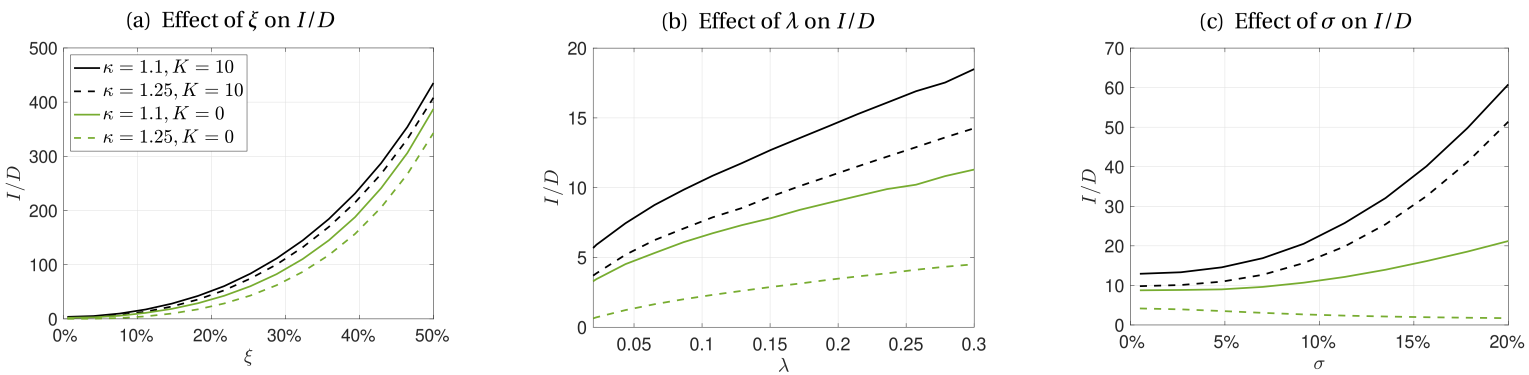


Figure 1.5: Effects of risk parameters (ξ, λ, σ) on deposit insurance premium I/D. The green lines represent the case when there are no fixed bankruptcy costs, i.e., $K = 0$. The other parameters are according to Table 1.1. All values are in basis points.



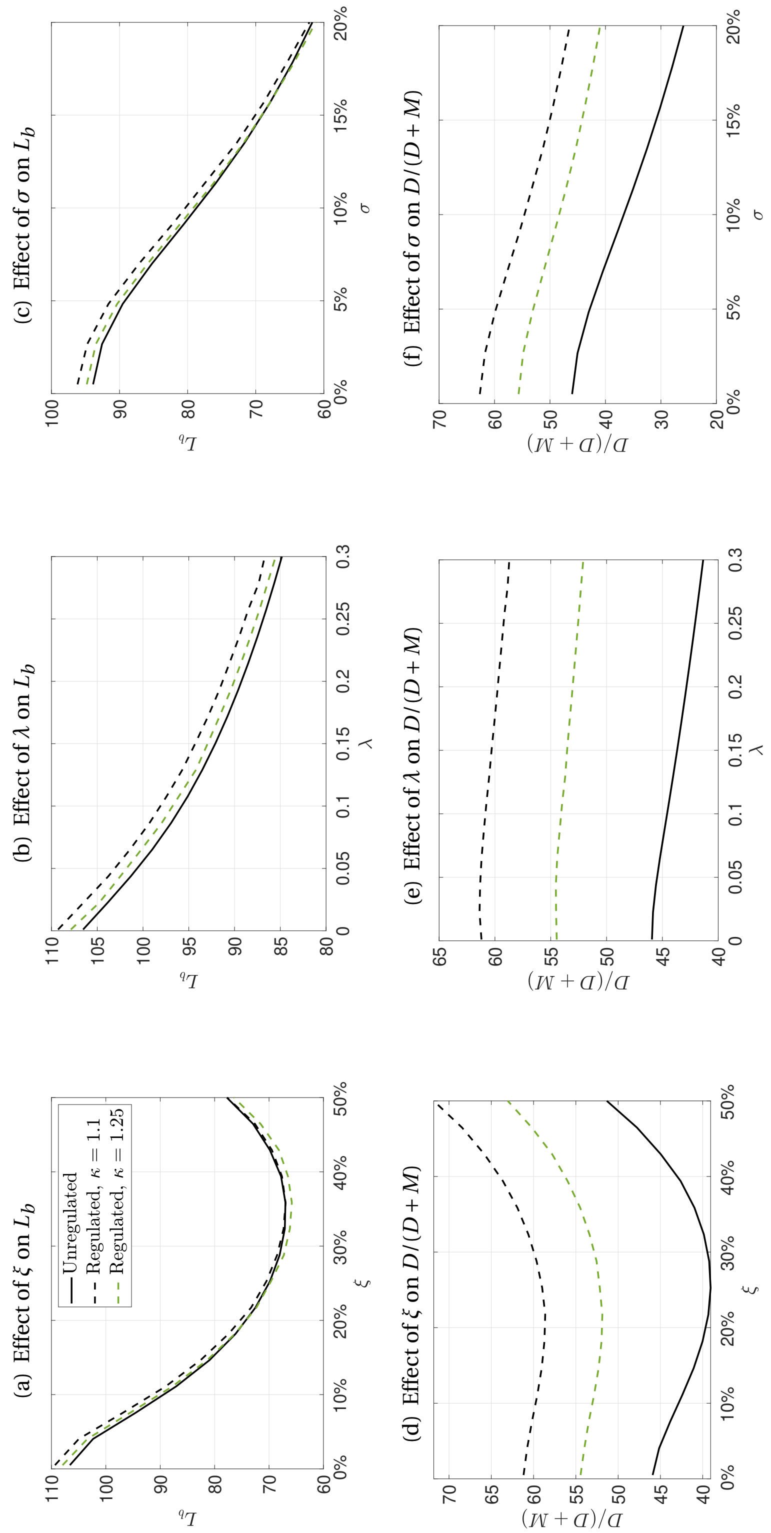


Figure 1.6: Effects of risk parameters (ξ, λ, σ) on book leverage ratio L_b and deposit-to-debt ratio $D/(D+M)$ for an unregulated and a regulated bank for $\kappa = 1.1$ and $\kappa = 1.25$. The other parameters are according to Table 1.1. All values are in percentages.

2 Bank Regulation and Market Discipline in the Presence of Risk-Taking Incentives

2.1 Introduction

There is a broad consensus that the financial crisis of 2007-2009 is to a large extent the result of excessive risk-taking by poorly capitalized banks. Avoidance of this behavior has become a central concern of post-crisis banking regulation. Regulators have responded to the crisis by reforming the regulatory framework and enhancing supervision, aiming to improve the resilience of banks and curb risk-taking incentives. A key objective of the Basel III regulatory framework is the reduction of the excessive variability of banks' calculations of risk-weighted assets observed during the recent financial crisis, see Bank for International Settlements (2017). Furthermore, the Volcker Rule that was introduced in the Dodd-Frank Act limits the risk-taking possibilities of banks directly by prohibiting banks from using their accounts for short-term proprietary trading, see Richardson et al. (2010).

A complementary way for regulatory authorities to oversee banks is to let markets do their work and discipline financial institutions. Market discipline in the banking sector refers to the process by which uninsured debt holders monitor banks' risks and limit excessive risk-taking, such as requiring higher risk premiums and withdrawing funds. This type of discipline may reduce moral hazard incentives being the result of limited liability and government guarantees, see Jensen and Meckling (1976). For the market discipline channel to be effective, transparency is key. Pillar 3 of the Basel framework seeks to promote market discipline through regulatory disclosure requirements, see Basel Committee on Banking Supervision (2018).

An additional requirement for market discipline to be effective is that debt holders must believe that they will bear the cost of a bank becoming insolvent. Implicit or explicit government guarantees weaken market discipline by reducing the investor's incentives to monitor the bank. Calomiris and Jaremski (2019) argue that the introduction of deposit insurance schemes removed market discipline that had been constraining uninsured banking institutions, which has ultimately led to a wave of banking crises over the past four decades. Underpriced deposit insurance, which can be considered a put option on the bank's assets (see Merton (1977)), can create incentives for equity holders to take excessive risk (see Kim and Santomero (1988), Penati and Protopapadakis (1988)). Empirical studies confirm this behavior and find that deposit insurance schemes with flat premiums increase the risk-taking of banks, see Ioannidou and Penas (2010). This has motivated regulators to change the design of deposit insurance schemes towards risk-based insurance premiums.[1]

Whereas many economists have underlined the importance of capital regulation and market discipline, their interaction has not received much attention. This paper focuses on the synergetic effects of market discipline and regulation on the bank's optimal funding and investment risk. To do so, I formulate a structural continuous-time model of a bank whose equity holders can reallocate investments into riskier projects after debt is issued. This results in a wealth transfer from debtholders to equity holders, since equity holders reap the benefits of successful outcomes of high-risk projects while the losses of unsuccessful outcomes are borne by debtholders. Regulation takes the form of risk-contingent capital requirements and deposit insurance. I challenge the view that stricter capital requirements always lead to safer banks. Also, I show that mispriced deposit insurance premiums can increase market discipline in the presence of subordinated market debt.

The bank faces taxation and bankruptcy costs and finances itself through deposits, subordinated market debt, and equity. I assume customers value the ready availability of bank deposits, making them an attractive source of funding, see Gorton and Pennacchi (1990). Deposits are insured by the regulator in return for an endogenously determined deposit insurance premium that depends on the bank's investment risk. I allow for deposit insurance mispricing, resulting in a subsidy for the bank; see Duffie et al. (2003). Furthermore, the bank is subject to a risk-contingent capital requirement so that the regulator can close the bank when considered under-capitalized.

The bank chooses its capital structure to maximize total bank value. Once debt is in place, equity holders choose the bank's default policy and investment risk to maximize equity value. With perpetual debt and equity holders being able to optimize their default decision, equity is a convex function of asset value, which implies that equity holders have an incentive to increase risk once debt is in place. However, when higher risk levels come at the cost of a higher capital requirement and deposit insurance premium payments, equity holders trade off the benefits and costs of risk-shifting.

The model generates a number of key insights. First, I show that if the additional regulatory costs related to the high-risk portfolio are sufficiently high, the bank's shareholders prefer to invest in the low-risk portfolio. Since the risk strategy cannot be contracted *ex-ante*, equity holders commit to the low-risk strategy by choosing a capital structure that is different from the benchmark of a bank that is restricted to invest in the low-risk portfolio. More specifically, the bank takes less risk on the liability side of the balance sheet by choosing a lower leverage position, thereby increasing equity holders' skin-in-the-game. Note that when the regulator limits investment risk directly, the bank does not need to alter its capital structure to commit to low investment risk. This allows the bank to take more funding risk in the form of a higher

[1] The Federal Deposit Insurance Corporation Improvement Act of 1991 (FDICIA) mandated the transition from a flat rate towards a risk-based deposit insurance program in 1991. The new risk-based pricing system went into effect in 1994. However, in practice, banks were not charged when the FDIC fund was considered to be well-capitalized (a reserve ratio of 1.25%). As a result, 90% of banks paid very little deposit insurance premiums in the period 1996-2006, see Acharya et al. (2009). The FDIC implemented its current risk-contingent pricing framework after the implementation of the Dodd-Frank Act in 2011. Many European countries still have deposit insurance schemes in place with flat-rate premiums, see Barkauskaite et al. (2018).

leverage ratio. As such, a higher capital charge on high-risk assets and lower subsidies on deposit insurance premium payments can lead to higher insolvency risk and larger losses in default.

The positive interaction of market discipline and bank regulation coming from the commitment constraint only takes effect when the additional regulatory costs of taking more risk are set within a certain interval. When the additional regulatory costs are too low, equity holders will not be discouraged from increasing investment risk. In contrast, when the increase in regulatory costs is too high, equity holders do not need to choose a capital structure with less funding risk than the benchmark to commit to the low-risk portfolio.

Second, the model predicts that to commit to the low-risk portfolio, the bank issues less market debt and more deposits compared to the benchmark case of a bank that is restricted to the low-risk portfolio. Deposits are the main determinant of the regulatory costs in terms of the regulatory closure threshold and deposit insurance premium. By replacing market debt with deposits, the bank can commit to the low-risk portfolio, as a shift to the high-risk portfolio would result in a significant increase in regulatory costs when deposits make up a large share of liabilities.

Third, contrary to intuition, the model shows that in the intermediate region described above, bank value is increasing in regulatory measures. In the absence of the commitment friction, the optimal bank value is decreasing in the capital requirement and the deposit insurance payments. However, when risk cannot be contracted ex-ante, the commitment friction becomes less constraining for higher regulatory costs, so that total bank value is increasing in regulatory costs.

These results imply that the regulator should incorporate the bank's endogenous response to regulatory measures. Without considering the synergetic effects of regulation and market discipline, the regulator underestimates the impact of regulation on the bank's investment and funding risk decisions.

The model presented in this paper builds on the continuous-time corporate finance models studying optimal capital structure. The early contribution of Merton (1974) shows that equity can be viewed as a call option on the firm's asset and predicts that equity value increases with the volatility of the firm's assets. This creates incentives for equity holders to increase asset risk once debt has been issued. This topic was further explored by Leland (1998), who studied the joint determination of capital structure and asset risk. From the banking literature, the model builds on the work of Sundaresan and Wang (2017). This paper extends the workhorse model of Leland (1994) by studying the optimal capital and liability structure of banks in the presence of capital requirements and subsidized deposit insurance.

There is an extensive literature on the market's ability to limit bank risk-taking behavior. An early study of Flannery and Sorescu (1996) concludes that as implicit guarantees from the government diminished through legislative changes, uninsured debt holders became more aware that they were no longer protected from potential losses and responded by pricing default risk more accurately. Evanoff et al. (2011) point out the important role of subordinated debt in the effectiveness of market discipline. Acharya et al. (2016) argue that bond credit spreads are not sensitive to risk for the largest *too big to fail* financial institutions. Recent work by Kato (2021) focused on the risk-reduction ability of market discipline through the interbank market.

The paper proceeds as follows. Section 2.2 presents the model assumptions and set-up. Section 2.3 presents the bank valuation and the optimal capital structure. Section 2.4 presents the numerical analysis and comparative statics. Lastly, Section 2.5 concludes.

2.2 Model

Time is continuous, and all agents are risk-neutral. I study a single bank that is owned by shareholders who have limited liability and maximize shareholder value. Figure 1.1 represents the bank's balance sheet.

2.2.1 Assets

The bank owns a portfolio of risky assets valued at V_t generating a continuous stream of cash flows δV_t that is perfectly observable by all agents.[2] It is assumed that under the risk-neutral measure $\mathbb{Q}$, the asset value evolves according to the following geometric Brownian motion:

$$\frac{dV_t}{V_t} = (r-\delta)dt + \sigma dW_t, \quad V_0 = V. \tag{2.1}$$

where (r, δ) are constant parameters representing the risk-free rate of interest and the cash flow rate of the bank, respectively. Furthermore, $(W_t)_{t\geq 0}$ is a standard Brownian motion under the risk-neutral measure $\mathbb{Q}$ with diffusion parameter $\sigma \in \{\sigma_H, \sigma_L\}$ with $\sigma_H > \sigma_L$, depending on the bank's selected risk level $s \in \{H, L\}$.

2.2.2 Liabilities

The bank's capital structure consists of a privately optimal combination of deposits, subordinated market debt, and equity. The bank's liabilities are contingent claims on the asset value dynamics described by Eq. (2.1). Below, the characteristics of the three types of financing are discussed.

Deposits The bank issues perpetual deposits with face value D at $t = 0$ and pays an endogenously determined coupon C_D to depositors per unit of time. Coupon payments are deductible from taxes, where the corporate tax rate is denoted by $\theta \in (0, 1)$. Following Sundaresan and Wang (2017), customers value the safety and readily availability of bank deposits and are willing to pay for this convenience. I model the liquidity premium by parameter $\pi \in (0, r)$, so that the interest rate on deposits becomes $r - \pi$. Deposits are insured by the regulator against bank failure and can thus be considered safe. As a result, bank runs do not appear in this model. In exchange for the deposit insurance, equity holders pay an endogenously determined insurance premium I. I allow for deposit insurance mispricing and assume that

[2]This is an important assumption in this model, as for market discipline to be effective, market participants must be able to monitor the risks of banks.

the bank pays a fraction $\omega \in [0,1]$ of the endogenously determined actuarially fair premium I^o, i.e., $I = \omega I^o$.

Market debt Additionally, the bank issues perpetual market debt. Let $M_s = M(V;\sigma_s)$ and C_M denote the endogenously determined face value of market debt and the corresponding coupon, respectively, for risk level $s \in \{H, L\}$. Similar to deposits, the coupon payments of market debt are tax-deductible, making the net cost of market debt coupon payments equal $(1-\theta)C_M$. Market debt holders are subordinated to depositors in case of bank failure. That is, when the bank defaults, the regulator has first claim on the bank's assets, and the remainder, if positive, goes to market debt holders. Because the lower priority protects deposits in default, perpetual subordinated market debt is considered Tier 2 capital.

Equity Equity holders receive the residual value of the bank after paying the contractual obligations to depositors, the regulator, and market debt holders, and is denoted by $E_s = E(V;\sigma_s)$. That is, the total dividend paid to equity holders is the difference between the asset cash flow and the total net coupon payments to depositors and deposit insurance premium payments to the regulator: $\delta V - (1-\theta)(C_D + C_M) - I$.

At $t = 0$, the bank's shareholders choose the capital structure $\mathcal{C} := (C_D, C_M)$ that maximizes the total market value of the bank $v_s = v(V;\sigma_s)$, which can be decomposed into deposit value D, market debt value M_s and equity value E_s. Once debt is in place, equity holders can increase the riskiness of the assets, and they have the possibility to default on their obligations. I assume that equity holders can choose between two risk levels, $s \in \{L, H\}$, where L and H stands for the low- and high-risk portfolio, respectively. Strategic default occurs when asset value hits or falls below endogenous default boundary V_B. Let $\tau_B := \inf\{t : V_t \leq V_B\}$ be the first time that the asset value drops below the endogenous default boundary.

Capital regulation and default The regulator closes the bank when the bank's total capital falls below a capital requirement. The bank's total capital is the sum of Tier 1 and Tier 2 capital, which in this model equals the sum of tangible equity value $V - D - M_s$ and subordinated market debt value M_s, and sums up to $V - D$. The regulator closes the bank when total capital drops below a fraction $e \in (0,1)$ of total asset value, that is, $eV_A = V_A - D$. Define capital requirement $\kappa := 1/(1-e)$ and rewrite the regulatory closure threshold as $V_A = \kappa D$. The level of the capital requirement depends on the bank's risk strategy, which is observed by the regulator and creditors. When the bank selects the low-risk portfolio, low capital requirement κ_L applies. In case the bank shifts to the high-risk portfolio, the regulator requires the bank to hold more capital relative to its assets, which I model by setting a higher capital requirement $\kappa_H > \kappa_L$.[3] This can be summarized as follows:

$$\kappa = \begin{cases} \kappa_L, & \text{for } \sigma = \sigma_L, \\ \kappa_H, & \text{for } \sigma = \sigma_H. \end{cases}$$

[3] In practice, all banks are subject to the same capital requirement in terms of the ratio of equity to risk-weighted assets. The assumption of two capital requirements captures the variation in risk-weights across assets.

Let $\tau_A := \inf\{t : V_t \leq V_A\}$ denote the first time that the asset value hits or drops below the regulatory closure threshold V_A. The bank defaults at τ_A or τ_B, whichever happens first, so that the default time is given by $\tau := \min\{\tau_A, \tau_B\}$. Equivalently, the bank defaults when asset value reaches or drops below $V_D := \max\{V_A, V_B\}$. I assume that a fraction $\alpha > 0$ of assets is lost in default.

2.3 Optimal investment and funding risk

This section studies the optimal capital structure and investment risk resulting from the trade-off that shareholders face between risk-shifting incentives and corresponding increased regulatory costs. The expressions for the valuation of the bank's deposits, market debt, equity, and total value as determined by Sundaresan and Wang (2017) can be found in Appendix A.2.1.

2.3.1 Optimization problem

At $t = 0$, the bank chooses its initial capital structure $\mathcal{C}$ to maximize total bank value. Once debt is in place, equity holders choose the endogenous default boundary V_B and the risk profile $\sigma \in \{\sigma_H, \sigma_L\}$ that maximizes equity value. It is assumed that the risk decision cannot be contracted *ex-ante*. These two optimization problems are entangled and can be solved in two stages. In the first-stage problem, equity holders choose endogenous default boundary V_B and risk level $\sigma \in \{\sigma_H, \sigma_L\}$ to maximize equity value for a given capital structure $\mathcal{C}$. The bank conducts the second-stage optimization to maximize bank value, as the debt holders anticipate the decisions of the equity holders once debt is in place. This can be formalized into the following optimization problem:

$$\begin{aligned} & \max_{\mathcal{C}} v(V;\sigma), && \text{(OP.1)} \\ s.t. \quad & (V_B,\sigma) = \arg\max_{(V_B,\sigma)} E(V;\sigma)|_{V=V_0}. \end{aligned}$$

The equity value in the constraint of the above optimization problem depends on the risk strategy of the bank, which I assume is known to the regulator and debt holders. Furthermore, the deposit insurance premium set by the regulator $I = \omega I^o$ takes into account the risk choice of the bank at $t = 0$. As a result, the bank's equity holders pay a higher deposit insurance premium when selecting the high-risk asset portfolio and are subject to a higher capital requirement.

Optimization problem (OP.1) can be considered a trade-off for equity holders between risk-taking benefits and the increase of the regulatory costs. Since equity can be thought of as a call option on bank's assets with a strike price equal to the bank's total debt, risk-shifting leads to a wealth transfer from debt holders to equity holders. At the same time, investing in the high-risk portfolio increases the regulatory costs, in the form of a higher capital requirement and higher deposit insurance premium payments. As a result, optimization problem (OP.1) can be decomposed in selecting the best option of the following two optimization problems:

$$\max_{\mathcal{C}} v_H, \qquad \text{(OP.1.1)}$$

$$s.t. \quad V_B = \arg\max_{V_B} E(V;\sigma_H)|_{V=V_0},$$

and,

$$\begin{aligned} &\max_{\mathcal{C}} v_L, && \text{(OP.1.2)} \\ s.t. \quad &V_B = \arg\max_{V_B} E(V;\sigma_L)|_{V=V_0}, \\ &E_L \geq E_H. \end{aligned}$$

Optimization problem (OP.1.1) finds the optimal capital structure of a bank that invests in the high-risk portfolio. In this scenario, equity holders select the endogenous default boundary corresponding to a high-risk portfolio. Sundaresan and Wang (2017) showed that a closed-form solution exists to this optimization problem, which I denote by $\mathcal{C}_H := (C^*_{D,H}, C^*_{M,H})$ and can be found in Appendix A.2.1.

Optimization problem (OP.1.2) finds the optimal capital structure of a bank that invests in the low-risk investment portfolio, but has to commit to not increasing investment risk *ex-post*. The constraint $E_L \geq E_H$ guarantees that equity holders do not find it optimal to increase asset risk once debt is in place. This implies that if equity holders want to convince the market that it will not move to a high-risk portfolio, it potentially has to deviate from its first-best optimal capital structure absent this commitment constraint. Let $\tilde{\mathcal{C}}_L := (\tilde{C}_{D,L}, \tilde{C}_{M,L})$ denote the optimal coupon values for this restricted optimization problem, for which unfortunately no closed-form solution exists.

2.3.2 Optimization problem of a restricted low-risk bank

As a benchmark case, I consider the optimal capital structure and valuation of a bank that has no access to riskier investment opportunities. I will refer to this bank as the 'restricted bank'. This limitation can result from regulatory restrictions, such as the Volcker Rule, which limits the risk-taking possibilities of banks directly by prohibiting banks from proprietary trading. The restricted bank is subject to low capital requirement κ_L and pays a deposit insurance premium corresponding to the low-risk level. The optimization problem of the restricted bank is as follows:

$$\begin{aligned} &\max_{\mathcal{C}} v_L, && \text{(OP.2)} \\ s.t. \quad &V_B = \arg\max_{V_B} E(V;\sigma_L)|_{V=V_0}. \end{aligned}$$

Denote by $\mathcal{C}^*_L := (C^*_{D,L}, C^*_{M,L})$ the capital structure that maximizes above optimization problem. Sundaresan and Wang (2017) showed that a closed-form solution exists to this problem, see Appendix A.2.1. In comparison to (OP.1), optimization problem (OP.2) does not have the commitment constraint $E_L \geq E_H$. In other words, as the restricted bank does not have the possibility to switch to the more volatile portfolio, it does not have to adjust its capital structure to do so.

2.3.3 Optimal investment risk decision

Equity holders balance the benefits of risk-shifting with the corresponding regulatory costs. If there would be no additional regulatory costs as a result of risk-taking, equity holders would always increase risk, as equity is a convex function of asset value, see Appendix A.2.2. Note that total bank value is decreasing in asset volatility.

Proposition 2.1. *In the absence of an increase in regulatory costs resulting from risk-shifting, equity value is a strictly convex function of asset value V. As a result, equity holders find it optimal to invest in a high-risk asset portfolio.*

Proof. See Appendix A.2.2. □

The incentives for equity holders to invest in the high-risk portfolio decrease when doing so comes with higher regulatory costs. The following section analyzes how the bank chooses its optimal investment risk and capital structure as a function of high-risk capital requirement κ_H and deposit pricing parameter ω.

Effects of high-risk capital requirement on investment risk choice

When the high-risk capital requirement κ_H is only marginally larger than low-risk capital requirement κ_L, it is optimal for equity holders to invest in the high-risk portfolio. However, when κ_H is substantially larger than κ_L, the cost of investing in the riskier assets becomes so large that equity holders prefer to invest in the low-risk asset portfolio. The following proposition classifies the optimal risk-taking decision as a function of κ_H into three regions.

Proposition 2.2. *Let $\mathcal{C}_H^*(\kappa_H)$, $\tilde{\mathcal{C}}_L^*(\kappa_H)$ and $\mathcal{C}_L^*(\kappa_H)$ be the optimal capital structures of optimization problem (OP.1.1), (OP.1.2) and (OP.2), respectively, as functions of κ_H. The bank's optimal risk-taking decision can be split into three regions for $\kappa_H \geq \kappa_L$:*

(i) Risk-taking: $\kappa_H \in [\kappa_L, \kappa_{H,1}^*)$,

(ii) No risk-taking, constrained: $\kappa_H \in [\kappa_{H,1}^*, \kappa_{H,2}^*)$,

(iii) No risk-taking, unconstrained: $\kappa_H \geq \kappa_{H,2}^*$,

where

$$\kappa_{H,1}^* := \begin{cases} \tilde{\kappa}_{H,1}^* = \{\kappa_H : v_H(\mathcal{C}_H^*(\kappa_H)) = v_L(\tilde{\mathcal{C}}_L^*(\kappa_H))\}, & \text{if } \exists \tilde{\kappa}_{H,1}^* > \kappa_L, \\ \kappa_L, & \text{else}, \end{cases}$$

$$\kappa_{H,2}^* := \inf\{\kappa_H : v_L(\tilde{\mathcal{C}}_L^*(\kappa_H)) = v_L(\mathcal{C}_L^*(\kappa_H))\}.$$

Proof. See Appendix A.2.3 for a formalization of the regions and parameter conditions. □

In the risk-taking region $\kappa_H \in [\kappa_L, \kappa_{H,1}^*)$, the high-risk capital requirement κ_H is low enough for the benefits of risk-shifting to exceed increased regulatory costs. As a result, equity holders choose to invest in the high-risk assets and select capital structure $\mathcal{C}_H^*$. In the next region, $\kappa_H \in [\kappa_{H,1}^*, \kappa_{H,2}^*)$, the regulatory costs of shifting to a high-risk portfolio are sufficiently high to deter the bank's equity holders from selecting the riskier assets. However, its capital structure is different from the optimal capital structure of a bank that does not have access to riskier investments, i.e., $\tilde{\mathcal{C}}_L^* \neq \mathcal{C}_L^*$. If in this region, first-best capital structure $\mathcal{C}_L^*$ is selected, equity holders would want to increase risk once debt is in place. This is anticipated by debt holders and results in a lower market price of debt. Instead, it is optimal for the bank to set the capital structure so that equity holders do not want to increase risk at the cost of debt holders anymore and get a better market price of debt instead. Later on, the numerical analysis shows that the corresponding leverage ratio is lower in this region so that equity holders have sufficient skin-in-the-game to be discouraged from risk-shifting. In the third region, $\kappa_H \geq \kappa_{H,2}^*$, the regulatory cost of increasing risk becomes so high that equity holders do no longer need to be discouraged from risk-shifting. That is, the commitment constraint $E_L \geq E_H$ in optimization problem (OP.1.2) is no longer binding in this region. As a consequence, the optimal capital structure of a bank that has access to riskier investments coincides with the optimal capital structure of a restricted bank, i.e., $\tilde{\mathcal{C}}_L^* = \mathcal{C}_L^*$.

Figure 2.1(a) gives a graphical representation of the three regions described in Proposition (2.2). It shows the optimal bank value for different values of high-risk capital requirement κ_H of (i) a bank that is restricted to take low investment risk, (ii) a bank that is restricted to take high risk, and (iii) a bank that commits to low risk. The marked red line represents the optimal value of the bank that cannot commit to low-risk investments.

The bank that can commit to the low-risk strategy has the highest total value, which is indifferent to κ_H as it is subject to low capital requirement κ_L instead. The bank with high asset risk has a lower value than the low-risk bank, and its value decreases in capital requirement κ_H. The value of a bank that commits to a low-risk strategy by setting a different capital structure starts below the value of the bank that is restricted to the low-risk investment. This is a direct result of the binding constraint on the capital structure to commit to the low-risk strategy. One can observe that as κ_H increases, total bank value goes up too, and eventually coincides with the total value of a bank that is restricted to the low-risk strategy. As the regulatory costs associated to higher investment risk increase, the benefits of taking more become smaller, so that the commitment constraint becomes less restrictive and eventually non-binding.

Effects of deposit insurance premium on investment risk choice

One can perform a similar analysis for deposit insurance pricing parameter ω. The following proposition gives a classification of the optimal investment risk decision of the bank into three regions as a function of ω.

Proposition 2.3. *Let $\mathcal{C}_H^*(\omega)$, $\tilde{\mathcal{C}}_L^*(\omega)$ and $\mathcal{C}_L^*(\omega)$ be the optimal capital structures of optimization problem (OP.1.1), (OP.1.2) and (OP.2), respectively, as functions of ω. The bank's optimal risk-taking decision can be split into three regions for $\omega \in [0,1]$:*

(i) Risk-taking: $\omega \in [0, \omega_1^*)$,

(ii) No risk-taking, constrained: $\omega \in [\omega_1^*, \omega_2^*)$,

(iii) No risk-taking, unconstrained: $\omega \in [\omega_2^*, 1]$,

where

$$\omega_1^* := \begin{cases} \tilde{\omega}_1^* = \{\omega : v_H(\mathcal{C}_H^*(\omega)) = v_L(\mathcal{C}_L^*(\omega))\}, & \text{if } \exists \tilde{\omega}_1^* > 0, \\ 0, & \text{else,} \end{cases}$$

$$\omega_2^* := \inf\{\omega : v_L(\tilde{\mathcal{C}}_L^*(\omega)) = v_L(\mathcal{C}_L^*(\omega))\}.$$

Proof. See Appendix A.2.3 for a formalization of the regions and parameter conditions. □

In the risk-taking region $\omega \in [0, \omega_1^*)$, the regulatory costs of increasing risk is outweighed by the benefits of risk-shifting to equity holders. As a result, equity holders choose to increase the riskiness of the asset portfolio. In the region $\omega \in [\omega_1^*, \omega_2^*)$, the bank does not invest in the risky assets, but commits to the low-risk assets by setting the capital structure differently from the capital structure of a bank that is restricted to investing in the low-risk assets. Similarly to the analysis of κ_H, in this region of ω, total bank value is maximized by committing to the low-risk asset portfolio and getting a better debt pricing. In the region $\omega \in [\omega_2^*, 1]$, the benefits of risk-shifting are outweighted by the corresponding additional deposit insurance premium costs. In this region, the commitment constraint is no longer binding and the bank selects the benchmark capital structure $\mathcal{C}_L^*$.

Figure 2.1(b) gives a graphical representation of the three regions of ω of (i) a bank that is restricted to take low risk, (ii) a bank that always takes high risk, and (iii) a bank that has access to high-risk investments but commits to take low risk by taking a different capital structure. A bank that is restricted to the low-risk assets has a higher total value than a bank that is restricted to take high risk. For both banks, total bank value decreases in ω, as the present value of deposit insurance subsidies decreases in ω. Similar to the case of κ_H, the value of a bank that commits to taking low-risk starts below the value of a bank that is restricted to low risk as a result of the binding commitment constraint. As ω gets larger, this constraint becomes less restrictive and eventually non-binding, causing the lines of the restricted and unrestricted low-risk banks to coincide.

2.3.4 Capital structure adjustments to commit to low investment risk

This section investigates how the bank adjusts its capital structure $\mathcal{C} = (C_D, C_M)$ in response to regulatory costs and risk-shifting possibilities. The funding risk decision of equity holders is determined by the trade-off of several effects.

Effects asset risk on equity value I first discuss the effects of risk-taking on equity value through the default state price, which is the value of a security that pays one dollar in the event of default, see Appendix A.2.1. Whereas in the benchmark case $V_B^* = V_A^*$, see Appendix A.2.1, this is generally no longer the case when the bank decides to deviate its capital structure to satisfy the commitment constraint. As such, one has to consider both cases $V_D = V_B$ and

$V_D = V_A$. Generally speaking, for small values of C_D, endogenous default boundary V_B, which is a function of C_D and C_M, dominates regulatory closure threshold V_A, which is a function of C_D only, so that $V_D = V_B > V_A$. Increasing asset risk decreases V_B, which reduces the default state price. However, the increased volatility of the asset dynamics increases the speed of reaching the default threshold. Numerical computations show that the latter effect tends to dominate so that the default state price is increasing in risk even when $V_D = V_B$. When C_D is relatively large, regulatory closure threshold V_A dominates. When equity holders choose the high-risk portfolio and become subject to high capital requirement κ_H, this increases V_A. This, together with the increased speed of reaching the default boundary, raises the default state price.

An increase of the default state price affects the equity value in several ways. A + (−) sign indicates that risk-taking increases (decreases) equity value through this channel.

+ *Present value coupon payments.* When the default state price goes up as a result of higher asset risk, the present value of coupon payments goes down, which has a positive effect on equity value.
– *Insurance premium payments.* When the default state price goes up, the insurance premium payments go up, which reduces equity value. This effect is especially relevant for large values of ω.
– *Expected loss in default.* When the default state price goes up, the present value of the loss of asset value in default goes up, which lowers equity value. When V_D goes down as a result of risk-taking, the increased volatility of the assets tends to dominate such that the lost value in default still goes up.

Having described these effects, I explore how changing coupons C_D and C_M affect the commitment constraint in optimization problem (OP.1.2).

Deviating market debt I show now that the violation of the commitment constraint can be reduced by decreasing market debt coupon C_M. Keeping C_D constant, a decrease in C_M lowers endogenous default boundary V_B but does not alter regulatory threshold V_A. As a result, the relevant default boundary remains V_A. Define the violation of the commitment constraint by $\Delta E := E_H - E_L$ and consider the following derivative:

$$\frac{\partial \Delta E}{\partial C_M} = \frac{1}{r}(1-\theta)(p_H - p_L) > 0.$$

In other words, increasing market debt coupon C_M increases the gap between E_H and E_L as a result of the reduced present value of coupon payments. Flipping it around, this means that the violation of the commitment constraint is reduced when C_M is lowered, keeping C_D constant. Hence, one way for the bank to show the market that it will not deviate to a high-risk portfolio is by issuing less market debt. To see how this effect moves with different values of κ_H, consider the following cross-derivative:

$$\frac{\partial^2 \Delta E}{\partial C_M \partial \kappa_H} = \frac{1}{r}(1-\theta)\frac{\partial p_H}{\partial \kappa_H} = \frac{1}{r}(1-\theta)\frac{\gamma_H p_H}{\kappa_H} > 0.$$

This implies that lowering C_M becomes a more effective tool to close the gap of the commitment constraint when κ_H is large. Hence, the bank has to decrease the market debt coupon C_M compared to the first-best choice $C^*_{M,L}$ by a larger extent when κ_H is small. Note that the cross derivative of ΔE with respect to C_M and ω is zero under the assumption that C_D is kept constant.

Figure 2.2(a) displays the effect of increasing C_M on the risk-taking behavior of equity holders for κ_H ranging from 1.1 to 1.3. Deposit coupon C_D is fixed at 1.2 and C_M varies from 0.4 to 2. The grey (white) area displays the combinations of coupons and regulatory costs for which the equity holders select the high (low)-risk portfolio. For small values of C_M, equity holders only choose to increase risk when κ_H is sufficiently small. Increasing risk leads to a higher deposit insurance premiums and default costs, which dominates the positive effects of risk-taking. When C_M gets larger, V_B dominates and an increase in risk leads to a lower default boundary. In this case, the positive effects of risk-taking dominate the negative effects. A similar argument applies to the choice of risk-taking as a function of ω, see Figure 2.2(c).

Deviating deposits The effects of deviating C_D from its optimal value $C^*_{D,L}$ are less clear-cut. See Appendix A.2.4 for an analysis of how C_D affects risk-taking preferences of equity holders. Unlike in the case of market debt, the derivative of ΔE can be either positive or negative. The ambiguity can by explained by the fact that like market debt, increasing deposits leads to a reduced present value of coupon payments. However, in contrast to market debt, deposits are the main determinant of regulatory costs in terms of the regulatory closure threshold V_A and deposit insurance premium I. An increase in deposits C_D, makes it more costly for equity holders to shift to the high-risk portfolio as a result of the corresponding increase in regulatory costs. This channel dominates in the determination of C_D, so that in effect the bank commits to the low-risk strategy by substituting market debt for deposits.

Figure 2.2 shows the optimal risk-taking decision of equity holders for a capital structure (C_D, C_M) and different values regulatory parameters κ_H and ω. In Figure 2.2(b), the market debt coupon C_M is fixed at 1.5 and the deposit coupon C_D varies from 1 to 3. The risk-taking region in terms of κ_H is decreasing in C_D. For small values of C_D, the negative effect of risk-taking on equity value through a higher deposit insurance premium is limited in absolute value. The positive effect of a lower present value of coupon payments dominates the negative effects, so that equity holders want to increase risk. When C_D gets larger, the insurance premium gets higher and the loss of asset value in default goes up. As a result, equity holders want to increase risk only for lower values of κ_H. A similar reasoning applies to Figure 2.2(d).

Bringing these observations together, one can conclude that the equity holders can commit to the low-risk portfolio by substituting market debt for deposits. As deposits are the primary driver of regulatory costs (in terms of the regulatory closure threshold and deposit insurance pricing), a shift towards a high-risk portfolio would significantly increase regulatory costs when deposits make up a large share of the liability side.

2.4 Numerical analysis

Closed-form solutions exist for the optimal capital structure of a bank that is either restricted to the low-risk portfolio or the high-risk portfolio, see Appendix A.2.1. For the optimization problem that includes the commitment constraint, numerical optimization methods are used to examine the model predictions for the bank's optimal capital structure and investment risk strategy.

2.4.1 Calibration of model parameters

Table 2.1 reports the exogenous parameter values for the asset dynamics, financial frictions, and regulatory policies. The asset starting value V is set to 100. The risk-free rate of interest r and the payout rate δ are set to 4% and 3%, respectively. The liquidity premium is set to $\pi = 0.5\%$ and asset volatility of the low-risk portfolio is set to $\sigma_L = 10\%$, based on estimates of Sundaresan and Wang (2017). I take $\sigma_H = 12\%$ as the baseline volatility of the high-risk assets but explore alternative values in a range between 10% and 20%. The tax rate is set to 30%, which is in line with the effective corporate tax rate for banks as found by Heckemeyer and De Mooij (2013). The proportional bankruptcy costs α is assumed to be 30%, which is in line with estimates found by James (1991).

The baseline capital requirement for a low-risk portfolio is set to $\kappa_L = 1.1$. This value corresponds to a requirement of the bank having to hold a fraction $e_L = 1 - \kappa_L^{-1} \approx 9\%$ of total capital to total asset value. The baseline value for the capital requirement of a bank selecting high investment risk is $\kappa_H = 1.12$, corresponding to a required fraction $e_H = 1 - \kappa_H^{-1} \approx 11\%$ of total capital to total asset value. In the baseline model, the bank pays $\omega = 50\%$ of the fair insurance premium to the regulator. I study the effects of κ_H and ω on the bank's funding and investment risk decisions by letting κ_H range from 1.1 to 1.3 and ω from 0 to 1.

2.4.2 Endogenous variables

The optimal capital and liability structure of the bank can be characterized by a set of endogenously determined variables as a function of choice variables $\mathcal{C} = (C_D, C_M)$ and asset risk level σ. First, I look at the composition of total bank value v_s into equity value E_s, deposit value D, and market debt value M_s. I define the book leverage ratio as the sum of deposits and market debt as a fraction of the book value of assets, i.e., $L_b := (D + M_s)/V$. The market leverage ratio is defined as total debt value as a fraction of the market value of assets, i.e., $L_m := (D + M_s)/v_s$. The deposits-to-debt ratio is given by $D/(D + M_s)$.

The bank's charter value $v_s - V$, which is the difference between bank value and asset value, can be split into the present value of the tax benefits, liquidity premium benefits, subsidy benefits, and bankruptcy costs. The insurance premium-to-deposits ratio is defined as I/D, and the market debt credit spread equals $s_D := (C_M/M_s - r) \times 100\%$. Lastly, the 1-year default probability $\mathbb{P}(\tau < 1)$ is reported, where the probability of hitting default boundary V_D within a time horizon T equals (see Ingersoll (1987)):

$$\mathbb{P}(\tau < T) = 1 - \Phi(d_1) + \left(\frac{V_D}{V}\right)^{2(r-\delta)\sigma^{-2}-1} \Phi(d_2).$$

Here, Φ denotes the cumulative distribution function of a standard normal random variable and

$$d_1 := \frac{\log(V/V_D) + (r - \delta - 0.5\sigma^2)}{\sigma\sqrt{T}}, \quad d_2 := \frac{-\log(V/V_D) + (r - \delta - 0.5\sigma^2)}{\sigma\sqrt{T}}.$$

Lastly, the loss given default is denoted by $\mathcal{L}_\tau := (D + M_s - (1-\alpha)V_D)^+$, where operator $x^+ := \max\{x, 0\}$.

Table 2.2 compares the optimal capital structure of a bank that is restricted to a low-risk strategy and a bank that invests in the high-risk asset portfolio. One can observe that total bank value goes down when the bank engages in risk-shifting. As equity holders set the risk-shifting policy *ex-post*, there is a wealth transfer from debt holders to equity holders. The bank issues fewer deposits when engaging in risk-shifting, as it is now subject to a stricter capital requirement. The coupon on market debt is slightly higher for the high-risk bank, but the value of market debt is lower as a result of the higher probability of default.

Tax benefits and liquidity premium benefits are lower for the high-risk bank since it issues less debt and is expected to default earlier. Deposit insurance subsidy benefits are slightly larger for the high-risk bank, for the actuarially fair premium is higher when the bank takes more risks, which results in more benefits when insurance is mispriced. Despite the lower default threshold, bankruptcy costs for the high-risk bank are higher because of the increased probability of default.

2.4.3 Comparative statics high-risk capital requirement

Figure 2.1(a) already showed how high-risk regulatory capital requirement κ_H affects the optimal investment risk strategy of a bank. In particular, it shows that total bank value v reaches its lowest value in high-risk region $\kappa_H < \kappa^*_{H,1}$. This is because the risk-taking strategy is chosen to maximize equity value rather than total bank value. The total bank value increases in κ_H until it overlaps with the total bank value in the absence of risk-shifting possibilities.

When $\kappa_H < \kappa^*_{H,1} \approx 1.12$, the risk-shifting benefits outweigh the additional regulatory costs resulting from the higher capital requirement. For $\kappa_H > \kappa^*_{H,1}$, equity holders do not engage in risk-shifting anymore. For $\kappa_H \in (\kappa^*_{H,1}, \kappa^*_{H,2}]$, where $\kappa^*_{H,2} \approx 1.26$, the bank invests in the low-risk portfolio, but its capital structure differs from the optimal capital structure of a restricted bank. In this region, the additional regulatory costs are sufficiently high for the bank to commit to the low-risk assets by deviating from the first-best capital structure. The closer κ_H gets to indifference point $\kappa^*_{H,2}$, the less the optimal capital structure deviates from the restricted optimal capital structure, resulting in a positive relationship between total bank value and κ_H. Lastly, for $\kappa_H > \kappa^*_{H,2}$, regulatory costs are so high that equity holders do not need to be discouraged from increasing risk anymore. As a consequence, the optimal capital structure of an unrestricted and restricted bank coincide.

Figure 2.3 takes a closer look at the effects of increasing high-risk regulatory capital requirement κ_H on a number of characteristics related to the bank's capital structure. The low-risk capital requirement κ_L is set to 1.1, and the high-risk capital requirement κ_H varies from 1.1 to 1.3. The solid line represents the optimal capital structure characteristics in the presence of risk-shifting possibilities, and the dashed line represents the benchmark case of a bank that has no access to riskier investments.

Figure 2.3(a) presents the book leverage ratio L_b as a function of κ_H. The leverage ratio of a risk-taking bank is lower than that of a restricted bank. This is because the increased riskiness of the bank leads to higher deposit insurance premium payments and a higher market debt credit spread. Furthermore, in the region $\kappa_H \leq \kappa^*_{H,1}$, the leverage ratio is slightly decreasing in κ_H. When $\kappa_H > \kappa^*_{H,1}$, the bank commits to a low funding risk strategy by choosing a lower leverage ratio. When κ_H increases, the leverage ratio increases until it reaches the point at $\kappa_H = \kappa^*_{H,2}$ where it coincides with the capital structure of a restricted bank. This figure shows that increasing the high-risk capital requirement does not lead to a lower leverage ratio. It follows that if the regulator wants to limit both investment risk and funding risk in terms of leverage, it should not put direct restrictions on the bank's investment projects, as by doing so, the market discipline effect disappears. Furthermore, the regulator should put the capital requirement high enough so that it is suboptimal for the bank to increase risk but low enough that the market discipline channel is effective.

The effects of changing κ_H on the deposits-to-debt ratio can be observed in Figure 2.3(b). In the risk-shifting area, the deposits-to-debt ratio is lower than in the case of a restricted bank. As in this region, the bank is subject to high capital requirement κ_H, regulatory closure threshold $V_A = \kappa_H D$ becomes more sensitive to changes in D. To limit the increase in V_A, the bank issues fewer deposits in the risk-taking region. In the constrained risk-taking region, the deposit-to-debt ratio jumps up and is higher than for a restricted bank. One can also see in Figure 2.3(f) that there is a large drop in the issuance of market debt. These observations are in line with the result of Section 2.3.4 that substituting market debt by regulatory-sensitive deposits reduces risk-taking incentives.

Figure 2.3(c) displays the 1-year default probability. One can observe that increasing the capital requirement κ_H is not a guarantee that the default probability will decrease. Around the point $\kappa^*_{H,1}$, the default probability decreases as the bank switches to the low-risk portfolio. However, as κ_H further increases, the default probability initially does but eventually decreases to the level of the restricted low-risk bank. There is a clear link with the deposits coupon choice in Figure 2.3(e) which also shows a non-monotonic pattern. This is a result of the ambiguous effect of deposits on risk-taking incentives, as was discussed in Section 2.3.4. On the one hand, deposits increase risk-taking incentives in a similar way to market debt by the potential of a wealth transfer from debt holders to equity holders due to the convex payoff structure. On the other hand, deposits are the main drivers of regulatory costs, making them a device to commit to low-risk. As a result, loosening the commitment constraint by increasing κ_H leads to a positive relationship between C_D and κ_H at first, but later revers.

Figure 2.3(d) shows how the high-risk capital requirement κ_H affects the loss given default. The pattern looks similar to the leverage ratio in Figure 2.3(a). In the high-risk region, the loss given default is relatively high, albeit lower than of the benchmark bank, being the result of the relatively low leverage position. When market discipline becomes active, and the leverage ratio drops, this also leads to a drop of the loss given default. The losses in default start increasing when the market discipline weakens as a result of a stricter κ_H.

The results imply that the regulator should incorporate the bank's endogenous response to stricter capital requirements. For sufficiently large κ_H, the bank refrains from taking high investment risk. However, increasing κ_H further reduces the market discipline channel that curbs the bank's leverage position. One could argue that if the regulator wants to make the bank as safe as possible, it should set κ_H very large. However, the losses in default in the corresponding region are larger than where market discipline is active.

2.4.4 Comparative statics deposit insurance premium

One can do a similar analysis for deposit insurance pricing parameter ω. Figure 2.1(b) shows that the total value of a bank that can invest in riskier projects is smaller or equal to the value of a bank that has no risk-shifting possibilities. The deposit insurance is fully subsidized by the regulator when $\omega = 0$, whereas it is fully financed by the bank's equity holders when $\omega = 1$.

One can distinguish the three regions that are described in Section 2.3.3. For $\omega < \omega_1^* \approx 0.2$, the bank's equity holders increase asset risk once debt is in place. In this region, the benefits of risk-shifting outweigh the additional regulatory costs coming from the higher deposit insurance premium. Furthermore, when ω decreases in this region, the present value of subsidy benefits goes down, resulting in a reduction of bank value. For $\omega \in [\omega_1^*, \omega_2^*)$, where $\omega_2^* \approx 0.84$, the bank does not increase its risk once debt is in place, but its capital structure is different from the optimal capital structure of a bank that has no risk-taking possibilities. In this region of ω, the value-maximizing strategy is to commit to the low-risk asset portfolio by setting its capital structure in such a way that the benefits of increasing risk are dominated by the cost in terms of increased deposit insurance premium payments. The closer ω gets to ω_2^*, the less the optimal capital structure has to deviate from the optimal capital structure in the absence of risk-shifting possibilities. As a result, the total bank value is increasing in ω in this region. Lastly, for $\omega > \omega_2^*$, the bank does not engage in risk-shifting, and its capital structure coincides with the capital structure of a restricted bank.

In addition to Figure 2.1(b), Figure 2.4 shows the bank's optimal capital structure characteristics as a function of ω, the non-subsidized fraction of the fair insurance premium. The effects of ω on the book leverage ratio L_b can be found in Figure 2.4(a). In this risk-taking region, the leverage ratio is lower than in case the bank is restricted in its investments. Furthermore, the leverage ratio is decreasing in this region. When ω gets bigger, the subsidy on deposit insurance gets smaller, and the bank is less incentivized to issue deposits. For $\omega > \omega_1^*$, the leverage ratio drops as a result of the market discipline effect. As this effect gets weaker when ω increases, leverage ratio L_b goes up until it coincides with the leverage ratio of a restricted bank at $\omega = \omega_2^*$.

Figure 2.4(b) presents the deposits-to-debt ratio as a function of ω. The deposits-to-debt ratio is slightly decreasing in the risk-shifting region $\omega < \omega_1^*$. Furthermore, it is lower for a risk-taking bank than for a restricted bank. At ω_1^*, the deposits-to-debt ratio spikes up. This is due to the increase in regulatory-sensitive deposits and a decrease of market debt, visible in

Figure 2.4(e) and 2.4(f). Substituting market debt for deposits reduces risk-taking incentives, as shown in Section 2.3.4, so that equity holders can credibly commit to the low-risk strategy. Upon further increase of ω, the market discipline effect weakens, and the substitution reverses.

Figure 2.4(c) shows the effects of ω on the 1-year default probability of the bank. Not surprisingly, the default probability of a bank that takes high investment risk is higher than the restricted bank. What might come as a bigger surprise is that the default probability goes up when the bank switches to the low-risk portfolio. This is a result of the jump in deposits, as can be observed in Figure 2.4(e). Lastly, Figure 2.4(d) shows that the loss given default shows a similar pattern as the book leverage ratio when varying ω.

Similar to the analysis of κ_H, this analysis shows that if the regulator wishes to limit both investment risk and funding risk in terms of bank leverage, it should not directly restrict the bank's investment projects. Instead, it should consider how to best set parameter ω to make the best use out of the market discipline channel to limit default risk and the magnitude of bank losses.

2.4.5 Comparative statics risk and regulatory parameters

Figure 2.5 presents the risk-taking regions for different values of regulatory parameters κ_H and ω, and high-risk parameter σ_H. The dark grey area represents the parameter combinations for which the bank engages in risk-taking. In the light grey area, the bank commits to the low-risk portfolio by choosing a different capital structure than in the first-best case. The white area represents the parameter combinations for which the bank does not engage in risk-shifting, and its optimal capital structure coincides with the one of a restricted bank. The x-axis starts at a value slightly stricter than $\sigma_L = 0.1$, to ensure that $\sigma_H > \sigma_L$.

Figure 2.5(a) shows that the risk-taking region as a function of σ_H is slightly hump-shaped. That is, the acceptable capital requirement κ_H for the bank to select high investment risk is initially slightly increasing and later decreasing in σ_H. The light grey area is monotonically increasing in σ_H. Consider Figure 2.1 for the effects of σ_H on the construction of the risk-regions. When σ_H increases, the dashed line representing the value of the high-risk bank moves downwards. This drives the point $\kappa^*_{H,1}$ to the left, thereby making the area of risk-shifting smaller. On the other hand, an increase of σ_H also drives down the bank value of a bank committing to low-risk, as equity holders need to deviate the capital structure by more to not have risk-shifting incentives once debt is in place. This drives both $\kappa^*_{H,1}$ and $\kappa^*_{H,2}$ upwards. This second effect dominates at first, so that there is a positive relation between σ_H and $\kappa^*_{H,1}$, but is later taken over by the first effect. A similar reasoning applies to the effects of σ_H on risk-regions ω^*_1 and ω^*_2 in Figure 2.5(b).

2.5 Conclusion

This paper presents a bank capital structure model in which equity holders can increase investment risk once debt is in place. The bank is subject to a capital requirement that depends on the bank's risk strategy. Furthermore, the deposits are insured for which the bank pays risk-contingent premium payments in return. I show that there are three regions for the bank's investment risk and funding risk decision. In the first region, where regulatory costs associated with risk-shifting are sufficiently small, equity holders select high investment risk, as by doing so, they can extract wealth from debt holders. In the second region, regulatory costs are sufficiently high so that shareholders are discouraged from engaging in risk-shifting, but the selected capital structure is different from first-best. In order to commit to low-risk, equity holders select a lower leverage ratio where, compared to first-best, market debt is substituted by deposits that bear regulatory costs. The extent to which equity holders need to deviate the capital structure decreases as regulatory costs increase. Ultimately, in the third region, regulatory costs associated with risk-shifting are so high that deviating from the first-best capital structure is not necessary anymore, and the market discipline effect disappears.

The analysis shows that the regulator should incorporate the bank's endogenous response to regulatory measures. Without taking into account the synergetic effects of regulation and market discipline, the regulatory might underestimate the effect of regulation on the bank's investment and funding risk decisions. Furthermore, if the regulator wants to limit bank losses in default and the likelihood of default, it could benefit from the market discipline channel that is only effective when regulatory costs are not set too high.

The model presented in this paper relies on the simplifying assumptions of market debt being perpetual and market debt holders not being able to withdraw their funds. Adding short-term debt and giving market debt holders the possibility to not roll over their debt is a potentially interesting extension of this model.

Furthermore, the model presumes full transparency of the bank's asset risk towards creditors and the regulator. Despite regulatory disclosure requirements, this is arguably a strong assumption, given the complex and opaque nature of the banking industry. The literature has argued that the issuance of market debt strengthens the market discipline channel. In a model with uninsured market debt holders that can diminish informational asymmetries, the bank might want to issue more market debt to encourage this process. This creates a countervailing force against the prediction of the model that if the bank wants to commit to a low-risk portfolio, it replaces market debt with deposits.

Tables and Figures of Chapter 2

Table 2.1: Baseline parameters values.

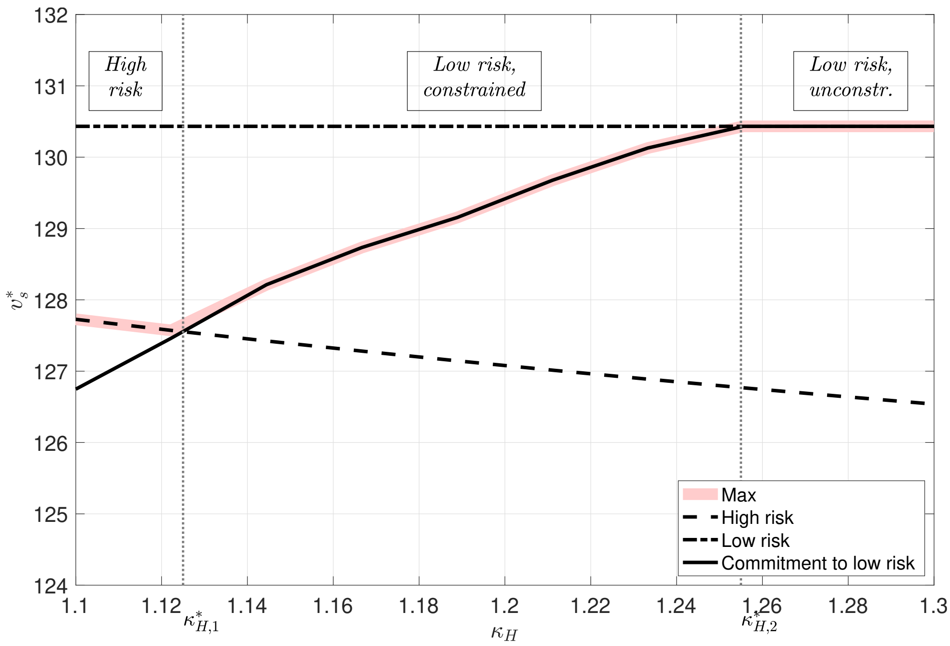
	Notation	Value
Initial asset value	V	100
Interest rate	r	4%
Cash flow rate	δ	3%
Liquidity premium	π	0.5%
Asset volatility low	σ_L	10%
Asset volatility high	σ_H	12%
Bankruptcy costs	α	30%
Corporate tax rate	θ	30%
Pricing deposit insurance	ω	50%
Regulatory closure low	κ_L	1.1
Regulatory closure high	κ_H	1.12

Table 2.2: This table shows the effects of higher investment risk on the bank's privately optimal capital structure characteristics. All parameters are according to Table 2.1.

	Notation	Low risk σ_L	High risk σ_H
Total value	v	130.43	127.59
Equity value	E	26.51	29.02
Deposit value	D	53.59	48.41
Market debt value	M	50.33	50.16
Book leverage ratio (%)	L_b	103.93	98.57
Market leverage ratio (%)	L_m	79.68	77.25
Deposits-to-debt ratio (%)	$D/(D+M)$	51.57	49.11
Tax benefits		26.80	25.10
Liquidity premium benefits		5.57	4.79
Deposit insurance subsidy benefits		1.04	1.09
Bankruptcy costs		2.98	3.39
Default threshold	V_D	58.95	54.22
1Y default probability (100 bp)		0.10	0.30
Loss in default		62.66	60.61
Ins. premium to deposits (bp)	I/D	9.31	11.39
Market debt credit spread (bp)	s_M	80.94	105.50
Coupon deposits	C_D	1.88	1.69
Coupon market debt	C_M	2.42	2.54

Figure 2.1: Optimal bank value for different regulatory parameters. This figure shows the optimal value for different regulatory parameters (κ_H, ω) of (i) a bank that is restricted to take low risk, (ii) a bank that is restricted to take high risk, and (iii) a bank that commits to low risk. The red line marks the maximum value of a bank that can either take high risk or commit to low risk. Parameters are set according to Table 2.1, except for $\delta = 0.02$ in Figure (b) with the purpose of showing all three relevant regions.

(a) Optimal bank values for different values of κ_H.



(b) Optimal bank values for different values of ω.

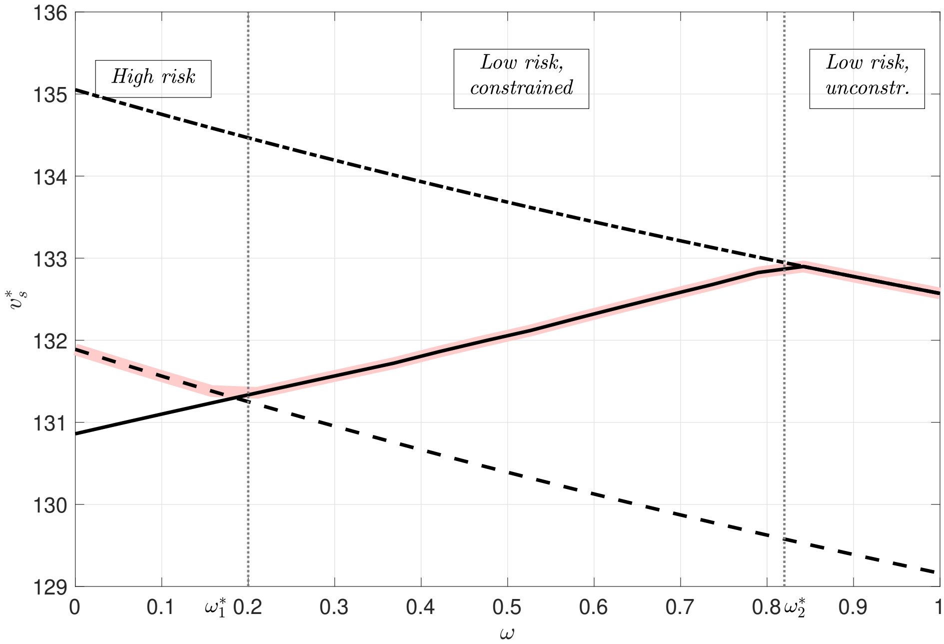


Figure 2.2: This figure displays the equity holders risk-taking decisions for different combinations of regulatory parameters ω and κ_H and coupons C_D and C_M. The grey area represents the combinations for which $E_H > E_L$ and the white area the composite. In figures (a) and (c), $C_D = 1.2$, and in figures (b) and (d), $C_M = 1.5$. All other parameters are according to Table 2.1.

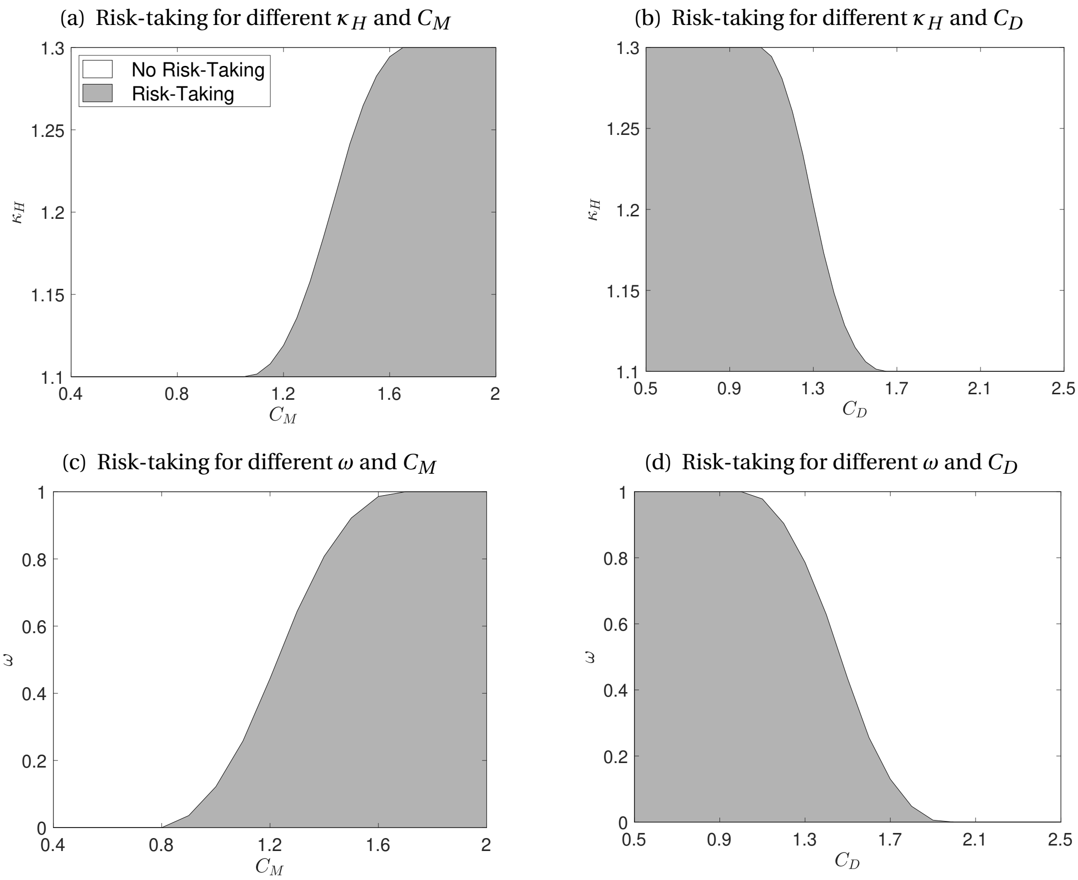


Figure 2.3: This figure displays the effects of increasing the high-risk regulatory capital requirement κ_H. In this setting, the lower capital requirement κ_L is set to 1.1 and the high capital requirement κ_H varies from 1.1 to 1.3. All other parameters are according to Table 2.1. The solid line represents the optimal capital structure characteristics in the presence of risk-shifting possibilities, and the dotted line represents the baseline case where the bank has no possibility to invest in riskier assets.

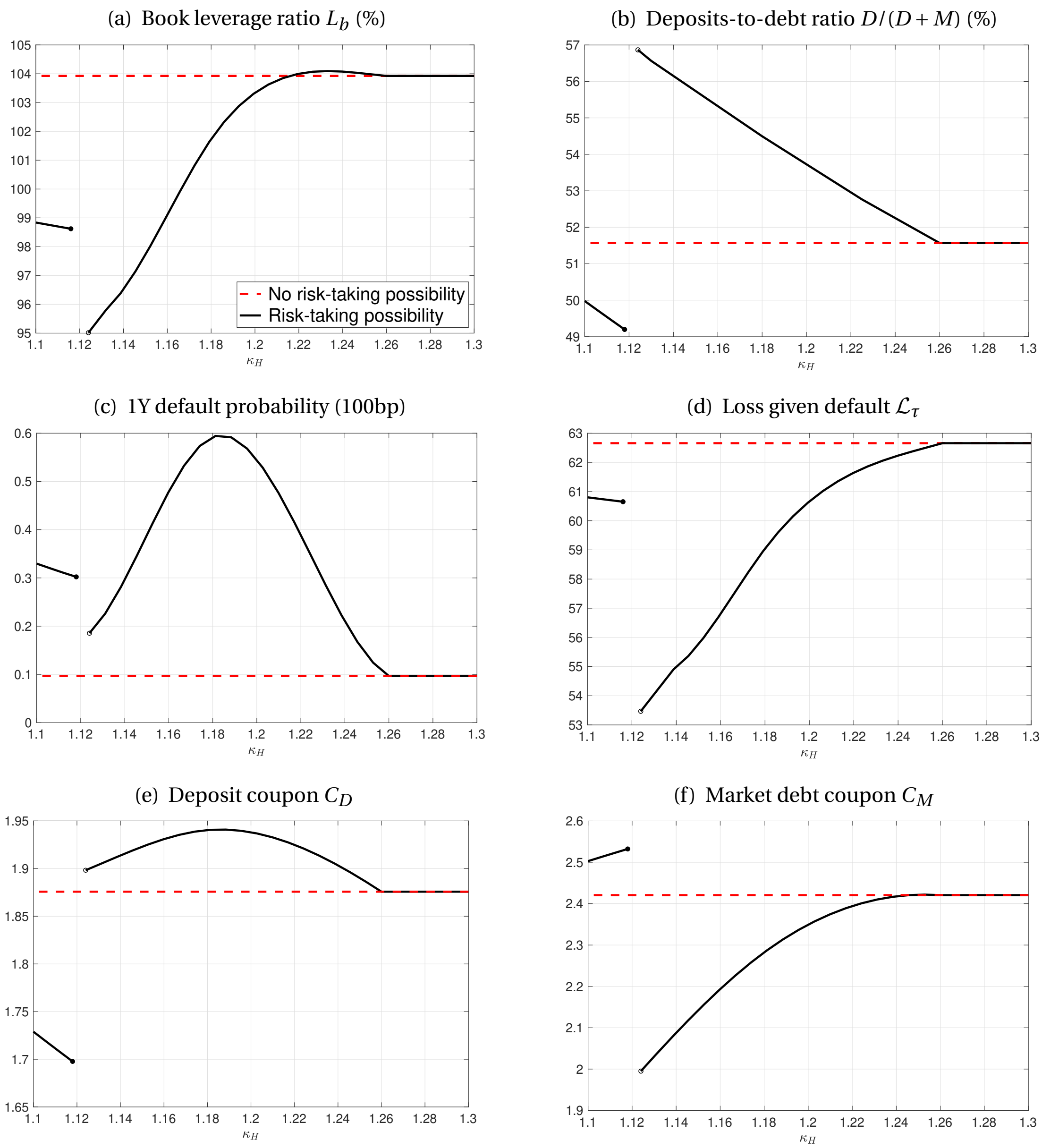


Figure 2.4: This figure displays the effects of increasing the deposit insurance pricing parameter ω. All other parameters are according to Table 2.1. The solid line represents the optimal capital structure characteristics in the presence of risk-shifting possibilities, and the dotted line represents the baseline case where the bank has no possibility to invest in riskier assets.

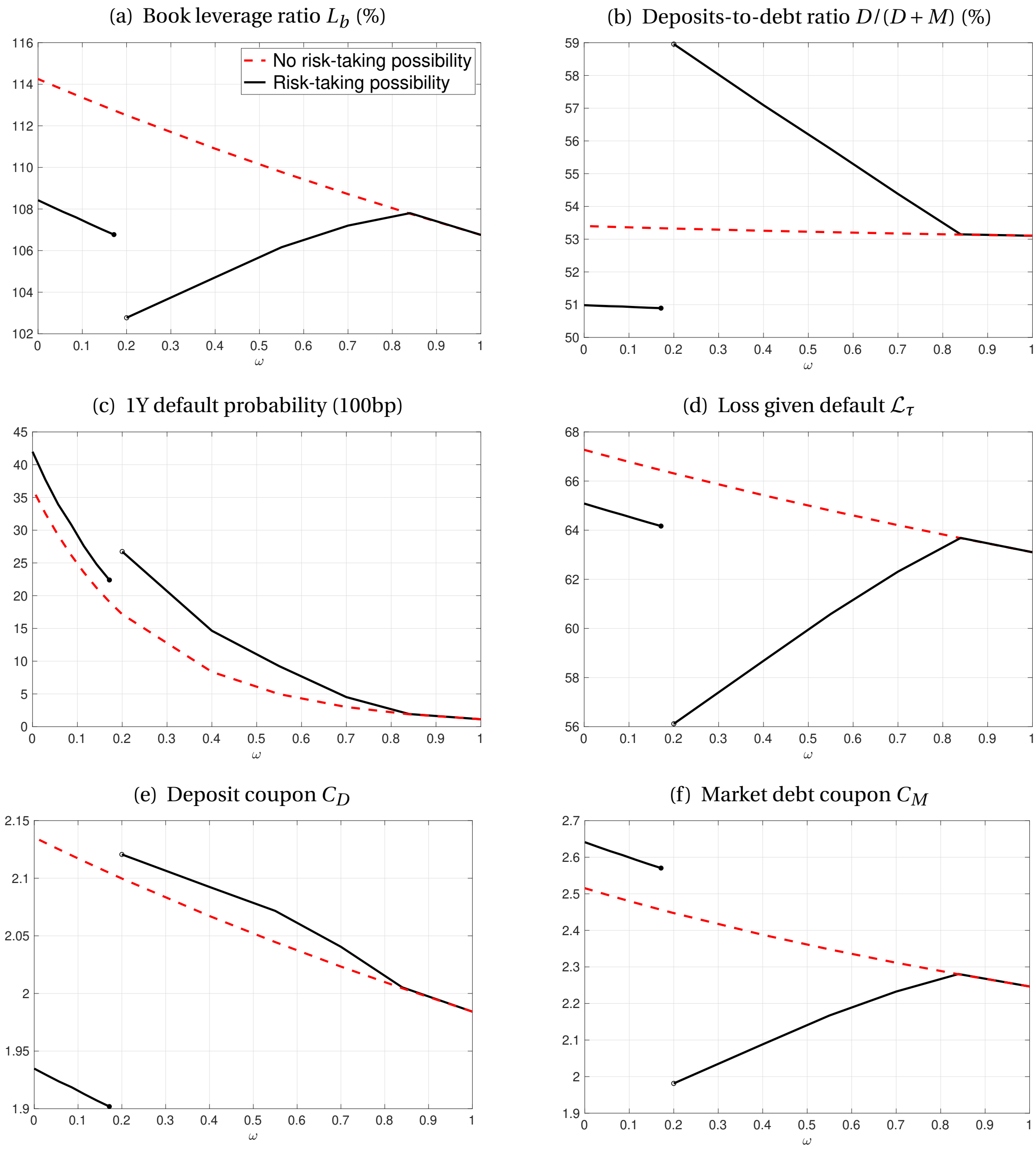
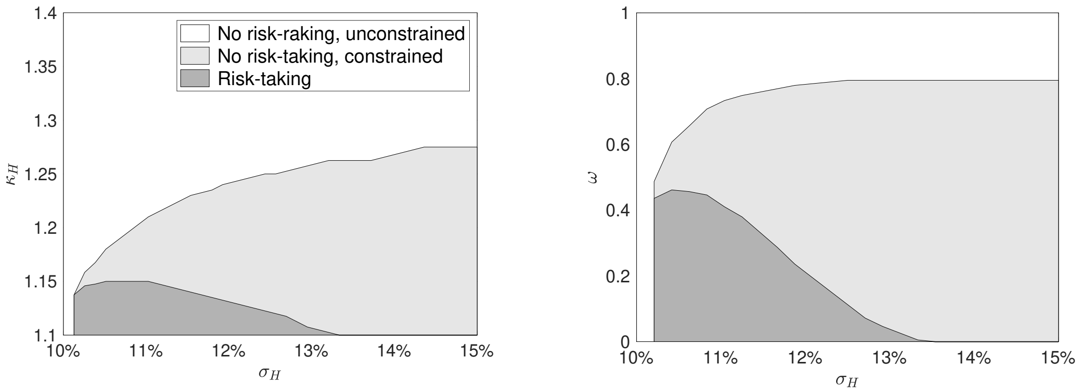


Figure 2.5: This figure displays risk-taking and no risk-taking regions for different values of regulatory parameters κ_H and ω, and of high-risk volatility parameter σ_H. All other parameters are according to Table 2.1. The dark grey area represents the region for which the bank engages in risk-taking. The bank does not engage in risk-taking in the light grey and white areas. In the light grey area, the capital structure of the bank is constrained whereas it is unconstrained in the white area.

(a) Risk-taking for different κ_H and σ_H

(b) Risk-taking for different ω and σ_H



3 Asymmetric Information and Dividend Restrictions

with Mads Nielsen (Université de Lausanne, Swiss Finance Institute)

3.1 Introduction

Payout restrictions have become an increasingly important part of the macro-prudential toolbox of central banks. Examples are the countercyclical capital buffer and the capital conservation buffer introduced in Basel III, which, when triggered, restrain banks from paying out dividends and buying back shares.[1] More recently, both the Federal Reserve and the European Central Bank responded to the Covid-19 outbreak by imposing strict limitations on banks' distributions to shareholders, leading to a decline of 57% of aggregate dividends paid out in 2020 compared to the year before, see Hardy (2021).[2] In the presence of informational frictions generated by the opaque and complex nature of the banking sector, we argue that these measures might have unintended consequences and ultimately be counterproductive in achieving their goal of improving banks' resilience to crises. However, we also show that regulation can, under some circumstances, mitigate the distortions of the laissez-faire equilibrium.

Due to their central role in the financial system, bank defaults can have significant adverse spill-over effects on the real economy, see Acharya et al. (2009). Therefore, regulators aim to limit the likelihood and mitigate the impact of these events. Since the banking industry is among the industries with the highest payout ratios, see Guntay et al. (2015), one way for the regulator to achieve this is by requiring banks to build sufficient buffers before distributing funds to investors. However, the high level of dividends observed in the banking sector

[1]The capital conservation buffer requires banks to hold 2.5% of common Tier equity capital on top of the minimum capital requirement.

[2]In June 2020, the Fed barred banks from share buybacks and capped dividend payments to the amount paid in the second quarter of 2020 and further limited to an amount based on recent earnings, see Federal Reserve System (2020). On March 2021, it was announced that this measure ends for most banks on June 30, 2021, see Federal Reserve System (2021). In May 2020, the European Central Bank asked member banks to refrain from dividend payments completely. This recommendation was addressed to significant institutions (SIs) that are under the direct supervision of the ECB and to national competent authorities (NCAs) that supervise less significant institutions (LSIs). See European Systemic Risk Board (2020b) for an overview of the regulatory announcement made by the NCAs. The recommendation was later revised to a limit on dividend payments and is in place until at least September 2021, see European Central Bank (2020).

suggests that dividends are essential for its investors. The explanation that we consider is that banks use dividends as a signaling device, e.g., Boldin and Leggett (1995) and Zheng (2018). This strategic behavior complicates the implications of regulatory intervention.

This paper studies how information asymmetry affects banks' optimal dividend payout policy and what, in relation to that, the consequences of dividend restrictions are. We develop a dynamic model of a bank that controls its cash reserves by paying out dividends. The bank's management has superior information about the impact of a pending shock to the bank's cash reserves. For simplicity, we assume that the good type is unaffected by the liquidity shock, whereas the bad bank loses a fixed amount of its cash reserves. The liquidity shock can be interpreted in several ways, e.g., a large trading loss[3], a regulatory fine[4], or a margin call[5]. The bank's type is private information of bank management and can therefore not be observed by the regulator and potential outside investors. We assume that when the liquidity crisis hits, the market learns about the bank's type.

In the tradition of the literature on dividend signaling starting with Miller and Rock (1985), an incentive to signal follows from the assumption that the bank acts in the joint interest of long-term shareholders and short-term shareholders. Whereas the long-term shareholders care about the long-term intrinsic value of the bank, the short-term shareholders are concerned with the market valuation, as they want to be able to sell their stocks at any point in time. A micro-foundation for such short-termism could be that investors themselves are exposed to liquidity shocks or that they face a stochastic investment set leading to a certain probability that re-balancing is necessary. Alternatively, focusing directly on management, this assumption could reflect that management's remuneration scheme is tied to stock price performance.

Under full information and appropriate parameter settings, the good bank pays out dividends at a lower cash level than the bad bank considering the latter wants to hold an additional precautionary savings buffer to withstand the liquidity shock. In the presence of asymmetric information, the bad type has an incentive to mimic the good type to boost its market valuation. When the market cannot distinguish the two bank types, both bank types' market valuation will be a weighted average of its correct valuations. Since this is disadvantageous for the good bank, it has incentives to signal its type by distorting its dividend policy and thereby imposing mimicking costs on the bad bank. By trading off the costs of increased default risk versus the benefit of higher market valuation, the good bank might forgo adopting an aggressive separating strategy and accept being pooled with the bad bank instead. We establish the conditions for the existence of the separating and pooling equilibria.

The model generates several novel insights. First of all, the model predicts that in the separating equilibrium, a good bank pays out dividends more aggressively compared to the symmetric

[3]For example, the collapse of Archegos Capital Management brought severe trading losses to a group of large banks, see The Economist (2017).

[4]The Economist (2021b) reports that global banks were hit with \$10.4 billion in regulatory fines for money-laundering activities, an increase of more than 80% compared to 2019.

[5]The European Systemic Risk Board (2020a) report considers the implications of large margin calls from cash and derivatives positions on bank and non-bank entities. According to the report, some banks have experienced a significant increase in initial margins and, as a result, increased liquidity constraints in terms of liquid assets and available collateral.

information benchmark, whereas a bad bank adopts its first-best strategy. This strategic behavior can result in the good bank having a higher risk of default than the bad bank, despite not being exposed to the liquidity shock. Conversely, a good bank pays dividends at a higher cash level and a bad bank at a lower cash level than their respective first-best targets in the pooling equilibrium. As a result, the bad bank becomes more prone to default and the good bank less than in the symmetric information benchmark.

Second, we study the implications of dividend restrictions imposed by the regulator. We show that a dividend restriction *before* arrival of the liquidity shock has the potential to break the separating equilibrium. When the dividend restriction is set sufficiently high, the bank moves to a pooling equilibrium. This change leads to an increased (decreased) target cash level of the good (bad) bank and the effects on default risk described in the previous paragraph. On an industry level, the regulator faces a trade-off between reduced default risk of the good bank and increased default risk of the bad bank.

Third, considering the additional dimension of industry value, we find that there are up to three regions for the impact of regulation. In the first region, regulation is so lax that it does not affect the equilibrium outcome. In the third region, regulation is so tight that both bank types follow a more conservative dividend policy than their first-best. In this region, regulation in the form of dividend restrictions makes the industry safer, but at the same time, reduces the average value of banks. From a regulatory perspective, the most interesting is the intermediate region, which exists when the unregulated equilibrium is of the separating type. Breaking this separating equilibrium has the potential to *both* lower the average default risk and increase the average bank value. However, depending on the characteristics of the banking industry and the liquidity shock, the outcome might turn out the opposite way, i.e., raising the average default risk *and* destroying value.

We identify two opposing channels through which the *scope* of the liquidity shock (i.e., the fraction of banks exposed to the liquidity shock) affects the impact of regulation and explain the previous result. The *direct* channel captures the fact that, other things equal, the impact of regulation on banks exposed to the shock weighs heavily on aggregate outcomes when they constitute a significant fraction of the industry. The *indirect* channel arises from how banks strategically adapt to the scope of the liquidity shock. In moving from a separating to a pooling equilibrium, the bad bank's dividend policy distortion is more substantial when only a few banks are exposed to the shock, and vice versa. Through scenario analysis, we establish how the *size* of the shock determines which channel dominates. For a large and concentrated shock, regulation tends to be beneficial by simultaneously lowering the bank's average default risk and increasing industry value. For a small and widespread shock, the opposite outcome materializes, making regulation harmful. In both scenarios, the indirect channel dominates. For a shock of medium-sized but concentrated shock, the direct channel dominates, leading to opposite conclusions. In the scenario of a small concentrated shock, banks tend to already be in a pooling equilibrium.

Next to the economic fundamentals of the shock, i.e., the scope and size, the degree to which investors put weight on the bank's (short-term) market valuation influences the effectiveness of regulation. We argue that a high degree of short-term focus improves the outlook for regulation when it can prevent aggressive distortion of the good type's payout policy.

Throughout this paper, analyzed firms are considered to be banks. This is in line with the characteristics of the banking industry as described above, i.e., regulatory scrutiny, high degree of complexity, exposure to tail risk, and high payout ratios. However, as we abstract from certain institutional features on the liability side to keep the analysis tractable, the model can be applied to non-financial firms too.[6]

This paper relates to different strands of the literature. The idea that firms use dividends to signal their quality was suggested by Miller and Modigliani (1961) and later theoretically formalized by Bhattacharya (1979), Miller and Rock (1985), and Kale and Noe (1990).[7] More recently, Guntay et al. (2015) studied the informational role that regulators have in the banking industry with a model in which a regulator with information superior to the market has to approve dividend payments by banks. A dividend restriction that restricts only the weakest banks in the economy might trigger a bank run, whereas the opaqueness resulting from strict dividend restrictions promotes bank stability. In contrast, we find that a pooling equilibrium resulting from dividend restrictions *can* be less stable than a laissez-faire separating equilibrium. Additionally, we pose the problem in a continuous-time liquidity management framework, as opposed to static models of the papers mentioned above, see Moreno–Bromberg and Rochet (2018).

Acharya et al. (2011) provide an overview of the dividends paid out by the largest banks before and during the crisis period of 2007-2009. They demonstrate that banks had been paying out significant dividends during the crisis period despite widely anticipated credit losses. The authors attribute this behavior to the short-term nature of the banks' funding and the implicit and explicit government guarantees. As banks are funded with short-term debt, a dividend cut could trigger a market debt run. We take a different approach by abstracting from the bank's liability side and focus on dividends as a signaling device for exposure to adverse shocks.

In the wake of the financial crisis, Acharya et al. (2011) and also Admati et al. (2013) advocate payout restrictions to promote the stability of the financial industry. Furthermore, Goodhart et al. (2010) and Acharya et al. (2017) argue that payout dividend restrictions are desirable when banks' balance sheets are intertwined. Muñoz (2019) adopts a DSGE modeling approach and concludes that bank dividend prudential targets induce welfare gains associated with Basel III-type capital regulation. We contribute to this discussion by adding nuances to the trade-offs involved in imposing such policies due to informational asymmetries.

The paper is organized as follows. Section 3.2 presents the model and the bank's valuation in the symmetric information case. Section 3.3 studies the effects of asymmetric information on the bank's dividend policy. Section 3.4 considers the implications of dividend restrictions on the bank's dividend strategy, valuation, and default likelihood for different parametric scenarios. Section 3.5 concludes.

[6] For example, parts of the aviation sector were subject to dividend restrictions after being bailed out in response to the Covid-19 outbreak; German airliner Lufthansa agreed to not pay out dividends of 2019 in exchange for a 10 billion euro bail-out, see Reuters (2021).

[7] Following Myers and Majluf (1984), investment decisions can work as an alternative signaling device, see also Morellec and Schürhoff (2011).

3.2 The model

3.2.1 Set-up

We develop a continuous-time model of a bank that is owned by shareholders who have limited liability and is run by management. Agents are risk-neutral and discount the future at a rate $\rho > 0$. The bank's assets consists of liquid reserves and a fixed volume of assets in place than generate cash flows X_t with dynamics:

$$dX_t = \overline{\mu} dt + \sigma dZ_t, \quad X_0 = 0.$$

Here, $Z = \{Z_t, t \geq 0\}$ is a Brownian Motion, representing small and continuous movements in the cash flows. The drift and volatility parameters $\overline{\mu}$ and σ are positive and known constants. It is assumed that the bank is partly financed by debt that is already in place and for which the bank pays coupon payment $c < \overline{\mu}$ per time period dt. The resulting cumulative earnings C_t evolve according to:

$$dC_t = (\overline{\mu} - c)dt + \sigma dZ_t = \mu dt + \sigma dZ_t, \quad C_0 = 0. \tag{3.1}$$

Here, μ denotes the drift of the bank's cash flows after interest payments to debt holders. Throughout the paper, we abstract from debt financing decisions and focus on the bank's equity valuation.

The bank's type can either be good or bad, denoted by $\ell \in \{G, B\}$. The fraction of good banks in the economy is $\alpha \in (0,1)$, and the complementary fraction $1 - \alpha$ is of the bad type. We assume that the bad banks in the economy are subject to a liquidity shock that hits all bad banks at the same time. One could think of a large and widespread trading loss, regulatory fine, or margin call.[8] When hit by a liquidity shock, the bad banks in the economy all suffer a shock $f > 0$ to their liquid reserves. Define the time when the shock takes place as

$$\tau^* = \inf\{t > 0 : N_t = 1\},$$

where $N = \{N_t, t \geq 0\}$ is a Poisson process with intensity λ. For simplicity, we assume that the bad bank is only subject to a single shock. Furthermore, we assume that management (the insiders) knows the bank's type, which the regulator and investors only learn when the shock hits or when the bank credibly signals its type. We find it most natural to think that this applies to investors regardless of whether they have invested in the bank or not, but it is sufficient for our results that investors who want to sell shares in the secondary market cannot credibly signal the type of the bank to potential buyers in the secondary market. Note that the common earnings dynamics as described in Eq. (3.1) and the occurrence of a single shock ensure that outsiders cannot learn the bank's type by observing the liquid reserves before the arrival of the shock.

To add some interpretation to the difference between bank types, one could think of the average earnings parameter μ as the rate banks have to achieve in order to be competitive. One interpretation is that bad banks have to accept some tail risk to get to this level, whereas good banks have projects that do not require the additional tail risk to get to cash flow drift μ.

[8] We discuss these cases more in detail in Section 3.4.3.

An alternative interpretation is that banks have assets in place and that management learns at time $t = 0$ whether the bank's assets are exposed to the shock or not. As the weights of good and bad banks in the economy are exogenous in our model, the two interpretations are equivalent. However, extending the model to endogenize the choice of type would be more relevant under the former than the latter.[9]

The bank controls its cash reserves by paying out dividends. Let L_t be the cumulative dividends paid out over $[0, t]$. We assume that dividend process $L = \{L_t, t \geq 0\}$ is non-decreasing, $(\mathcal{F}_t)$-adapted and càdlàg. For simplicity, we assume that the reserves are not renumerated. The dynamics of the bank's cash reserves given a strategy L are:

$$M^L_{\ell,t} = m + C_t - L_t - \mathbb{1}_{\{t \leq \tau^*, \ell = B\}} f N_t,$$

where m denotes the initial level of liquid reserves and the last term with zero-one indicator function $\mathbb{1}_{\{\cdot\}}$ reflects the negative liquidity shock that applies to the bad bank. We assume that outsiders can observe the bank's cash reserves, so that the bank's type is revealed when the shock hits, and that the bank has to announce a dividend policy ex-ante.

In order to introduce the risk of liquidation in the model, it is assumed that primary capital markets are closed.[10] As a result, the bank defaults when its liquid reserves are fully depleted.[11] Let τ^L_ℓ be the liquidation time of bank type ℓ defined for a strategy L:

$$\tau^L_\ell = \inf\{t > 0 : M^L_{\ell,t} \leq 0\}.$$

To generate a signaling incentive, the model relies on managerial short-term incentives. Management acts in the joint interest of short- and long-term shareholders. Short-term shareholders care about the bank's current market value as they might sell their stocks on the secondary market sooner rather than later. Long-term shareholders only care about the intrinsic value of the bank. Let $k \in (0, 1)$ denote the fraction of short-term shareholders, and the complementary fraction $1 - k$ long-term shareholders. The short-term focus could reflect that investors face liquidity concerns or stochastic investment opportunity sets or that management pay is tied to stock price performance. As such, k can be interpreted more generally as capturing the relative importance of the market value (perceived value) $V^L_{\tilde{\ell}}(m)$ and the intrinsic value $V^L_\ell(m)$ under a strategy L. Therefore, the bank's objective function is given by the weighted sum of the bank's shareholder value as perceived by the market and the intrinsic bank's shareholder value.

$$V_{\ell,\tilde{\ell}}(m) := \max_{L \in \mathcal{A}} \; k \underbrace{V^L_{\tilde{\ell}}(m)}_{\substack{\text{market value}\\ \text{(perceived value)}}} + (1-k) \underbrace{V^L_\ell(m)}_{\text{intrinsic value}}, \tag{3.2}$$

[9] For a sketch of what endogenizing this choice might mean for regulation, see Section 3.4.6.

[10] This restriction is equivalent to assuming that the cost of raising new equity is high enough to make it an unattractive alternative to default, see Chapter 2 in Moreno–Bromberg and Rochet (2018).

[11] One could easily generalize this to a set-up with a liquidity requirement, i.e., a strictly positive level of liquid reserves imposed by the regulator similar to Milne and Whalley (2005).

where $\mathcal{A}$ is the set of all admissible strategies, and

$$V_{\ell}^{L}(m) = \mathbb{E}\left[\int_0^{\tau_{\ell}^{L}} e^{-\rho t} dL_t | M_{\ell,0}^{L} = m\right], \quad V_{\tilde{\ell}}^{L}(m) = \mathbb{E}\left[\int_0^{\tau_{\tilde{\ell}}^{L}} e^{-\rho t} dL_t | M_{\tilde{\ell},0}^{L} = m\right],$$

are the present value of future dividends to shareholders for a bank of type ℓ and $\tilde{\ell}$, respectively.

3.2.2 Value function

To determine the bank's shareholder value, we first solve the value function $W(m)$ after the shock has hit. This value function satisfies the following Hamilton-Jacobi-Bellman (HJB) equation for all $m \geq 0$:

$$\max\left\{\frac{1}{2}\sigma^2 W''(m) + \mu W'(m) - \rho W(m), 1 - W'(m)\right\} = 0,$$

together with the boundary condition $W(0) = 0$. Once this function has been established, one can determine the value function defined in Eq. (3.2), which satisfies for all $m \geq 0$:

$$\max\left\{\frac{1}{2}\sigma^2 V''_{\ell,\tilde{\ell}}(m) + \mu V'_{\ell,\tilde{\ell}}(m) - (\rho + \lambda) V_{\ell,\tilde{\ell}}(m), 1 - V'_{\ell,\tilde{\ell}}(m)\right\} = 0,$$

with boundary condition $V_{\ell,\tilde{\ell}}(0) = 0$. The optimal payout strategy is of the so-called barrier type. This strategy is characterized by an optimal target level of liquid reserves $m_{\ell,\tilde{\ell}}$ (or equivalently, an optimal payout strategy), such that all liquid reserves beyond this point are distributed as dividends, and nothing is paid out below this point.

The bank's value function is a weighted sum of its market valuation and its intrinsic valuation. This following proposition presents the intrinsic value function $V_{\ell}(m; m_{\ell})$ of a bank of type $\ell \in \{G, B\}$.[12] We first determine the value function after the liquidity shock has hit. Note that it is assumed that when the shock occurs, the types are learned. For that reason, the value function after the shock $W(m)$ does not depend on type ℓ, and the corresponding dividend strategy is set optimally, i.e., absent any signaling considerations.

Proposition 3.1. *The value of a bank of any type $\ell \in \{G, B\}$ after the shock is given by*

$$W(m) = \begin{cases} \sum_{i=1}^{2} \overline{A}_i e^{\overline{r}_i (m - \overline{m}^*)}, & \text{for } m \in [0, \overline{m}^*), \\ m - \overline{m}^* + \sum_{i=1}^{2} \overline{A}_i, & \text{for } m \geq \overline{m}^*, \end{cases}$$

where $\overline{m}^*$ is the optimal cash target after the shock. Let m_{ℓ} be the target cash level of bank type ℓ. We distinguish two cases for the intrinsic value of the good bank before the arrival of the shock:

[12] Note that the notation V_{ℓ} with the single subscript ℓ represents the intrinsic value of a bank of type ℓ. In the presence of asymmetric information, the double subscript $V_{\ell,\tilde{\ell}}$ denotes the weighted sum of a bank of type ℓ that is considered to be of type $\tilde{\ell}$ by the market, as in Eq. (3.2).

(i) For $m_G < \overline{m}^*$:

$$V_G(m) = V_G(m; m_G) = \begin{cases} \sum_{i=1}^{2} A_i^G e^{r_i(m-m_G)} + W(m), & \textit{for } m \in [0, m_G), \\ \sum_{i=1}^{2} A_i^G + W(m_G) + m - m_G, & \textit{for } m \geq m_G. \end{cases}$$

(ii) For $m_G > \overline{m}^*$:

$$V_G(m) = V_G(m; m_G) = \begin{cases} \sum_{i=1}^{2} A_i^G e^{r_i(m-m_G)} + W(m), & \textit{for } m \in [0, \overline{m}^*), \\ \sum_{i=1}^{2} B_i^G e^{r_i(m-m_G)} + \beta_G + \gamma m, & \textit{for } m \in [\overline{m}^*, m_G), \\ \sum_{i=1}^{2} B_i^G + \beta_G + (\gamma - 1) m_G + m, & \textit{for } m \geq m_G. \end{cases}$$

We distinguish three cases for the value of the bad bank before the shock arrives:
(i) For $0 < m_B - f < \overline{m}^*$:

$$V_B(m) = V_B(m; m_B) = \begin{cases} \sum_{i=1}^{2} A_i^B e^{r_i(m-m_B)}, & \textit{for } m < f, \\ \sum_{i=1}^{2} B_i^B e^{r_i(m-m_B)} + W(m-f), & \textit{for } m \in [f, m_B], \\ \sum_{i=1}^{2} B_i^B + W(m_B - f) + m - m_B, & \textit{for } m > m_B. \end{cases}$$

(ii) For $m_B - f \geq \overline{m}^*$:

$$V_B(m) = V_B(m; m_B) = \begin{cases} \sum_{i=1}^{2} A_i^B e^{r_i(m-m_B)}, & \textit{for } m \in [0, f), \\ \sum_{i=1}^{2} B_i^B e^{r_i(m-m_B)} + W(m-f), & \textit{for } m \in [f, f + \overline{m}^*], \\ \sum_{i=1}^{2} C_i^B e^{r_i(m-m_B)} + \beta_B + \gamma m, & \textit{for } m \in [f + \overline{m}^*, m_B), \\ \sum_{i=1}^{2} C_i^B + \beta_B + \gamma m_B + m - m_B, & \textit{for } m \geq m_B. \end{cases}$$

(iii) For $m_B - f \leq 0$:

$$V_B(m) = V_B(m; m_B) = \begin{cases} \sum_{i=1}^{2} A_i^B e^{r_i(m-m_B)}, & \textit{for } m < m_B, \\ \sum_{i=1}^{2} A_i^B + m - m_B, & \textit{for } m \geq m_B. \end{cases}$$

Proof. The derivations, including the expressions of all the coefficients $\bar{A}_i$, A_i^ℓ, B_i^ℓ, C_i^B, after-shock dividend target $\overline{m}^*$, the constants β_G, β_B, and γ, and the characteristic roots $\bar{r}_i$ and r_i, $i \in \{1, 2\}$, can be found in Appendix A.3.1. □

Observe that in the region $m < f$, the bad bank defaults upon arrival of the liquidity shock. Furthermore, note that when $m_G > \overline{m}^*$ for the good bank and $m_B > \overline{m}^* + f$ for the bad bank, an additional region shows up in the value function. When $m \in (\overline{m}^*, m_\ell]$ after the shock, shareholders receive a lump-sum payment of $m - \overline{m}^*$. We will encounter this scenario later on in the pooling equilibrium, in which case the market cannot distinguish the good and bad types.

3.2.3 Benchmark case: full information

Before analyzing the effects of asymmetric information on the bank's dividend strategy, we consider the benchmark case in which all agents have full information about the bank's type. In this scenario, both good and bad banks follow their privately optimal dividend policy. The valuations of the two bank types in the full information case are summarized in the following proposition. Define the operator $x^+ := \max\{x, 0\}$.

Proposition 3.2. *Under full information, the value of a bank of type ℓ before the shock is given by:*

$$V^*_\ell(m) = V_{\ell,\ell}(m; m^*_\ell) = V_\ell(m; m^*_\ell),$$

where optimal target cash level m^*_ℓ is pinned down by high-contact condition:

$$\lim_{m\uparrow m^*_\ell} V''_\ell(m; m^*_\ell) = \lim_{m\downarrow m^*_\ell} V''_\ell(m; m^*_\ell).$$

In specific, the following relation holds at m^*_ℓ:

$$V^*_\ell(m^*_\ell) = \frac{\mu}{\rho+\lambda} + \frac{\lambda}{\rho+\lambda}(m^*_\ell - f\mathbb{1}_{\{\ell=B\}}) = (1-\gamma)W(\overline{m}^*) + \gamma W((m^*_\ell - f\mathbb{1}_{\{\ell=B\}})^+).$$

For the good bank, $m^*_G = \overline{m}^*$ and above relation simplifies to:

$$V^*_G(m^*_G) = W(m^*_G) = \frac{\mu}{\rho}.$$

Proof. See Appendix A.3.1 □

The optimal dividend strategy m^*_ℓ is the cash level at which the marginal benefit of retaining cash equals the marginal benefit of paying out cash. For the good bank, this trade-off boils down to having a precautionary savings motive against the Brownian shock versus the impatience of its shareholders. The above proposition states that the optimal dividend policy of the good bank corresponds to the optimal after-shock strategy, which is characterized in Eq. (A.21). This is an intuitive result, as the good bank is not affected by the liquidity shock and it is fairly priced in the full-information benchmark. As a result, the value of the good bank at its optimal value simplifies to μ/ρ, being the discounted value of a perpetual bond payer a continuous dividend μ per unit of time.

The bad bank faces a more complicated trade-off when deciding on its optimal dividend strategy, as it also has to incorporate the Poisson risk component. Figure 3.2 shows that the relation between the optimal payout boundary of the bad bank m^*_B and shock size f for different values of cash flow volatility σ. What may come across as unexpected is that the link between m^*_B and f can go in two ways. Figure 3.2(a) shows that for a low value of σ, the bad bank pays out dividends at a higher cash level when f increases. For high values of σ, this relationship inverses, and eventually becomes flat, as is visible in Figure 3.2(b).

As the good bank's value at its first-best strategy should be larger than the bad bank's value at its first-best strategy, we have that $W(m_G^*) \geq W(m_B^* - f)$, which by the monotonicity of W implies that $m_G^* \geq m_B^* - f$. In changing m_B^* in response to a higher f, it is never optimal to increase the buffer more than the increase of the potential loss. Therefore, $m_G^* + f$ serves as an upper bound of m_B^*. As a result, case (ii) of the bad bank's value function in Proposition 3.1 is irrelevant.

In Figure 3.2(a), the boundaries are ordered as follows: $m_B^* > m_G^* > m_B^* - f > 0$. When $m_B^* < f$, the bad bank has optimally set the default boundary so low that it will be wiped out when the shock hits. In this scenario, their exists a closed-form expression for m_B^*, which is smaller than m_G^* and can be found in Eq. (A.24), so that overall $m_G^* > m_B^* > 0 > m_B^* - f$. This implies that the bad bank hoards less cash to hedge against the Browian default risk compared to the case where there is no Poisson risk. This case corresponds to the flat part of the function in Figure 3.2(b). The decreasing left part of this part corresponds to the ordering $m_G^* > m_B^* > m_B^* - f > 0$.

For the remainder of this paper, we will focus on the case where the precautionary savings motives dominate the effect of impatience and that the bad bank's first-best dividend strategy is more conservative than the good bank's.

Assumption 3.1. *Parameter values are set such that* $m_B^* > m_G^*$.

We argue that this is a reasonable assumption for the banking industry, which is among the industries with the largest payout ratios. The numerical analysis shows that the above assumption holds for reasonable values of cash flow volatility σ and is only violated for relatively high values of σ. This is in line with our view that banks have relatively stable cash flows in normal times, but are subject to tail risk events.[13]

For the sake of completeness, we provide the set-up of a parallel analysis when Assumption 3.1 is violated in Appendix A.3.4. In this scenario, the bad bank can mimic the good bank by increasing its target cash level. In response, the good bank can decide to signal its quality by further increasing its dividend payout level.

3.3 Signaling through dividend policy

In the perfect information case, different bank types choose different target cash levels. This might not be the case under asymmetric information. As the bank's objective function includes a market-valuation component, the bad bank has incentives to mimic the good bank's dividend policy at the cost of adopting a sub-optimal dividend policy. In return, the good bank does not wish to be mimicked by the bad bank, as this reduces its market valuation. For that reason, the good bank has an incentive to impose mimicking costs on the bad bank by distorting its dividend policy. The bad bank might accept a more aggressive dividend policy in return for a higher market valuation, but anticipating the pending shock, it has an additional precautionary

[13] An example of the opposite case could be some of the most successful companies in the volatile technology sector, building seemingly excessive cash buffers, see The Economist (2017).

savings motive, so that there is a limit to how far the bad bank wants to go in following the good bank's strategy.

In this section, we first confirm that the dividend policy can be used as a signaling mechanism by showing under which conditions the Spence-Mirrlees condition holds. Then, we will analyze the separating and pooling equilibrium.

3.3.1 Single-crossing condition

We will now show that the dividend policy can be used as a signaling device. When deciding whether to mimic or separate, each bank type makes a trade-off between the cost of distorting the dividend policy with the change in the market valuation. The single-crossing condition in Proposition 3.3 shows that the elasticity between the change of market valuation and the dividend policy depends positively on the type ℓ. This implies that in the region defined, it is less costly for the good bank to distort its dividend policy and get a higher market valuation than it is for the bad bank. As a result, outside investors can view the dividend policy, or equivalently, the target cash level, as a credible signal. Functions Δ and Γ are defined in Eq. (A.31) and (A.32).

Proposition 3.3. *If the following condition is satisfied:*

$$\left.\frac{\partial V_G(m;m_D)}{\partial m_D}\right|_{m_D=\overline{m}^*} < \left.\frac{\partial V_B(m;m_D)}{\partial m_D}\right|_{m_D=\overline{m}^*}$$
$$\iff (1-W'(\overline{m}^*-f))\Gamma(\overline{m}^*)+\Delta(\overline{m}^*)W''(\overline{m}^*-f)+W'(0)\Delta'(f)<0,$$

there exists a unique point $m_{SC} \in (f, \overline{m}^*)$ such that for every $m_D \geq m_{SC}$, the single-crossing property holds:

$$\frac{V_{G,G}(m;m_D)-V_{G,B}(m;m_D)}{\partial V_{G,\tilde{\ell}}/\partial m_D} > \frac{V_{B,G}(m;m_D)-V_{B,B}(m;m_D)}{\partial V_{B,\tilde{\ell}}/\partial m_D}.$$

This condition is equivalent to:

$$\frac{\partial V_G(m;m_D)}{\partial m_D} < \frac{\partial V_B(m;m_D)}{\partial m_D}, \quad \forall m \geq 0, m_D \geq m_{SC}.$$

This implies that the high-type bank finds it less costly to distort the dividend policy than the low-type bank regardless of its current cash-level.

Proof. See Appendix A.3.3. □

This proposition implies that lowering the dividend policy m_D is considered a valid signal for all values $m_D \in (m_{SC}, \overline{m}^*)$, which is a sufficient condition for a separating equilibrium to exist. Note that for $m_D = f$, the single-crossing condition is always violated, meaning that a good bank cannot signal its type by pushing down its dividend boundary to a level f. The reason is that for $m_D \leq f$ the bad bank is wiped out when the shock arrives, which alters its optimal behavior (see Chapter 5.1 of Moreno–Bromberg and Rochet (2018)). Limited liability and the impatience introduced by the future wipe-out lead the bank to pay out earlier. Even at levels of m_D above f this effect might dominate the banks' precautionary savings motive, and m_{SC} is therefore strictly above f. In our numerical analysis, under our Assumption 3.1 the precautionary savings motive is strong enough for the existence of m_{SC}. Furthermore, m_{SC} is systematically lower than $\overline{m}^S$.

Preposition 3.3 additionally establishes that the validity of dividend policy as a signal does not depend on the current cash levels. There is no incentive for a bank to pretend to follow a different policy than it would at its payout threshold if it, for instance, gets close to default. Therefore an additional commitment device is not necessary for investors to trust banks' policy announcements.

3.3.2 Separating equilibrium

When the market cannot observe the bank's type, the good bank can decide to signal its type by paying out dividends earlier, to the extent that the bad bank does not want to mimic the good bank. We describe the mechanism underlying the separating equilibrium below. When deciding whether to mimic or not, the bad bank balances the cost of having to issue dividends out earlier versus the benefit of having a higher market valuation. By deviating from its first-best strategy, the good bank can affect this trade-off. A more aggressive payout policy lowers the market value of a good bank, making it less attractive to mimic. Furthermore, the bad bank suffers a mimicking cost by hoarding less cash than in the first-best strategy. We establish the existence of a dividend payout level such that the bad bank does not find it profitable to mimic anymore.

First, one needs to determine whether the incentive compatibility constraint (ICC) of the bad bank holds. Suppose the good bank picks a dividend payout strategy m^S. If the bad bank mimics, its value function will be $V_{B,G}(m;m^S)$. If instead the bank refrains from mimicking the good bank, it follows its first-best strategy so that its value function becomes $V_{B,B}(m;m_B^*)$. Evaluated at m^S, the bad bank prefers mimicking the good type at $m^S < m_B^*$ when:

$$\underbrace{V_{B,B}(m^S;m_B^*)}_{\text{first-best}} \geq \underbrace{V_{B,G}(m^S;m^S)}_{\text{value when mimicking}} \tag{3.3}$$

When this condition does not hold at $m^S = m_G^*$, the good bank will have to deviate from its privately optimal strategy m_G^* in the separating equilibrium. The following proposition shows that there exists a solution $\overline{m}^S$ to Eq. (3.3). In all the numerical applications, this solution is unique. See also Figure 3.1 for a graphical representation of the two functions and their intersection points.

Proposition 3.4. *A solution $\overline{m}^S \in (0, m_B^*)$ exists to the equation $V_{B,B}(m^S;m_B^*) = V_{B,G}(m^S;m^S)$.*

Proof. Note at $m^S = m_B^*$ the value when mimicking dominates the first-best value, i.e., $V_{B,B}(m_B^*;m_B^*) < V_{B,G}(m_B^*;m_B^*)$. At $m^S = 0$, we have $V_{B,B}(0;m_B^*) = V_{B,G}(0;0) = 0$. Denote $\tilde{V}_{B,G}(m_S) := V_{B,G}(m_S;m_S)$, and $\tilde{V}_\ell := V_\ell(m_S;m_S)$ for $\ell \in \{G,B\}$. A sufficient condition for existence of $\overline{m}^S$ is that $V'_{B,B}(0;m_B^*) > \tilde{V}'_{B,G}(0)$. After some algebraic manipulations, it follows that

$\tilde{V}'_G(0) = \tilde{V}'_B(0) = 1$, such that $\tilde{V}'_{B,G}(0) = k\tilde{V}'_G(0) + (1-k)\tilde{V}'_B(0) = 1$. Since $V'_{B,B}(0; m^*_B) > 1$, the existence condition is satisfied. □

To determine whether paying out dividends at or below $\overline{m}^S$ is an equilibrium strategy, we check incentive compatibility of the good bank. The good bank has an incentive to separate when its value in the separating equilibrium is larger than its value when mimicking the bad bank. That is:

$$\underbrace{V_{G,G}(m^S; m^S)}_{\text{value in separating eqbm}} \geq \underbrace{V_{G,B}(m^S; m^*_B)}_{\text{value when mimicking}} . \tag{3.4}$$

The threshold $\underline{m}^S$ for which Eq. (3.4) is binding represents the lowest target cash level such that the good bank prefers separation over mimicking and such that observing the target cash level m^S can safely be interpreted as a signal by outsiders. A separating equilibrium exists only if $\underline{m}^S \leq \overline{m}^S$. Note that by the optimality of m^*_G in the full information case, it follows that $\underline{m}^S \leq m^*_G$.

A sufficient condition for $m^S \in [\underline{m}^S, \overline{m}^S]$ to be a Perfect Bayesian Equilibrium (PBE) is that the good bank does not have an incentive to defect to a different strategy given a set of out-of-equilibrium beliefs. It suffices to show that this holds under the pessimistic belief that the good bank is of the bad type instead, which corresponds to the following condition:

$$V_{G,G}(m^S; m^S) \geq V_{G,B}(m^S; m^*_{G,B}), \tag{3.5}$$

where $m^*_{G,B}$ is the cash target chosen by the good bank when it is considered to be of the bad type by the market.

A separating equilibrium exists when there is a m^S for which the three conditions in Eq. (3.3), (3.4) and (3.5) are jointly satisfied. Observe that when $\underline{m}^S \geq m^*_G$, there will be a separating equilibrium in which both banks choose a strategy that coincides with the first-best strategy. In the reverse case, the good bank has to deviate from its optimal strategy to prevent the bad bank from mimicking. Denote by $\underline{m}_L$ and $\underline{m}_H (> \underline{m}_L)$ the two solutions to Eq. (3.4) and let $\tilde{m}_L$ and $\tilde{m}_H (> \tilde{m}_L)$ be the two solutions to Eq. (3.5). It is straightforward to show that $\underline{m}_L < \tilde{m}_L < m^*_G < \tilde{m}_H < \underline{m}_H$. A separating equilibrium exists only if $\overline{m}^S \geq \tilde{m}_L$. Since paying out dividends earlier than m^*_G is costly for good banks, it will select the minimum of $\overline{m}^S$ and m^*_G. The good bank has no incentive to deviate from this strategy which can be sustained under pessimistic beliefs. After applying the Cho-Kreps Intuitive Criterion, see Cho and Kreps (1987), the least-cost separating contract strategy is uniquely selected. The following proposition formalizes this.

Proposition 3.5. *There exists a separating equilibrium in which both banks' market valuations correspond to their intrinsic valuations when $\overline{m}^S \geq \tilde{m}_L$. In the least-cost separating equilibrium, the good bank pays out dividends more aggressively than in the first-best case and its value is* *given by:*

$$V_G^{lcs}(m) = \begin{cases} V_G(m;\overline{m}^S), & \text{for } \overline{m}^S < m_G^*, \\ V_G(m;m_G^*), & \text{otherwise.} \end{cases}$$

The bad bank pays out at its first-best strategy and has value $V_B(m;m_B^*)$.

3.3.3 Pooling equilibrium

In the pooling equilibrium, outsiders are not able to determine the bank's type. As a result, for dividend strategy m^P, the market valuation component of both bank types is

$$V_p(m;m^P) = \alpha V_G(m;m^P) + (1-\alpha)V_B(m;m^P).$$

To determine the existence of the pooling equilibrium, we first determine whether mimicking the good type is an optimal strategy for the bad bank. This is the case when the following incentive compatibility constraint holds:

$$\underbrace{V_{B,p}(m^P;m^P)}_{\text{value when pooling}} \geq \underbrace{V_{B,B}(m^P;m_B^*)}_{\text{first-best}} \tag{3.6}$$

Let $\overline{m}_L^P$ and $\overline{m}_H^P (> \overline{m}_L^P)$ be the two solutions to Eq. (3.6). Since $V_p(m;m^P) > V_B(m;m^P)$, the threshold $\overline{m}_L^P \in (\overline{m}^S, m_B^*)$ and $\overline{m}_H^P > m_B^*$.

Without further refinements, we face multiplicity of equilibria, which is a common feature of signaling games. Maskin and Tirole (1992) consider the mechanism design game in which the informed principal (bank management in our setting) offers a contract ex ante to the uninformed outsiders. They show that only those pooling equilibria survive that Pareto-dominate the least-cost separating equilibrium as was characterized in Proposition 3.5. Therefore, the remaining restriction is that the value of the good bank in the pooling equilibrium is larger than in the least-cost separating equilibrium:

$$\underbrace{V_{G,p}(m^P;m^P)}_{\text{value when pooling}} \geq \underbrace{\mathbb{1}_{\{m_G^* \leq \overline{m}^S\}} V_{G,G}(m^P;m_G^*) + \mathbb{1}_{\{m_G^* > \overline{m}^S\}} V_{G,G}(m^P;\overline{m}^S)}_{\text{value when separating}}. \tag{3.7}$$

Let $\underline{m}_L^P$ and $\underline{m}_H^P$ be the two solutions to Eq. (3.7). There will be pooling equilibria if and only if there is a range of m^P for which conditions (3.6) and (3.7) hold. Note that in the case that $m_G^* \leq \overline{m}^S$, condition (3.7) is violated because the good bank cannot do better than its first-best strategy. Furthermore, if $\overline{m}_L^P > \underline{m}_H^P$, there will not be a strategy m^P for which conditions (3.6) and (3.7) hold.

Let $m_{\ell,p}^*$ be the best pooling equilibrium target cash level of bank type ℓ, see Appendix A.3.1. As $m_{G,p}^* < m_{B,p}^*$ for the parameters considered, there will not be a single Pareto-optimal pooling equilibrium. Notice that a necessary condition for a pooling equilibrium to exist is that $m_{G,p}^*$ satisfies condition (3.7). Furthermore, note that possible pooling strategies outside the range $[m_{G,p}^*, m_{B,p}^*]$ are Pareto-dominated by either $m_{G,p}^*$ or $m_{B,p}^*$.

In the range of Pareto-dominant pooling equilibria, we focus our attention on the best pooling equilibrium for the good type $m^*_{G,p}$. When outsiders infer there is a pooling equilibrium, they expect the good bank to be the first type to start paying out dividends at $m^*_{G,p}$, being a more aggressive policy than $m^*_{B,p}$. The bad bank does not want to reveal its type and follows. The selection of the pooling equilibrium will not alter the results qualitatively, only quantitatively.

Proposition 3.6. *A pooling equilibrium exists in which the market valuation of both bank types is $V_p(m) := \alpha V_G(m) + (1-\alpha)V_B(m)$ and both types pay out dividends at threshold m^P if conditions (3.6) and (3.7) are satisfied. Compared to the first-best case, good banks pay dividends later and bad banks pay earlier in the pooling equilibrium.*

3.3.4 Numerical analysis

Exogenous parameters

Table 3.1 displays the parameter baseline values. The cash reserve at time $t = 0$ is assumed to be $m = 1$.[14] The risk-free rate is set to $\rho = 0.035$. The mean after-coupon cash flow is $\mu = 0.1$ and the volatility σ is set to 0.1. These parameter values, which all assumed to be annual rates, are similar in size to those used in Hugonnier and Morellec (2017) and Klimenko and Moreno–Bromberg (2016). In the baseline case, we assume that bad banks compromise a fraction $1-\alpha = 0.2$ in the economy being subject to a liquidity shock of size $f = 0.15$ with an expected waiting time of $\lambda^{-1} = 5$ years. Lastly, we assume that the weight that management puts on the market valuation is $k = 0.5$.

Figure 3.3 displays the selected equilibrium strategies for different parameter values in the absence of any regulatory measures. We consider parameters corresponding to three different model elements: shock arrival rate and size, investor beliefs and preferences, and cash flow drift and volatility.

Liquidity shock

Figure 3.3(a) shows the comparative statics for liquidity shock arrival rate λ. Naturally, all lines coincide at $\lambda = 0$, as at this point, the good and bad types are identical, making signaling behavior irrelevant. As λ increases, the optimal cash target of the bad bank increases, while the optimal target of the good bank is unaltered. At first, higher λ makes mimicking more attractive so that the good bank needs to lower its cash target more aggressively to achieve a separating equilibrium. Eventually, the effect of a more likely shock on the bad banks' intrinsic value dominates, and the good bank can separate with a relatively smaller deviation from its first-best strategy. Facing this reaction function, the good bank accepts the pooling equilibrium for low values of λ where the cost of being pooled with the bad bank is relatively small. As λ increases, the cost of the pooling equilibrium relative to the cost of separating by distorting from optimal strategy m^*_G decreases. As a result, the equilibrium switches to a separating equilibrium.

[14]This value is generally higher than the resulting dividend thresholds in our model, implying that banks make a lump-sum payment at $t = 0$.

Figure 3.3(b) shows the effects of shock size f. Again, all lines coincide at $f = 0$. With effects similar to increasing the shock arrival rate, a pooling equilibrium forms for low values of f. Eventually, it is replaced by a separating equilibrium that gradually converges to a first-best equilibrium where the good bank does not need to distort its payout policy to deter the bad bank.

Investors

Figure 3.3(c) displays the effects of the fraction of good banks α on the equilibrium outcome. One can observe that only the target cash level corresponding to the pooling equilibrium moves in α. With a small fraction of good banks, the market value of the average bank in the pooling equilibrium is dominated by the value of bad banks. This makes the cost of being pooled very high for the good banks in the economy, resulting in a separating equilibrium. As α increases, the payout policy of the pooling equilibrium converges to the first-best policy of a good bank. The value of the bad banks drags down the market value of the average bank, which enters the value function of the good bank in the pooling equilibrium and its optimization for $m^*_{G,p}$, see Section 3.3.3. The decreasing degree of distortion implies that the pooling equilibrium gradually becomes more attractive for a good bank while the separating equilibrium strategy remains unchanged. Therefore, the banks switch to a pooling equilibrium at some point. In the extreme case where $\alpha = 1$ and there are only good banks, the optimal pooling strategy coincides with the good bank's first-best strategy.

The effects of changing short-term investor fraction k (or interpreted alternatively, the strength of investors' liquidity concerns) can be found in Figure 3.3(d). As was the case for α, first-best policies m^*_G and m^*_B are unaffected by changing k as market value and intrinsic value coincide under full information. However, as the weight on the market value in the value function increases, so does the bad bank's benefit of mimicking the good bank. As a result, the good bank cannot deter the bad bank without distorting its payout policy. Since the good bank sets a higher cash target when it is pooled with the bad bank, pooling equilibrium policy $m^*_{G,p}$ is increasing in k. The good bank is motivated to do so because its market value depends on the intrinsic value of the bad bank in the pooling equilibrium. As can be observed in the plot, the (negative) slope of the deterioration policy is steeper than the (positive) slope of the pooling policy, making it increasingly costly for the good bank to separate and leading up to a pooling equilibrium.

Cash flow process

Figure 3.3(e) shows the effects of changing cash flow drift μ. For low values of μ, the relative effect of liquidity shock f is larger than for large values of μ, as the time to build a buffer sufficient to offset the shock is longer (in expectation). This effect creates stronger mimicking incentives for the bad bank, making it more costly for the good bank to deter it, resulting in a pooling equilibrium is selected. As the first-best target cash level of the good bank m^*_G decreases faster in μ than that of the bad bank m^*_B, the good bank's cost of distorting its policy becomes small enough for it to prefer a separating equilibrium.

Lastly, Figure 3.3(f) looks at the effects of cash flow volatility σ. For low values of σ, the probability of default as a result of the Brownian risk component is relatively low. As σ increases, the relative risk of being wiped out by the Poisson risk relative to the Brownian risk becomes smaller, so that the first-best strategies of the good and bad bank slowly converge. When σ is small, the difference between the optimal strategy of the good and bad bank is relatively big, making it rather costly for the bad bank to mimic the good bank. As a result, the good bank does not need to distort its strategy. As σ increases further, the bad bank's benefit of mimicking the good bank increases, so that the good bank needs to distort its dividend strategy (more) to deter it. For high σ, the cost of being pooled for the good bank is smaller since the two banks are relatively more similar and a pooling equilibrium prevails.

3.4 Dividend restrictions

This section considers the effects of the regulator imposing restrictions on the bank's payout policy, or equivalently, the bank's required cash levels. Throughout the analysis, we assume that the dividend restriction is lifted upon arrival of the liquidity shock.[15] We will now look at the effect of dividend restrictions in the case of (i) a pooling equilibrium, (ii) a separating equilibrium, and (iii) the first-best separating equilibrium. We will see that dividend restrictions have the potential to break the separating equilibrium.

3.4.1 Construction of restricted equilibrium

(i) Pooling equilibrium m^P

First, suppose that the bank plays a pooling equilibrium m^P in the absence of a dividend restriction. When $m^R \leq m^P$, the pooling equilibrium is not affected. For $m^R > m^P$, the restriction starts to constrain the pooling equilibrium. The restricted pooling equilibrium $\tilde{m}^P$ needs to satisfy the following conditions. Similar to condition (3.6), the bad bank should prefer to pool rather than to play its now *restricted* first-best strategy:

$$V_{B,p}(\tilde{m}^P;\tilde{m}^P) \geq V_{B,B}(\tilde{m}^P;\max\{m_B^*, m^R\}).$$

Furthermore, the good bank should prefer to pool rather than to mimic the bad bank:

$$\underbrace{V_{G,p}(\tilde{m}^P;\tilde{m}^P)}_{\text{value when pooling}} \geq \underbrace{V_{G,B}(\tilde{m}^P;\max\{m_B^*, m^R\}).}_{\text{value when mimicking bad bank}}$$

To ensure that the good bank has no incentive to deviate, the value in the pooling equilibrium should be larger than when the bank deviates to an out-of-equilibrium strategy. Under pessimistic out-of-equilibrium beliefs, this translates to the following condition:

$$V_{G,p}(\tilde{m}^P;\tilde{m}^P) \geq V_{G,B}(\tilde{m}^P;\max\{m_{G,B}^*, m^R\}).$$

In the unrestricted case, the pooling equilibrium is $\max\{m_{G,p}^*, \overline{m}_L^P\}$. In the scenario where $m_{G,p} > \overline{m}_L^P$, a restriction $m^R > m_{G,p}$, the good bank cannot play its optimal pooling strategy

[15] We have performed the analysis in which the dividend restriction remains active after the liquidity shock has arrived. As this did not significantly change the results, we leave these results untabulated.

anymore. As there is no gain in setting a higher dividend threshold than the restriction, it sets $\tilde{m}^P = m^R$, which will also be followed by the bad bank. A similar reasoning applies when $m^R > \overline{m}_L^P > m_{G,p}$.

(ii) Separating equilibrium $m^S = \overline{m}^S$
Suppose now that absent a dividend restriction, the bank plays a (least-cost) separating equilibrium with strategy $\overline{m}^S (< m_G^*)$. When $m^R > \overline{m}^S$, the separating equilibrium breaks down and a pooling equilibrium as described above arises.

(iii) First-best separating equilibrium $m^S = m_G^*$
Lastly, consider the case that absent a dividend restriction, the bank types are in the first-best separating equilibrium, that is, the good bank plays optimal $m_G^* \in [\underline{m}^S, \overline{m}^S]$ and the bad bank m_B^*. A dividend restriction $m^R < m_G^*$ will have no effect on the equilibrium. When m^R is set such that $m^R \in [m_G^*, \overline{m}^S]$, the restricted least-cost separating equilibrium is at the level m^R. Whereas in the first-best case, a pooling equilibrium did not exist, this can change in the presence of the restriction. A pooling equilibrium emerges when conditions (3.6) holds and

$$\underbrace{V_{G,p}(m^P; m^P)}_{\text{value when pooling}} \geq \underbrace{V_{G,G}(m^P; m^R)}_{\substack{\text{value in restricted least-cost} \\ \text{separating equilibrium}}}.$$

In the case that $m^R \geq \overline{m}^S$, the first-best separating equilibrium breaks into a pooling equilibrium as described before.

From this analysis, it becomes clear that dividend restrictions have the potential to break the separating equilibrium. Breaking the separating equilibrium makes the good bank less likely to default as it cannot use an aggressive dividend policy to signal its type. At the same time, provided that $m^R < m_B^*$, dividend restrictions that break the separating equilibrium make the bad bank less safe as it abandons its first-best optimal payout policy and pays out dividends at a lower level of cash-holdings to mimic the good bank. In the remainder of this section, we continue the numerical analysis and look at the effect of dividend restrictions on the bank types' payout strategies, 1-year default probability, and valuations.

3.4.2 Effects of dividend restrictions

Figure 3.4 shows the effects of a dividend restriction m^R that is in place *before* the liquidity shock for two different parameter settings. Parameter setting (i) represents a scenario with a large but concentrated shock, whereas the shock is small but widespread in parameter setting (ii).

The main metrics of interest are the average 1-year default probability and the value of the average bank in the economy.[16] In addition to the average bank value, the regulator cares about bank default, as it generally has large negative externalities on the economy. To not

[16]We do not distinguish between the market and intrinsic valuation of the average bank, as these metrics coincide. This follows naturally in the separating equilibrium where the banks signal their type to the market. In the pooling case, the market valuation of the average bank is $\alpha V_{G,p}(m) + (1-\alpha) V_{B,p}(m) = \alpha \left(k[\alpha V_G(m) + (1-\alpha) V_B(m)] + (1-k) V_G(m)\right) + (1-\alpha) \left(k[\alpha V_G(m) + (1-\alpha) V_B(m)] + (1-k) V_B(m)\right) = \alpha V_G(m) + (1-\alpha) V_B(m)$. This value corresponds to the average intrinsic value.

impose additional assumptions, we think of these externalities as being the same for both types, so that the regulator puts equal weight on their respective default risk.

Effects of dividend restriction on payout strategies

The dividend payout strategies of the good and bad bank are displayed in Figures 3.4(a) and 3.4(b). For low values of restriction m^R, the separating equilibrium is not affected, so that the good bank can signal its type by adopting a more aggressive dividend policy, and the bad bank sticks to its first-best strategy. As soon as m^R starts constraining the separating equilibrium, the equilibrium switches to the pooling type, which means that the bad bank pays out dividends at a lower cash level than it would have done in the first-best case. When restriction m^R starts binding the (unconstrained) pooling equilibrium, both banks pay dividends at m^R.

Effects of dividend restriction on 1-year default probability

One of the regulator's main concern is the effect of regulatory measures on the default probabilities in the banking industry. Let the probability at $t = 0$ that a bank defaults within a time horizon T be denoted by:

$$\mathrm{PD}_\ell^T = \mathbb{P}\left(\tau_\ell^\pi < T \mid M_{\ell,0}^\pi(t) = m\right).$$

In the numerical analysis of this paper, we consider the 1-year default probability, i.e., we set $T = 1$. A description of the computation of PD_ℓ^T can be found in Appendix A.3.2 and follows the methodology of Klimenko and Moreno–Bromberg (2016).

Figures 3.4(c) and 3.4(d) show the 1-year default probabilities of the good bank, the bad bank, and the average bank (i.e., the weighted sum of good and bad banks in the economy) for the two parameter settings. In both parameter settings, the good bank has a larger default probability than the bad bank in the separating equilibrium. Even though the good bank is not subject to Poisson risk, it sets its cash target so low that it becomes more likely to default than the bad bank. When m^R starts to constrain the separating equilibrium, the default probability of the bad bank spikes up, as it now hoards less cash than in the separating equilibrium. In contrast, the good bank becomes safer now that it does no longer play the aggressive separating policy. When m^R eventually starts binding the pooling equilibrium, both banks become safer again. The effect of the dividend restriction on the average default probability can go in two ways. Figure 3.4(c) shows that the average default risk increases when the separating equilibrium changes into a pooling equilibrium, whereas the opposite is true in Figure 3.4(d).

Effects of dividend restriction on bank valuations

The effect of dividend restriction m^R on the intrinsic, market, and total bank value can be found in Figures 3.4(e) and 3.4(f). Note that there is only a single line for the average bank, as the market valuation and the intrinsic valuation of the average bank coincide. This follows from the assumption of rational expectations that says that investors' beliefs about the fraction of the two types of banks are correct. An overvaluation of one type means an undervaluation of the other which cancels out on average. In line with this, observe that the market valuations of the good and bad bank in the pooling equilibrium coincide with the intrinsic valuation of the average bank.

Both figures show that when restriction m^R breaks the separating equilibrium, the intrinsic value of the good bank changes as it abandons its aggressive separating policy. In parameter setting (i), the intrinsic value slightly drops, which implies that the value of the good bank under the aggressive separating strategy m_G^* is slightly higher than in the pooling strategy $m_{G,p}^*$. For parameter setting (ii), the good bank's intrinsic value increases, as the good bank is not playing the aggressive separating policy anymore. By contrast, the good bank's market valuation drops in both parameter settings, since it is now indistinguishable from the bad bank for outsiders. The opposite effect applies to the bad bank. Initially, the bad bank's intrinsic value decreases when the separating equilibrium is broken by m^R since the bad bank now deviates from its first-best strategy. Meanwhile, its market valuation jumps up since it is now pooled with the good type. When the restriction is tightened further, both market and intrinsic valuations of the bad bank increase, up to the point where the restriction starts constraining the bank's respective first-best strategies.

A notable outcome of this type of dividend restriction is that in switching from the separating equilibrium to the pooling equilibrium, the payout policy of the good bank jumps up. With such a policy in place, it may very well seem like the dividend restriction is not binding, as it will be the case for a restriction below $m_{G,p}^*$. As such, the regulator might come to believe that a dividend restriction in place does not affect current bank financial policies.

Furthermore, in the event of a change of economic conditions, a previously non-binding restriction can become binding. As an example, consider an upward shift in the shock arrival rate λ from 0 to 0.1 as depicted in Figure 3.3(a). With no pending shock, the two bank types are identical and any restriction set below the current shared policy of 0.4 is not binding. For concreteness, consider dividend restriction level $m^R = 0.3$. Under the threat of a liquidity shock, the good bank would, in the absence of regulation, choose a more aggressive policy of $\overline{m}^S \approx 0.34$ to achieve separation. However, the presence of the dividend restriction makes this unachievable, and the laissez-faire separating equilibrium does not materialize. As an extension, a minor tightening, such as the activation of a counter-cyclical capital buffer, might have a major impact when imposed in response to changes in the economic environment.

Whether or not a dividend restriction is desirable depends on which of the two is the larger evil: a pooling equilibrium in which the bad bank pays out inefficiently early (and the good bank sub-optimally late), or the separating equilibrium, in which the good bank pays out inefficiently early. Next, we quantify these effects further by analyzing a number of relevant scenarios.

3.4.3 Scenario analysis

To illustrate the pitfalls and potential for regulatory intervention, we focus on two fundamental scenarios that can be mapped to the sources of shocks introduced above: a large but concentrated shock, and a smaller but more widespread shock, see Figure 3.4. We consider two relevant dimensions of the liquidity shock: the *scope* of the shock, i.e., the fraction of affected banks $1-\alpha$, and the *size* of the shock, i.e., the impact of the shock on the bad bank's liquid reserves f. We analyze two channels through which the scope of the shock operates when regulation enforces a pooling equilibrium: a *direct* channel and an *indirect* channel. The direct channel works as follows: more bad banks in the economy make, other things equal, dividend regulation less attractive, as the bad banks switch from their first-best to a distorted policy in the pooling equilibrium, thereby lowering their intrinsic values and increasing default risk, see Figure 3.4. The indirect channel represents the additional effect that arises from the banks' adjustment of their policies in response to the scope of the shock. That is, when there are few (many) bad banks in the economy, the pooling equilibrium strategy $m^*_{G,p}$ that is selected by the good bank tilts more (less) towards the first-best strategy of the good bank m^*_G, creating a bigger (smaller) distortion from the first-best of the bad bank m^*_B. The *size* of the shock f determines whether a separating equilibrium would have been selected in the absence of regulation, and if so, which of the two channels dominates.

Large concentrated shock

In the first scenario, we consider that a small number of banks (large α) are subject to a significant negative shock (large f). This scenario could arise from a third-party trading loss (e.g., Archegos capital) or a wave of fines from misconduct (e.g., North European money-laundering scandals). We find that a regulator should be cautious in imposing payout restrictions in this scenario, as it risks having an adverse effect on both of the industry-wide metrics by simultaneously decreasing the average value of banks *and* raising the risk of bank defaults, see the yellow lines in Figures 3.4(c) and 3.4(e), respectively.

Decomposing the average effects into their constituents, the big increase in default risk of bad banks and the large drop in their intrinsic value dominate the industry outcome, even though they only constitute a small fraction of the economy. This illustrates the importance of considering the indirect effect of the concentrated exposure through the strategic equilibrium behavior. On the one hand, the small fraction of bad banks implies that the payout policy under the pooling equilibrium heavily tilts towards the first-best policy of the good banks m^*_G, see Section 3.3.4. This requires a large deviation for bad bank from their first-best strategy m^*_B. On the other hand, this change also makes obtaining the market value of an average bank more attractive for the bad bank. In equilibrium, the relatively small number of bad banks have a seemingly out-sized impact on the industry outcome. This is especially surprising for the regulation-induced pooling equilibria, considering that the presence of the bad banks does not dramatically alter the behavior of the good banks. In summary, regulation has a relatively limited positive impact on the safety of a large base of banks, while making a small group radically more unsafe.

Furthermore, regulation that induces a pooling equilibrium results in a large value transfer from outsiders who were to buy the shares to the insiders of these banks taking the other side of that trade. Figure 3.4(e) shows that the bad bank's market value increases drastically and the intrinsic value decreases dramatically, see the dashed and solid black lines in Figure 3.4(e), respectively.

Small widespread shock

In the second scenario, we consider the presence of a minor shock (small f) that affects a broad segment of the banking industry (small α). Examples of this scenario are the risk of sudden moves in asset prices leading to margin calls on derivative contracts (see European Systemic Risk Board (2020a)), losses related to the deterioration of collateral resulting in higher haircuts (see Shleifer and Vishny (2011)), and costly restructuring of funding conditions. The concerns related to the banking sector during economic crises such as the Covid-19 crisis (see European Systemic Risk Board (2020b)), are more complex than what can be captured by a one-off shock. However, as a first approximation, a pending sector-wide liquidity shock can provide some intuition about the strategic response to regulation under such circumstances.[17]

In contrast to the large but concentrated shock studied above, the outlook for regulation in the second scenario is more promising. Breaking the separating equilibrium decreases the default risk *and* increases the value of the average bank, see the yellow lines in Figure 3.4(d) and 3.4(f). We classify this scenario in which regulation improves both metrics as a *regulatory Goldilock* scenario. The potential for value creation arises from the distortion introduced by signaling. Comparing the policy of the good bank in the previous case to the current, as captured in Figure 3.4(a) and 3.4(b) respectively, it is indeed the case that the good bank's target cash-level in the separating equilibrium is set more aggressively. Comparing the strategy of the bad bank in the same plots, we see that the smaller shock substantially lowers the bad bank's first-best payout boundary, which pushes the good bank to an even lower cash target in the separating equilibrium. Note that α has no impact on the payout levels in the separating equilibrium where information is symmetric. Once regulation breaks the aggressive separating equilibrium, the widespread nature of the shock tilts the pooling policy $m^*_{G,p}$ towards the first-best policy of the bad bank m^*_B. Since the bad bank's policy is not altered much by switching from the separating to the pooling equilibrium, the increase of the default probability and the loss of intrinsic value are limited for the bad bank.

As was the case in Section 3.4.3, the strategic behavior of the *smallest group* has the *biggest impact* on aggregate outcomes. The analysis in Section 3.4.1 already suggested that regulation shifts the distortion from the good bank to the bad bank by breaking the separating equilibrium. However, with this qualitative result in mind, we might expect that a larger fraction of the industry being exposed to the shock would render regulation sub-optimal as the effect on those bad banks is mechanically over-weighted on an industry level. Instead, we find that a sharp response of the minority drives the aggregate outcome in both scenarios discussed, reversing the logic of the more straightforward direct channel.

Alternative scenarios

Having described the most extreme scenarios of a large, concentrated shock and a small, widespread shock, we now discuss a few other scenarios without explicitly tabulating the

[17] In our model, the initial regulatory response of the ECB to ask banks to refrain from paying dividends corresponds to the limiting case of $m^R \to \infty$, which leads to the restricted pooling equilibrium of Section 3.4.1. The analysis of this section is more relevant for the situation when the ECB moved to a recommendation of limiting dividends rather than one to not payout at all (see European Central Bank (2020)), or the (eventual) response of the Federal Reserve (see Federal Reserve System (2020)).

results as in Figure 3.4. In the scenario where the scope and size of the shock are limited, i.e., $1-\alpha = 0.25$ and $f = 0.075$, banks are already in a pooling equilibrium in the absence of regulation. Payout restrictions lower default risk but also lower the value of the banking industry. With a medium jump size of $f = 0.125$, regulation becomes beneficial, like in the case of a small widespread shock, by reducing default risk and creating value. In this scenario, the direct effect that was described earlier dominates the adverse indirect effect of regulation. Combining these observations with that of Section 3.4.3, one see that when there is a small group of bad banks, payout restrictions lower stability and value when the shock is large ($f = 0.2$), fosters stability and creates value when the shock is medium-sized ($f = 0.125$), and increases stability but reduces value when the shock is small ($f = 0.075$). In the scenario where there are many bad banks and the shock is big, i.e., $1-\alpha = 0.75$ and $f = 0.2$, payout restrictions have a similar effect as in the scenario where the shock is big and there are few bad banks, i.e., $1-\alpha = 0.25$.

3.4.4 Short-termism/Investor liquidity concerns

In addition to the economic fundamentals of the liquidity shock, investor preferences can help predict the effectiveness of regulation. As discussed in the model set-up in Section 3.2.1, the parameter k reflects the importance of the possibility of selling shares on short notice to investors, whether it is because some investors have a short-term focus or because they are subject to liquidity concerns. In troubled times, investors might put more weight on the bank's market valuation, because a larger fraction of them have a short-term focus, or because their own liquidity concerns are stronger. For the latter case, investors might have to cover shortfalls in other parts of their portfolios, or want to liquidate their position in the bank to exploit new investment opportunities.

Based on the value of k, three regions of regulatory impact emerge, see Section 3.3.4 and Figure 3.3(d). For low values of k, banks separate without any distortion of the good bank's policy, and while regulatory intervention *might* lower the average default risk, it will surely be value-destroying by causing deviations from the first-best policies. For high values of k, banks are already in a pooling equilibrium, and regulatory intervention makes all banks safer. However, there tends to be an element of value-destruction when the regulator sets the threshold m^R above the optimal pooling strategy $m^*_{G,p}$. To fix ideas, consider the limiting case of $k = 1$, where the good bank optimizes market value, see Eq. (3.2). Since market value coincides with average bank value in the pooling equilibrium (see Section 3.4.2), any deviation from $m^*_{G,p}$ is suboptimal. Finally, in the intermediate region, banks play a separating equilibrium where the bad bank follows its first-best, but the good bank does not. At the upper end of this region, the good bank pays a relatively aggressive dividend policy, which corresponds to high default risk. Therefore, imposing restrictions is more likely to be beneficial for a value of k at the upper end rather than at the lower end of this region.

This observation applies to different scenarios for shock size and scope. While the boundary values of k for the different regions vary, the effect is the same, and for some cases, a large enough increment of k within the intermediate region has a strong enough effect to overturn a pessimistic outlook for regulation. This leads to the rough rule of thumb that regulation is more likely to be beneficial when investors are very focused on the (short-term) market value. A refinement of this guideline is possible if the regulator can identify the laissez-faire equilibrium; a higher k improves the outlook for regulation if it prevents aggressive distortion of the good bank's payout policy. The possibility of undoing this distortion is what enables regulation to not only lower average default risk, but even create value on an industry level.

3.4.5 Macro-prudential regulation

The analysis in Sections 3.4.3 and 3.4.4 shows that the presence of asymmetric information complicates the trade-off that regulators face in designing macro-prudential regulation. The intuitive trade-off between stability and bank value does not always apply. This caveat is particularly relevant around the threshold where restrictions start constraining the separating equilibrium. Rather than suggesting that regulators abstain from interventions, our findings emphasize the importance of a thorough assessment of the economic situation and provide support for allowing a certain level of discretion in applying restrictions. In particular, our analysis shows that it is not only the direct impact of the scope of the liquidity shock that is relevant, but that the indirect effect of strategic adjustments can be substantial as well. The new trade-off that information frictions induce is between signaling and mimicking distortions. These distortions tend to increase with the focus of investors on (short-term) market value. Suppose the build-up of systemic risk during economic upswings is accompanied by a shift in investor focus. In that case, mitigating distortions from asymmetric information could be an additional benefit of activating macro-prudential measures such as the counter-cyclical capital buffer.

3.4.6 Conservative regulation

In light of the risk of possible doubly adverse outcomes as exemplified by the scenario in Section 3.4.3, an approach that a regulator might want to take is to set the payout constraint m^R equal to or above the first-best payout threshold of a bad bank m_B^*. In this way, both good and bad banks are guaranteed not to be more likely to default than in the separating equilibrium, so that the average risk of default *must* be lower. It comes at the cost of lower overall industry value, but this is qualitatively in line with what would happen in a setting without asymmetric information. However, the heterogeneity introduces a value transfer from good to bad banks, since bad banks become more valuable when pooled with good banks at the cost of a reduction of the good bank's market valuation. This observation suggests that it becomes interesting to be a good bank in anticipation of such an intervention. An interesting extension of the model would be to endogenize the shares of good and bad banks in the economy. One way to do this is to allow a continuum of bank managers to incur a private cost to avoid tail risk exposure. We expect that fewer managers would find it beneficial to pay such a cost when regulation lowers the value of a good bank and increases the value of a bad bank. Such a mechanism could lead to the banking industry becoming riskier than the counterfactual.

3.5 Conclusion

This paper studies the effect of dividend restrictions on a bank's payout strategy and default risk in the presence of asymmetric information. We develop a continuous-time model of a bank whose exposure to a pending liquidity shock is private information to its management. To boost their short-term market valuation, the exposed banks have incentives to mimic the dividend policy of the unexposed banks. In response, the unaffected banks can signal their type by aggressively lowering their target cash level. Depending on the economic environment, this strategic interaction results in either a separating or a pooling equilibrium. Dividend restrictions imposed by the regulator have the potential to break the separating equilibrium, thereby decreasing the default risk of the unexposed banks but increasing the default risk of the exposed banks. The effect on the average bank depends on fundamental economic factors of the shock's scope and size, and on investors' focus on short-term market valuation. In the presence of asymmetric information, regulatory intervention has the potential to improve *both* average default risk and banking industry value. However, it comes with the pitfall of causing deterioration of both. A promising avenue for future research is the development of indicators to help regulators navigate this challenging environment and assess the right course of action.

A possible model extension would be the introduction of spillover effects and the resulting implications for the banks' strategic behavior. One way to do so is to assume that the good types are also exposed to the liquidity shock, albeit to a lesser extent. Alternatively, contagion effects could be created by assuming that a bank default affects other banks it is linked to through common assets and interbank market connections. Another direction would be the introduction of recurring shocks rather than the assumption in place of a single shock. Doing so would give more insights into how to set long-term dividend regulations. However, this requires capturing the learning dynamics of outsiders as they observe the bank's cash reserve. Apart from the added complexity, outsiders will eventually learn the bank's type with almost certainty. Absent shocks to bank types, the information asymmetry is resolved after a given period, just as it is in our model after the arrival of the shock.

Tables and Figures of Chapter 3

Table 3.1: Baseline parameter values.

	Notation	Value
Initial level cash reserves	m	1
Discount rate	ρ	0.035
Cash flow drift	μ	0.1
Cash flow volatility	σ	0.1
Shock arrival intensity	λ	0.2
Shock size	f	0.15
Fraction of good banks in economy	α	0.8
Fraction of short-term investors	k	0.5

Figure 3.1: Graphical representation of solution $\overline{m}^S$ to Eq. (3.3). The blue line displays the first-best value function of the bad bank. The red line shows the value of the bad bank for different values of cash level m^S when paying dividends at m^S and being valued by the market as a good bank. The 45° illustrates the tangent line of $V_{B,G}(m_S; m_S)$ at $m_S = 0$, having a slope of 1. Parameters values are according to Table 3.1.

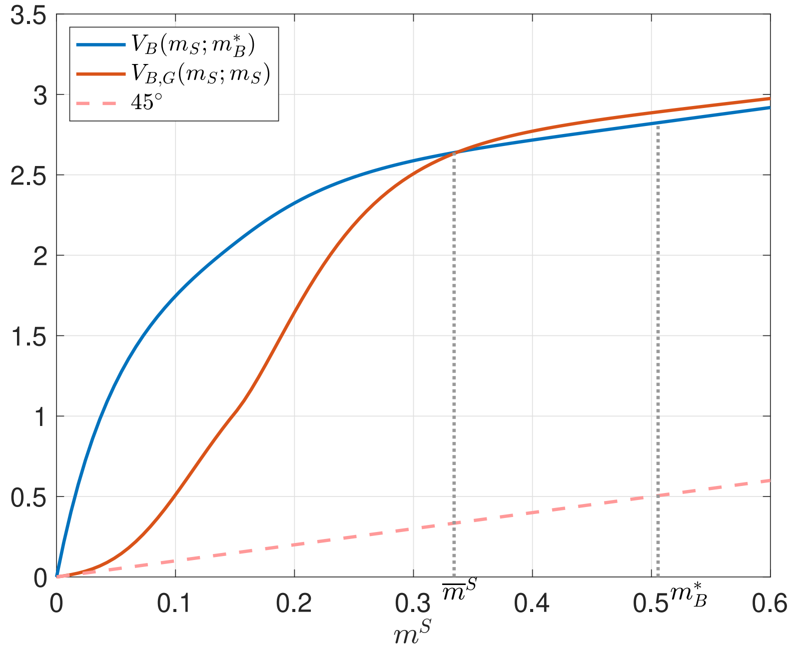


Figure 3.2: Optimal target cash level before the arrival of the shock for different values of liquidity shock f. Parameter values are according to Table 3.1.

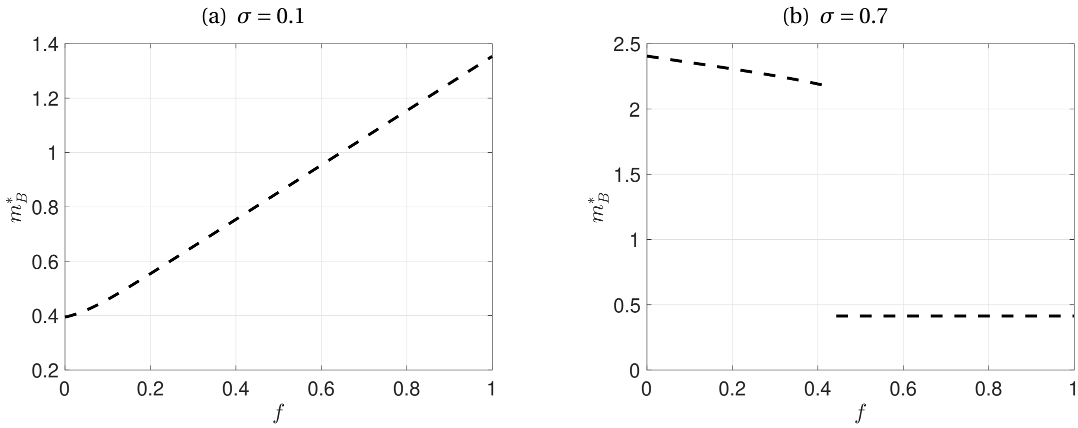


Figure 3.3: Dividend threshold and equilibrium selection. For different parameters, the graphs depict the dividend target (or equivalently, target cash level) in the least-cost equilibrium (green line), in the least-cost separating equilibrium (dashed), the first-best case of the good bank and the bad bank (the solid and dashed-dotted line, respectively), and the optimal target cash level of the good bank when pooled with the bad bank. The other parameters are according to Table 3.1.

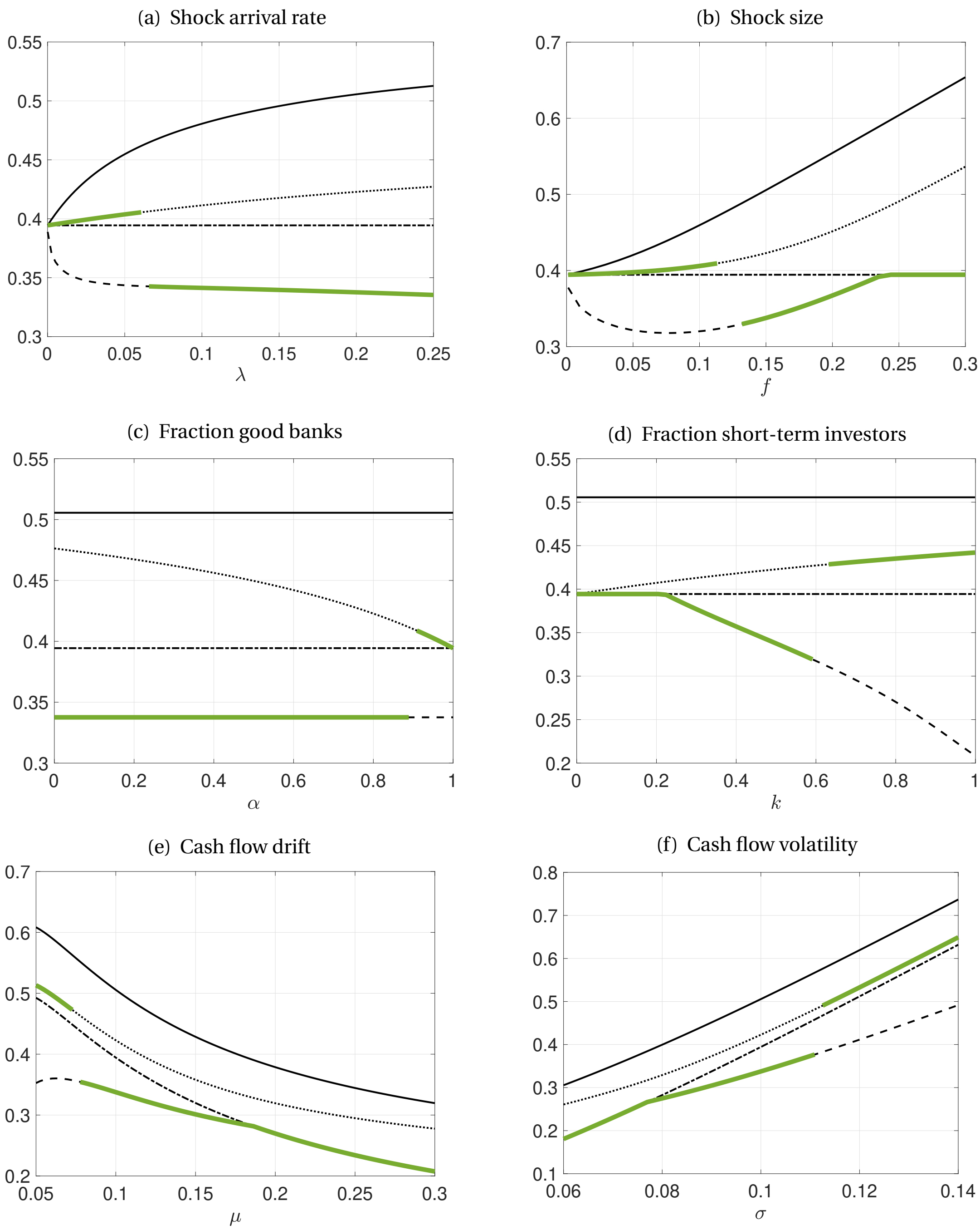
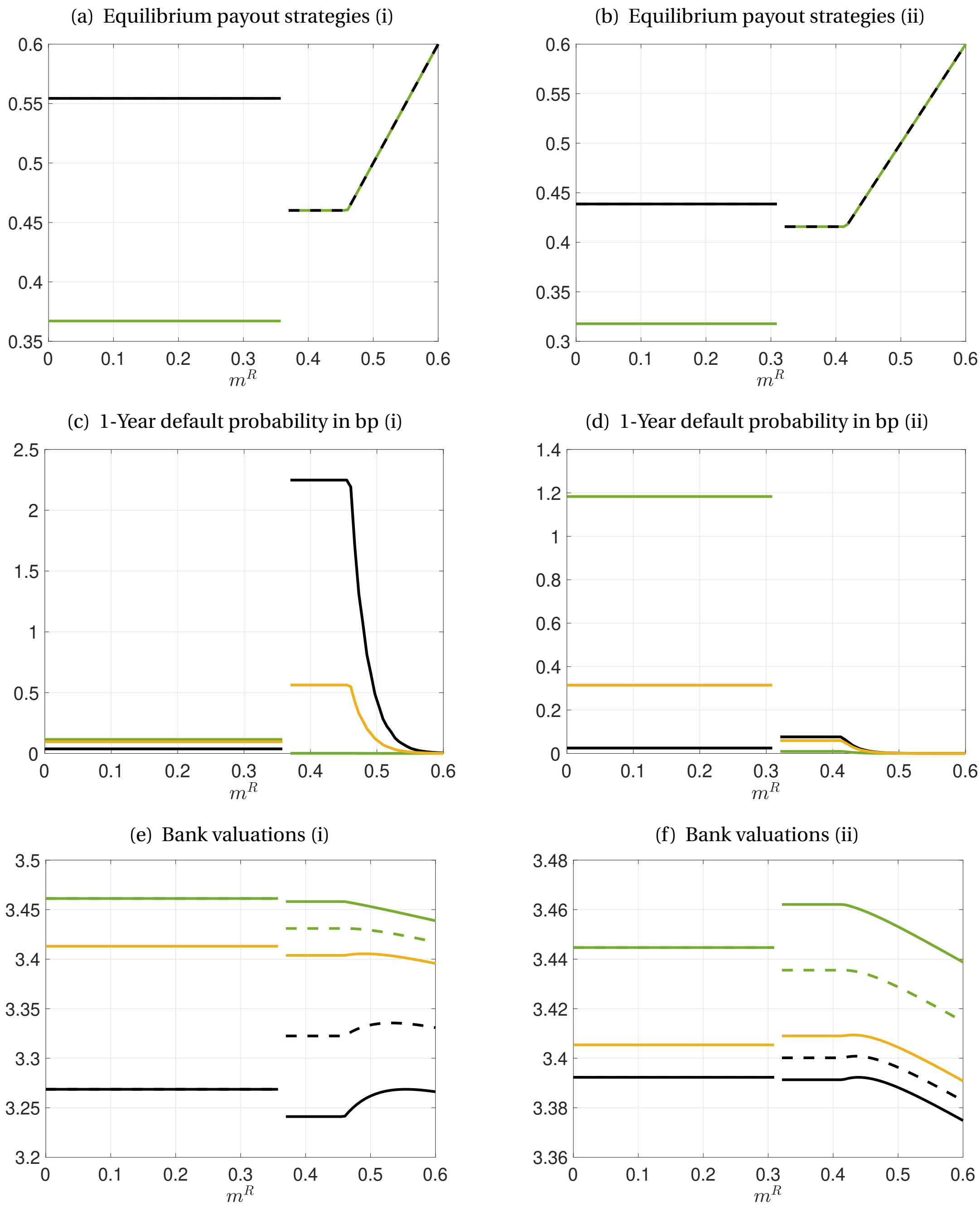


Figure 3.4: Dividend restrictions before shock. The parameters are based on Table 3.1, but parameter set (i) has $\alpha = 0.75$ and $f = 0.2$ (large concentrated shock), and parameter set (ii) has $\alpha = 0.25$ and $f = 0.075$ (small widespread shock). Figures (a) and (b) show the equilibrium pay out strategies of the good bank (green line) and bad bank (black line). Figures (c) and (d) show the 1-year default probability of the good bank (green), bad bank (black) and average bank (yellow). Figures (e) and (f) display for the good bank (green) and bad bank (black) the intrinsic value (solid) and combined intrinsic and market value (dashed), and the average value (yellow).



Conclusion

This thesis makes three contributions to the academic debate on banking and financial regulation. First, the thesis addresses the effects of tail risk on bank capital and liability structure. The model shows that tail risk, rather than diffusion risk, is the main driver of debt credit spreads, the actuarially fair deposit insurance premium, default probability, and magnitude of bank losses in the event of bank failure. Furthermore, whereas the relation between diffusion risk and optimal leverage is strictly negative, the model predicts a non-monotonic relation between tail risk exposure and optimal leverage. These results suggest that if the regulator wants to make a proper risk analysis of the bank, it should distinguish between the two types of risk.

Second, this thesis addresses the synergetic effects of market discipline and banking regulation in the form of capital requirements and deposit insurance. When regulatory measures are set within certain bounds, stricter regulation weakens the market discipline effect, which can lead to higher leverage ratios. The analysis shows that the regulator should incorporate the endogenous response to regulatory measures.

Third, the last chapter of this thesis studies the effect of dividend restrictions in light of the informational value that dividends carry. In the presence of informational frictions regarding the bank's exposure to a pending liquidity shock, banks use dividends as a signaling device. When dividend restrictions are set sufficiently high, the signaling function of dividends breaks down. Depending on the scope and size of the liquidity shock, this can have beneficial or adverse effects on the stability and valuation of the banking industry. Therefore, the regulator needs to be aware of the informational value of dividends, as imposing payout restrictions can have adverse effects.

A Appendices

A.1 Appendix to Chapter 1

A.1.1 Default state price and asset value in default

The bank defaults when the asset value hits or falls below the threshold value V_D. Kou and Wang (2003) showed that under the assumption of (double-)exponentially distributed jumps, closed-form solutions for the default time and the expected discounted asset value at default exist.

When the discount rate is r, the Lévy exponent corresponding to V_t is given by the following third-degree polynomial:

$$G(x) = r, \tag{A.1}$$
$$G(x) := \left(r - \delta - \frac{1}{2}\sigma^2 + \lambda\xi\right)x + \frac{1}{2}\sigma^2 x^2 + \lambda\left(\frac{\eta}{\eta + x} - 1\right).$$

Eq. (A.1) has three distinct real roots if $r > 0$, $\lambda > 0$ and $\eta < \infty$, denoted by $-\gamma_1, -\gamma_2$ and γ_3 such that:[1]

$$0 < \gamma_1 < \eta < \gamma_2 < \infty, \quad 0 < \gamma_3 < \infty.$$

When $\sigma > 0$, or $\sigma = 0$ and drift $r - \delta - \frac{1}{2}\sigma^2 + \lambda\xi < 0$, Kou and Wang (2003) showed that:

$$p_D := \mathbb{E}[e^{-r\tau}] = d_1\left(\frac{V_D}{V}\right)^{\gamma_1} + d_2\left(\frac{V_D}{V}\right)^{\gamma_2}, \tag{A.2}$$

$$\tilde{p}_D := V_D^{-1}\mathbb{E}[V_\tau e^{-r\tau}] = c_1\left(\frac{V_D}{V}\right)^{\gamma_1} + c_2\left(\frac{V_D}{V}\right)^{\gamma_2}, \tag{A.3}$$

where

$$c_1 := \frac{\eta - \gamma_1}{\gamma_2 - \gamma_1}\frac{\gamma_2 + 1}{\eta + 1}, \qquad c_2 := \frac{\gamma_2 - \eta}{\gamma_2 - \gamma_1}\frac{\gamma_1 + 1}{\eta + 1},$$
$$d_1 := \frac{\eta - \gamma_1}{\gamma_2 - \gamma_1}\frac{\gamma_2}{\eta}, \qquad d_2 := \frac{\gamma_2 - \eta}{\gamma_2 - \gamma_1}\frac{\gamma_1}{\eta}.$$

[1] For $\lambda = 0$, the polynomial $G(x) = r$ has only one negative root as the asset value dynamics are back to the regular diffusion process case, see Appendix A.1.2.

Eq. (A.2) represents the default state price, i.e., the price of a security that pays off one dollar in default. Eq. (A.3) is the present value of the bank's asset value in default, prior to deduction of bankruptcy costs, divided by the default boundary. Note that $c_1 + c_2 = 1$, $d_1 + d_2 = 1$, $d_1 > c_1$ and $d_2 < c_2$. Furthermore, when $\lambda \to 0$ or $\eta \to \infty$, $\gamma_1 \to -\frac{1}{2} + \left[(r-\delta) + \sqrt{(r-\delta-\frac{1}{2}\sigma^2) + 2\sigma^2 r}\right]\sigma^{-2}$ and $\gamma_2 \to \eta$, so that $(c_2, d_2) \to (0,0)$ and if $K = 0$, the model simplifies to the model of Sundaresan and Wang (2017); see Appendix A.1.2.

A.1.2 Model simplification: no tail risk

This section presents the pure diffusion case by setting $\lambda = 0$, so that the asset value dynamics simplify to a geometric Brownian motion, as studied by Sundaresan and Wang (2017):

$$\frac{dV_t}{V_t} = (r-\delta)dt + \sigma dW_t,$$

which has the well known solution

$$V_t = V_0 \exp\left[\left(r - \delta - \frac{1}{2}\sigma^2\right)t + \sigma W_t\right].$$

Furthermore, define the second-degree polynomial

$$G_0(x) := \left(r - \delta - \frac{1}{2}\sigma^2\right)x + \frac{1}{2}\sigma^2 x^2 = r,$$

of which the negative solution is given by $-\gamma_0 = \frac{1}{2} - \sigma^{-2}\left[(r-\delta) + \sqrt{(r-\delta-\frac{1}{2}\sigma^2) + 2\sigma^2 r}\right]$. Define the default state price as $p_D^0 := (V_D/V)^{\gamma_0}$. Table A1 provides an overview of the security values, default thresholds and, if applicable, the insurance premium for an unregulated and regulated bank. Note in the unregulated case, deposits can be considered safe as depositors can run exactly at the moment when the asset value hits the run threshold.

Table A1: Model simplification $\lambda = 0$

	Unregulated bank	**Regulated bank**
D	$\frac{C_D}{r-\pi}$	$\frac{C_D}{r-\pi}$
M	$\frac{C_M}{r}(1-p_D^0) + [(1-\alpha)V_D - K - D]^+ p_D^0$	$\frac{C_M}{r}(1-p_D^0) + [(1-\alpha)V_D - K - D]^+ p_D^0$
E	$V - \frac{(1-\theta)(C_D+C_M)}{r}(1-p_D^0) - V_D p_D^0$	$V - \frac{(1-\theta)(C_D+C_M)+I}{r}(1-p_D^0) - V_D p_D^0$
v	$D + M + E$	$D + M + E$
V_B	$\frac{\gamma_0}{1+\gamma_0}\frac{(1-\theta)(C_D+C_M)}{r}$	$\frac{\gamma_0}{1+\gamma_0}\frac{(1-\theta)(C_D+C_M)+I}{r}$
V_R	$\frac{C_D}{(1-\alpha)(r-\pi)}$	-
V_A	-	$\frac{\kappa C_D}{r-\pi}$
I^o	-	$r[D - V_D + \min\{V_D, \alpha V_D + K\}]^+ \frac{p_D^0}{1-p_D^0}$

A.1.3 Proof of proposition 1.1

This section considers the valuation of the unregulated bank's liabilities as contingent claims on asset value V.

Deposit and market debt value

The deposit face value can be decomposed into three parts: the discounted value of coupon payments until default, the discounted value of liquidity benefits until default and the expected proceeds in default. As depositors have seniority, in default they receive the minimum of the asset value after deduction of bankruptcy costs and their initial deposit value. This leads to the following deposit value equation:

$$
\begin{aligned}
D &= \mathbb{E}\left[\int_0^\tau C_D e^{-rt} dt\right] + \mathbb{E}\left[\int_0^\tau \pi D e^{-rt} dt\right] + \mathbb{E}\left[\min\{D, \max\{(1-\alpha)V_\tau - K, 0\} e^{-r\tau}\right] \\
&= \frac{C_D}{r}(1-p_D) + \frac{\pi D}{r}(1-p_D) + \mathbb{E}\left[\min\{D, \max\{(1-\alpha)V_\tau - K, 0\} e^{-r\tau}\right].
\end{aligned}
$$

Similarly, the value of the market debt is the sum of the expected coupons C_M until default and the proceeds in case of default. As market debt is subordinated to deposits, these proceeds are equal to the remaining asset value in default after depositors are paid, if positive.

$$
\begin{aligned}
M &= \mathbb{E}\left[\int_0^\tau C_M e^{-rt} dt\right] + \mathbb{E}[\max\{(1-\alpha)V_\tau - D - K, 0\} e^{-r\tau}] \\
&= \frac{C_M}{r}(1-p_D) + \mathbb{E}[\max\{(1-\alpha)V_\tau - D - K, 0\} e^{-r\tau}]. \qquad \text{(A.4)}
\end{aligned}
$$

Define the operator $x^+ := \max\{x, 0\}$. The expectation in Eq. (A.4) is equal to:

$$
\begin{aligned}
&\mathbb{E}\left[((1-\alpha)V_\tau - D - K)^+ e^{-r\tau}\right] \\
&= \mathbb{E}\left[((1-\alpha)V_\tau - D - K) e^{-r\tau}\right] + \mathbb{E}\left[(D + K - (1-\alpha)V_\tau)^+ e^{-r\tau}\right] \\
&= (1-\alpha)V_D \tilde{p}_D - (D+K)p_D + \mathbb{E}\left[(D + K - (1-\alpha)V_\tau)^+ e^{-r\tau}\right]. \qquad \text{(A.5)}
\end{aligned}
$$

The expectation term on the right-hand side of Eq. (A.5) can be interpreted as the expected discounted shortfall of depositors in the event of default. To determine this quantity, distinguish the following two cases:

Case 1: $\mathbf{V_D \le V_R}$ When the default boundary V_D is below the value at which depositors are fully reimbursed V_R, depositors always incur a loss, whether the default boundary is reached by diffusion or by a jump. This leads to:

$$
\mathbb{E}\left[(D + K - (1-\alpha)V_\tau)^+ e^{-r\tau}\right] = \mathbb{E}\left[(D + K - (1-\alpha)V_\tau) e^{-r\tau}\right] = (D+K)p_D - (1-\alpha)V_D \tilde{p}_D.
$$

In the unregulated case, $V_D = \max\{V_B, V_R\}$ and the expression becomes $(D+K)(p_D - \tilde{p}_D)$.

Case 2: $\mathbf{V_D > V_R}$ When default boundary V_D is higher than V_R, depositors do not face a loss when the default boundary is reached by diffusion. However, the tail risk component makes it possible for the value in default to be below V_R. This results in:

$$\mathbb{E}\left[(D+K-(1-\alpha)V_\tau)^+ e^{-r\tau}\right] = (D+K)\mathbb{E}\left[e^{-r\tau}\mathbb{1}_{\{V_\tau<V_R\}}\right] - (1-\alpha)\mathbb{E}\left[V_\tau e^{-r\tau}\mathbb{1}_{\{V_\tau<V_R\}}\right].$$

The first expectation on the right-hand side in the above equation equals:

$$\mathbb{E}\left[e^{-r\tau}\mathbb{1}_{\{V_\tau<V_R\}}\right] = \mathbb{E}\left[e^{-r\tau}\mathbb{1}_{\{V_D/V_\tau>V_D/V_R\}}\right] = \left(\frac{V_R}{V_D}\right)^{\eta}(\eta+1)(p_D-\tilde{p}_D),$$

where the following equality derived by Yin et al. (2014) was used:

$$\begin{aligned}\mathbb{E}\left[e^{-r\tau}\mathbb{1}_{\{V_D/V_\tau>Y\}}\right] &= Y^{-\eta}\frac{(\gamma_2-\eta)(\eta-\gamma_1)}{\eta(\gamma_2-\gamma_1)}\left[\left(\frac{V_D}{V}\right)^{\gamma_1}-\left(\frac{V_D}{V}\right)^{\gamma_2}\right]\\ &= Y^{-\eta}(\eta+1)(p_D-\tilde{p}_D), \qquad \forall Y\geq 1.\end{aligned}$$

To determine the other expectation, I use the result from Kou and Wang (2003) who showed that the stopping time τ and the undershoot problem V_D-V_τ are independent, conditional on $V_D-V_\tau>0$. This result depends on the assumption of the exponential jump distribution associated with the memoryless property. This assumption leads to the conditional memorylessness of the jump-diffusion process, and in particular $\mathbb{P}\left(X_D-X_\tau\geq x|X_D-X_\tau>0\right)=e^{-\eta x}$, where $X_D=\ln(V_D)$ and $X_\tau=\ln(V_\tau)$. It follows that under the assumption $V_D>V_R$:

$$\begin{aligned}\mathbb{E}\left[V_\tau e^{-r\tau}\mathbb{1}_{\{V_\tau<V_R\}}\right] &= V_D\mathbb{E}\left[e^{X_\tau-X_D}e^{-r\tau}\mathbb{1}_{\{X_D-X_\tau>X_D-X_R>0\}}\right]\\ &= V_D\mathbb{E}\left[e^{X_\tau-X_D}e^{-r\tau}\mathbb{1}_{\{X_D-X_\tau>X_D-X_R\}}|X_D>X_\tau\right]\mathbb{P}\left(X_D>X_\tau\right)\\ &= V_D\mathbb{E}\left[e^{-r\tau}\mathbb{1}_{\{X_D>X_\tau\}}\right]\mathbb{E}\left[e^{X_\tau-X_D}\mathbb{1}_{\{X_D-X_\tau>X_D-X_R\}}|X_D>X_\tau\right]\\ &= V_D(\eta+1)(p_D-\tilde{p}_D)\frac{\eta}{\eta+1}\left(\frac{V_R}{V_D}\right)^{\eta+1} = \eta V_R\left(\frac{V_R}{V_D}\right)^{\eta}(p_D-\tilde{p}_D),\end{aligned}$$

where it is used that

$$\mathbb{E}\left[e^{X_\tau-X_D}\mathbb{1}_{\{X_D-X_\tau>X_D-X_R\}}|X_D>X_\tau\right] = \int_{X_D-X_R}^{\infty} e^{-z}\eta e^{-\eta z}dz = \frac{\eta}{\eta+1}e^{(X_R-X_D)(\eta+1)}.$$

Bringing everything together, gives:

$$\begin{aligned}\mathbb{E}\left[(D+K-(1-\alpha)V_\tau)^+ e^{-r\tau}\right] &= \left[(D+K)(\eta+1)-(1-\alpha)\eta V_R\right]\left(\frac{V_R}{V_D}\right)^{\eta}(p_D-\tilde{p}_D)\\ &= (D+K)(p_D-\tilde{p}_D)\left(\frac{V_R}{V_D}\right)^{\eta}.\end{aligned}$$

The proceeds to market debt holders in default from Eq. (A.5) become:

$$\mathbb{E}\left[((1-\alpha)V_\tau-K-D)^+ e^{-r\tau}\right] = \left((1-\alpha)V_D\tilde{p}_D-(D+K)\left[p_D-(p_D-\tilde{p}_D)\left(\frac{V_R}{V_D}\right)^{\eta}\right]\right)\mathbb{1}_{\{V_D>V_R\}}.$$

Note that when $V_D\leq V_R$, the proceeds to market debt holders in default are zero so that the market debt value simplifies to $M=r^{-1}C_M(1-p_D)$. To determine the proceeds in default to depositors in the unregulated case, first solve the present value of the asset value in default and subtract from this the proceeds to depositors. The present value of the bankruptcy costs

$\min\{V_\tau, \alpha V_\tau + K\}$ equals:

$$\begin{aligned}\mathbb{E}\left[\min\{V_\tau, \alpha V_\tau + K\} e^{-r\tau}\right] &= \mathbb{E}\left[V_\tau e^{-r\tau}\right] - \mathbb{E}\left[((1-\alpha)V_\tau - K)^+ e^{-r\tau}\right] \\ &= \alpha V_D \tilde{p}_D + K p_D - \mathbb{E}\left[(K-(1-\alpha)V_\tau)^+ e^{-r\tau}\right].\end{aligned}$$

Define $V_K := K/(1-\alpha)$ and distinguish two cases:

$$\mathbb{E}\left[(K-(1-\alpha)V_\tau)^+ e^{-r\tau}\right] = \begin{cases} K p_D - (1-\alpha)V_D \tilde{p}_D, & \text{for } V_D \le V_K, \\ K(p_D - \tilde{p}_D)(V_K/V_D)^\eta, & \text{for } V_D > V_K, \end{cases}$$

so that as a result:

$$\mathbb{E}\left[\min\{V_\tau, \alpha V_\tau + K\} e^{-r\tau}\right] = \begin{cases} V_D \tilde{p}_D, & \text{for } V_D \le V_K, \\ \alpha V_D \tilde{p}_D + K\left(p_D - (p_D - \tilde{p}_D)(V_K/V_D)^\eta\right), & \text{for } V_D > V_K. \end{cases}$$

Equivalently, the remaining bank's asset value after bankruptcy costs are deducted equals:

$$\mathbb{E}\left[((1-\alpha)V_\tau - K)^+ e^{-r\tau}\right] = \begin{cases} 0, & \text{for } V_D \le V_K, \\ (1-\alpha)V_D \tilde{p}_D - K(p_D - (p_D - \tilde{p}_D)(V_K/V_D)^\eta), & \text{for } V_D > V_K. \end{cases}$$

The proceeds in default to depositors are equal to the difference between the remaining asset value in default and the proceeds in default to the subordinated debt holders:

$$\begin{aligned}&\mathbb{E}\left[\min\{D, \max\{(1-\alpha)V_\tau - K\}, 0\} e^{-r\tau}\right] \\ &= \begin{cases} 0, & \text{for } V_D \le V_K, \\ (1-\alpha)V_D \tilde{p}_D - K\left[p_D - (p_D - \tilde{p}_D)(V_K/V_D)^\eta\right], & \text{for } V_K < V_D < V_R, \\ K(p_D - \tilde{p}_D)\left[(V_K/V_D)^\eta - (V_R/V_D)^\eta\right] + D\left[p_D - (p_D - \tilde{p}_D)(V_R/V_D)^\eta\right], & \text{for } V_D \ge V_R. \end{cases}\end{aligned}$$

However, in the unregulated case $V_D \ge V_R > V_K$, so that the deposits are priced as follows:

$$D = \frac{C_D + \pi D}{r}\left(1 - p_D\right) + K(p_D - \tilde{p}_D)\left[\left(\frac{V_K}{V_D}\right)^\eta - \left(\frac{V_R}{V_D}\right)^\eta\right] + D\left[p_D - (p_D - \tilde{p}_D)\left(\frac{V_R}{V_D}\right)^\eta\right],$$

which can be rewritten as

$$D = \frac{C_D(1-p_D) - rK(p_D - \tilde{p}_D)((V_R/V_D)^\eta - (V_K/V_D)^\eta)}{(r-\pi)(1-p_D) + r(p_D - \tilde{p}_D)(V_R/V_D)^\eta}.$$

When $V_D = V_R$, this expression simplifies to

$$D = \frac{C_D(1-p_D) - rK(p_D - \tilde{p}_D)(1 - (V_K/V_R)^\eta)}{r(1-\tilde{p}_D) - \pi(1-p_D)}.$$

Equity value and endogenous default boundary

Equity holders pay (net of taxes) coupons until default and they lose the bank value in default:

$$
\begin{aligned}
E = E(V;V_D) &= V - \mathbb{E}\left[\int_0^{\tau}(1-\theta)(C_D+C_M)e^{-rt}dt\right] - \mathbb{E}\left[V_\tau e^{-r\tau}\right] \\
&= V - \frac{(1-\theta)(C_D+C_M)}{r}\left(1-p_D\right) - V_D\tilde{p}_D.
\end{aligned}
$$

Bank value is simply the sum of total debt and equity. The smooth pasting condition Eq. (1.4) determines the optimal endogenous default barrier V_B:

$$
\left.\frac{\partial E(V;V_B)}{\partial V}\right|_{V=V_B} = 1 - \frac{(1-\theta)(C_D+C_M)}{rV_B}(d_1\gamma_1+d_2\gamma_2)+c_1\gamma_1+c_2\gamma_2.
$$

Setting the last equation to 0 and solving for V_B gives the result from the proposition.

Uniqueness of deposit value

This proof is for the case $K=0$. Multiply both sides of Eq. (1.2) by r and subtract rD from both sides. Define the resulting function as follows:

$$
\begin{aligned}
g(D;V_D) := {} & C_D\left[1-d_1\left(\frac{V_D}{V}\right)^{\gamma_1}-d_2\left(\frac{V_D}{V}\right)^{\gamma_2}\right]-(r-\pi)D\left[1-d_1\left(\frac{V_D}{V}\right)^{\gamma_1}-d_2\left(\frac{V_D}{V}\right)^{\gamma_2}\right] \\
& - rD\left[(d_1-c_1)\left(\frac{V_D}{V}\right)^{\gamma_1}+(d_2-c_2)\left(\frac{V_D}{V}\right)^{\gamma_2}\right]\left(\frac{D}{(1-\alpha)V_D}\right)^{\eta}.
\end{aligned}
$$

To show that the deposit equation has two positive solutions, distinguish two cases:

Case 1: $V_D = V_B > V_R$ Let $p_B := d_1\,(V_B/V)^{\gamma_1} + d_2\,(V_B/V)^{\gamma_2}$ and $\tilde{p}_B := c_1\,(V_B/V)^{\gamma_1} + c_2\,(V_B/V)^{\gamma_2}$. Plugging in $V_D = V_B$ and rewriting this in polynomial form gives:

$$
\begin{aligned}
g(D;V_B) = {} & C_D\left[1-d_1\left(\frac{V_B}{V}\right)^{\gamma_1}-d_2\left(\frac{V_B}{V}\right)^{\gamma_2}\right]-(r-\pi)D\left[1-d_1\left(\frac{V_B}{V}\right)^{\gamma_1}-d_2\left(\frac{V_B}{V}\right)^{\gamma_2}\right] \\
& - rD\left[(d_1-c_1)\left(\frac{V_B}{V}\right)^{\gamma_1}+(d_2-c_2)\left(\frac{V_B}{V}\right)^{\gamma_2}\right]\left(\frac{D}{(1-\alpha)V_B}\right)^{\eta} \\
= {} & \frac{-r}{[(1-\alpha)V_B]^{\eta}}(p_B-\tilde{p}_B)D^{\eta+1}-(r-\pi)(1-p_B)D+C_D(1-p_B).
\end{aligned}
$$

Because the coefficients in front of $D^{\eta+1}$ and D are negative and the constant term $C_D(1-p_B)$ is positive, it follows from Descartes' rules of signs that the polynomial $g(D;V_B)=0$ has at most one positive solution.

Case 2: $V_D = V_R > V_B$ For ease of notation, let $V_\alpha := (1-\alpha)V$. Then, plug in $V_D = V_R$ and rewrite in polynomial form:

$$
g(D;V_R) = (C_D+\pi D)\left[1-d_1\left(\frac{D}{V_\alpha}\right)^{\gamma_1}-d_2\left(\frac{D}{V_\alpha}\right)^{\gamma_2}\right]-rD\left[1-c_1\left(\frac{D}{V_\alpha}\right)^{\gamma_1}-c_2\left(\frac{D}{V_\alpha}\right)^{\gamma_2}\right]
$$

$$= \frac{rc_2 - \pi d_2}{V_\alpha^{\gamma_2}} D^{\gamma_2+1} - \frac{C_D d_2}{V_\alpha^{\gamma_2}} D^{\gamma_2} + \frac{rc_1 - \pi d_1}{V_\alpha^{\gamma_1}} D^{\gamma_1+1} - \frac{C_D d_1}{V_\alpha^{\gamma_1}} D^{\gamma_1} - (r-\pi)D + C_D.$$

As $r > \pi$, $c_2 > d_2$ and $c_1 < d_1$, the coefficient $rc_2 - \pi d_2 > 0$. The coefficient $rc_1 - \pi d_1$ can be either positive or negative, depending on the size of π. If $\gamma_2 > \gamma_1 + 1$ and $rc_1 - \pi d_1 < 0$, or $\gamma_1 + 1 > \gamma_2$, Descartes' rule of signs says that the polynomial $g(D; V_R) = 0$ has at most two positive solutions. If $\gamma_2 > \gamma_1 + 1$ and $rc_1 - \pi d_1 > 0$, Descartes' rule of signs states that there are either zero, two or four positive solutions. Using from Eq. (1.2) that $D < C_D/(r-\pi)$, one can deduce that $(rc_1 - \pi d_1)D^{\gamma_1+1} - C_D d_1 D^{\gamma_1} < (r-\pi)d_1 D^{\gamma_1+1} - C_D d_1 D^{\gamma_1} < 0$, which implies the negative term with power γ_1 dominates the positive term with power $\gamma_1 + 1$ and hints that there are at most two positive solutions. However, to have a definite answer, one needs to determine the exact numbe of roots. One way to do is by applying the Euclidean algorithm for polynomials and taking the differences of the sign changes of the resulting sequence of polynomials at $D = 0$ and $D = \infty$, see Section 6.3 in Henrici (1988). Unfortunately, this process is too complicated in the setup of this problem, due to the variable and non-integer nature of the exponents. Luckily, in all the numerical computations, two

Over the entire domain, this makes there are two possibilities. Either there is one solution on $(0, (1-\alpha)V_B]$ and one solution on $((1-\alpha)V_B, \infty)$, or both solutions are on the domain $((1-\alpha)V_B, \infty)$. This concludes the proof that $g(D; V_D) = 0$ has at most two positive solutions. The trivial solution is $\tilde{D}_2 = (1-\alpha)V$. However, this solution implies that $V = V_D$, which violates the assumption that $V > V_D$ and will therefore be discarded. The remaining solution, $\tilde{D}_1$, cannot be determined in closed form because of the high polynomial degree. However, from Eq. (1.2) one can directly deduce that $\tilde{D}_1 \in (0, C_D/(r-\pi))$.

A.1.4 Proof of corollary 1.1

To prove that $V_D^* = V_B^* = V_R^*$, I distinguish two cases.

Case 1: $V_D = V_R > V_B$ Define $p_R := d_1(V_R/V)^{\gamma_1} + d_2(V_R/V)^{\gamma_2}$. The partial derivative of v with respect to C_M is given by:

$$\frac{\partial v}{\partial C_M} = \frac{\theta}{r}(1 - p_R) > 0,$$

for $\theta > 0$. This shows that the case $V_R > V_B$ is suboptimal, as the bank can create extra value by issuing more market debt.

Case 2: $V_D = V_B > V_R$ The partial derivatives of v with respect to C_M and C_D, respectively, are given by:

$$\begin{aligned} \frac{\partial v}{\partial C_D} &= \left(\frac{\pi}{r}\frac{\partial D}{\partial C_D} + \frac{\theta}{r}\right)(1-p_B) - \frac{\pi D + \theta(C_D + C_M)}{r}\frac{\partial p_B}{\partial C_D} - \alpha\left(\tilde{p}_B \frac{\partial V_B}{\partial C_D} + V_B \frac{\partial \tilde{p}_B}{\partial C_D}\right), \\ &- K\left[\frac{\partial p_B}{\partial C_D} - \frac{\partial(p_B - \tilde{p}_B)}{\partial C_D}\left(\frac{V_K}{V_B}\right)^\eta + (p_B - \tilde{p}_B)\frac{\eta}{V_B}\left(\frac{V_K}{V_B}\right)^\eta \frac{\partial V_B}{\partial C_D}\right], \end{aligned} \tag{A.6}$$

$$\frac{\partial v}{\partial C_M} = \left(\frac{\pi}{r}\frac{\partial D}{\partial C_M} + \frac{\theta}{r}\right)(1-p_B) - \frac{\pi D + \theta(C_D + C_M)}{r}\frac{\partial p_B}{\partial C_M} - \alpha\left(\tilde{p}_B\frac{\partial V_B}{\partial C_M} + V_B\frac{\partial \tilde{p}_B}{\partial C_M}\right),$$
$$-K\left[\frac{\partial p_B}{\partial C_M} - \frac{\partial(p_B - \tilde{p}_B)}{\partial C_M}\left(\frac{V_K}{V_B}\right)^\eta + (p_B - \tilde{p}_B)\frac{\eta}{V_B}\left(\frac{V_K}{V_B}\right)^\eta\frac{\partial V_B}{\partial C_M}\right].$$

Define $\Phi := (d_1\gamma_1 + d_2\gamma_2)/(1 + c_1\gamma_1 + c_2\gamma_2)$ and observe that:

$$\frac{\partial V_B}{\partial C_D} = \frac{\partial V_B}{\partial C_M} = \frac{(1-\theta)}{r}\Phi,$$

so that:

$$\frac{\partial p_B}{\partial C_D} = \frac{\partial p_B}{\partial C_M} = \frac{\partial p_B}{\partial V_B}\frac{\partial V_B}{\partial C_M} = \frac{1}{C_D + C_M}\left[\gamma_1 d_1\left(\frac{V_B}{V}\right)^{\gamma_1} + \gamma_2 d_2\left(\frac{V_B}{V}\right)^{\gamma_2}\right] > 0,$$
$$\frac{\partial \tilde{p}_B}{\partial C_D} = \frac{\partial \tilde{p}_B}{\partial C_M} = \frac{\partial \tilde{p}_B}{\partial V_B}\frac{\partial V_B}{\partial C_M} = \frac{1}{C_D + C_M}\left[\gamma_1 c_1\left(\frac{V_B}{V}\right)^{\gamma_1} + \gamma_2 c_2\left(\frac{V_B}{V}\right)^{\gamma_2}\right] > 0.$$

Now let C_D^* be the optimal deposit coupon that satisfies $\partial v/\partial C_D = 0$. Plugging in this condition, based on Eq. (A.6), in $\partial v/\partial C_M = 0$ gives after some simplifications:

$$\frac{\partial v(C_D^*, C_M)}{\partial C_M} = \frac{\pi}{r}(1-p_B)\left[\frac{\partial D}{\partial C_M} - \frac{\partial D}{\partial C_D^*}\right]. \tag{A.7}$$

To determine the sign of Eq. (A.7), rewrite Eq. (1.2) in polynomial form for $V_D = V_B$:

$$g(D; V_B) := \frac{r}{[(1-\alpha)V_B]^\eta}\frac{p_B - \tilde{p}_B}{1-p_B}(D+K)^{\eta+1} + (r-\pi)D - C_D - rK\frac{p_B - \tilde{p}_B}{1-p_B}\left(\frac{V_K}{V_B}\right)^\eta.$$

Assume without loss of generality that $\eta \in \mathbb{N}$ and set above expression equal to 0 and rewrite as follows:

$$\sum_{i=0}^{\eta+1} a_i D^i + (r-\pi)D + c = 0,$$

where

$$a_i := \binom{\eta+1}{i}\frac{r}{[(1-\alpha)V_B]^\eta}\frac{p_B - \tilde{p}_B}{1-p_B}K^{\eta+1-i}, \quad \text{and} \quad c := -C_D - rK\frac{p_B - \tilde{p}_B}{1-p_D}\left(\frac{V_K}{V_B}\right)^\eta.$$

It follows that:[2]

$$\frac{\partial D}{\partial a_i} = \frac{-D^i}{g'(D; V_B)}, \quad \text{and} \quad \frac{\partial D}{\partial c} = \frac{-1}{g'(D; V_B)},$$

[2] To determine the sensitivity of the polynomial's roots with respect to its coefficients, suppose that x is a root of the polynomial $P(z) := \sum_k a_k z^k$, so that $P(x) = \sum_k a_k x^k = 0$. Extracting the nth polynomial coefficient and taking the derivative with respect to x gives $da_n/dx = -\sum_{k\neq n} a_k x^{k-n-1} = -\sum_k (k-n)a_k x^{k-n-1} = -x^{-n}\sum_k k a_k x^{k-1} = -x^{-n}P'(x)$. Taking the inverse gives $dx/da_n = -x^n\left(P'(x)\right)^{-1}$.

where

$$g'(D;V_B) = \frac{p_B - \tilde{p}_B}{1-p_B}\frac{r(\eta+1)}{[(1-\alpha)V_B]^\eta}(D+K)^\eta + (r-\pi) > 0.$$

The derivatives of D with respect to C_D and C_M are given by:

$$\frac{dD}{dC_D} = \sum_{i=0}^{\eta+1}\frac{\partial D}{\partial a_i}\frac{\partial a_i}{\partial V_B}\frac{\partial V_B}{\partial C_D} + \frac{\partial D}{\partial c}\left(\frac{\partial c}{\partial C_D} + \frac{\partial c}{\partial V_B}\frac{\partial V_B}{\partial C_D}\right),$$
$$\frac{dD}{dC_M} = \sum_{i=0}^{\eta+1}\frac{\partial D}{\partial a_i}\frac{\partial a_i}{\partial V_B}\frac{\partial V_B}{\partial C_M} + \frac{\partial D}{\partial c}\left(\frac{\partial c}{\partial V_B}\frac{\partial V_B}{\partial C_M}\right).$$

As $\partial V_B/\partial C_D = \partial V_B/\partial C_M$, $\partial D/\partial c < 0$, and $\partial c/\partial C_D < 0$, it must be that $dD/dC_D > dD/dC_M$. Assuming that $\pi > 0$, it follows that Eq. (A.7) is strictly negative. This implies that the case $V_B > V_R$ is suboptimal too, as the bank value decreases in market debt when deposits C_D are kept optimal relative to C_M.

Therefore, assuming that $\theta, \pi > 0$, in the optimum we have that $V_D^* = V_B^* = V_R^*$. Plugging this in Eq. (1.2) and Eq. (1.3), and solving for D^* and M^* gives the results from the proposition. The deposit credit spread equals $s_D^* = C_D^*/D^* - (r-\pi)$ and the market debt credit equals $s_M^* = C_M^*/M^* - r$.

A.1.5 Proof of proposition 1.2

This section considers the valuation of the regulated bank's liabilities as contingent claims on asset value V.

Deposit and market debt value

As deposits are now insured, its value equals the perpetual value $C_D/(r-\pi)$. In this scenario, depositors will never initiate a bank run. Interpret $V_R = (D+K)/(1-\alpha)$ as the asset value at which depositors are fully reimbursed directly from the bank's asset value in default and the regulator does not need to step in. The market debt value is computed in the same way as in Appendix A.1.3:

$$M = \frac{C_M}{r}\left(1-p_D\right) + \mathbb{1}_{\{V_D > V_R\}}\left((1-\alpha)V_D\tilde{p}_D - (D+K)\left[p_D - (p_D - \tilde{p}_D)\left(\frac{V_R}{V_D}\right)^\eta\right]\right).$$

Equity value and endogenous default boundary

On top of the (net of taxes) coupons, equity holders now also pay an insurance premium I until default. Therefore, the equity value is given by:

$$E = E(V;V_D) = V - \mathbb{E}\left[\int_0^\tau((1-\theta)(C_D+C_M)+I)e^{-rt}dt\right] - \mathbb{E}\left[V_\tau e^{-r\tau}\right].$$
$$= V - \frac{(1-\theta)(C_D+C_M)+I}{r}\left(1-p_D\right) - V_D\tilde{p}_D.$$

Smooth pasting condition Eq. (1.4) pins down the optimal endogenous default boundary V_B:

$$\left.\frac{\partial E(V;V_B)}{\partial V}\right|_{V=V_B} = 1 - \frac{(1-\theta)(C_D+C_M)+I}{rV_B}(d_1\gamma_1 + d_2\gamma_2) + c_1\gamma_1 + c_2\gamma_2.$$

Setting the last equation to 0 and solving for V_B gives the result from the proposition.

A.1.6 Proof of proposition 1.3

The left hand side of Eq. (1.5) equals $r^{-1}I^o I(1-p_D)$. Distinguish three cases to derive the right-hand side. Using Appendix A.1.3, it follows that:

Case 1: $\mathbf{V_D \leq V_K}$ When the default boundary V_D is smaller than V_K, the bank has no value in default such that the regulator has to cover the full value of deposits at the time of default:

$$\mathbb{E}\left[(D - V_\tau + \min\{V_\tau, \alpha V_\tau + K\})^+ e^{-r\tau}\right] = Dp_D.$$

Case 2: $\mathbf{V_K < V_D \leq V_R}$ In this scenario, some asset value is left in default, but insufficient to reimburse all depositors, even in the case of default by diffusion.

$$\begin{aligned}
&\mathbb{E}\left[(D - V_\tau + \min\{V_\tau, \alpha V_\tau + K\})^+ e^{-r\tau}\right] = \mathbb{E}\left[(D - V_\tau + \min\{V_\tau, \alpha V_\tau + K\})\, e^{-r\tau}\right] \\
&= \mathbb{E}\left[De^{-r\tau}\right] + \mathbb{E}\left[(K-(1-\alpha)V_\tau)e^{-r\tau}\right] - \mathbb{E}\left[(K-(1-\alpha)V_\tau)^+ e^{-r\tau}\right] \\
&= (D+K)p_D - (1-\alpha)V_D\tilde{p}_D - K(p_D - \tilde{p}_D)\left(\frac{V_K}{V_D}\right)^\eta.
\end{aligned}$$

Case 3: $\mathbf{V_D > V_R}$ In the case default boundary V_D is larger than V_R, the regulator still has to step in and partly reimburse the depositos in case of default by a negative jump in asset value.

$$\begin{aligned}
&\mathbb{E}\left[(D - V_\tau + \min\{V_\tau, \alpha V_\tau + K\})^+ e^{-r\tau}\right] = \mathbb{E}\left[\left(D\mathbb{1}_{\{V_\tau < V_R\}} + (K-(1-\alpha)V_\tau)\mathbb{1}_{\{V_K < V_\tau < V_R\}}\right) e^{-r\tau}\right] \\
&= \frac{(\gamma_2-\eta)(\eta-\gamma_1)}{\eta(\eta+1)(\gamma_2-\gamma_1)}\left[\left(\frac{V_D}{V}\right)^{\gamma_1} - \left(\frac{V_D}{V}\right)^{\gamma_2}\right]\left[(D+K)\left(\frac{V_R}{V_D}\right)^\eta - K\left(\frac{V_K}{V_D}\right)^\eta\right] \\
&= (p_D - \tilde{p}_D)\left[(D+K)\left(\frac{V_R}{V_D}\right)^\eta - K\left(\frac{V_K}{V_D}\right)^\eta\right].
\end{aligned}$$

Multiplying by $r(1-p_D)^{-1}$ gives the resulting actuarially fair deposit insurance premium I^o from the proposition.

A.1.7 Proof of corollary 1.2

To prove that in the regulated case $V_D^* = V_B^* \geq V_A^*$, distinguish 6 cases. First define $p_A := d_1(V_A/V)^{\gamma_1} + d_2(V_A/V)^{\gamma_2}$ and $\tilde{p}_A := c_1(V_A/V)^{\gamma_1} + c_2(V_A/V)^{\gamma_2}$.

Case 1: $V_A > V_B$ Taking the partial derivative of bank value with respect to C_M gives:

$$\frac{\partial v}{\partial C_M} = \frac{\theta}{r}(1 - p_A) > 0,$$

when $\theta > 0$. This shows that the case $V_A > V_R > V_B$ is suboptimal, as the bank can increase its value by issuing more market debt. Note that insurance premium I^o is not a function of C_M.

Case 2a: $V_D = V_B > V_A > V_R$ In this case, the insurance premium and bank value are given by:

$$I^o = r\frac{p_B - \tilde{p}_B}{1 - p_B}\left[(D+K)\left(\frac{D+K}{(1-\alpha)V_B}\right)^{\eta} - K\left(\frac{K}{(1-\alpha)V_B}\right)^{\eta}\right],$$
$$v = V + \left(\frac{\pi D + \theta(C_D + C_M) + (1-\omega)I^o}{r}\right)(1 - p_B) - \alpha V_B \tilde{p}_B - K\left[p_B - (p_B - \tilde{p}_B)\left(\frac{V_K}{V_B}\right)^{\eta}\right].$$

The marginal change in bank value by increasing deposits C_D equals:

$$\begin{aligned}\frac{\partial v}{\partial C_D} &= \frac{1}{r}(1 - p_B)\left(\frac{\pi}{r-\pi} + \theta + (1-\omega)\frac{\partial I^o}{\partial C_D}\right) \\ &- \frac{\partial V_B}{\partial C_D}\left\{\frac{1}{r}\frac{\partial p_B}{\partial V_B}\left(\frac{\pi C_D}{r-\pi} + \theta(C_D + C_M) + (1-\omega)I^o + rK\left[1 - \left(\frac{V_K}{V_B}\right)^{\eta}\right]\right)\right. \\ &\left. + \frac{\partial \tilde{p}_B}{\partial V_B}\left(\alpha V_B + K\left(\frac{V_K}{V_B}\right)^{\eta}\right) + \alpha\tilde{p}_B + \eta K(p_B - \tilde{p}_B)\left(\frac{V_K}{V_B}\right)^{\eta}\frac{1}{V_B}\right\}.\end{aligned} \tag{A.8}$$

Similarly, the marginal change in bank value by increasing market debt C_M equals:

$$\begin{aligned}\frac{\partial v}{\partial C_M} &= \frac{1}{r}(1 - p_B)\left(\theta + (1-\omega)\frac{\partial I^o}{\partial C_M}\right) \\ &- \frac{\partial V_B}{\partial C_M}\left\{\frac{1}{r}\frac{\partial p_B}{\partial V_B}\left(\frac{\pi C_D}{r-\pi} + \theta(C_D + C_M) + (1-\omega)I^o + rK\left[1 - \left(\frac{V_K}{V_B}\right)^{\eta}\right]\right)\right. \\ &\left. + \frac{\partial \tilde{p}_B}{\partial V_B}\left(\alpha V_B + K\left(\frac{V_K}{V_B}\right)^{\eta}\right) + \alpha\tilde{p}_B + \eta K(p_B - \tilde{p}_B)\left(\frac{V_K}{V_B}\right)^{\eta}\frac{1}{V_B}\right\},\end{aligned}$$

Let C_M^* be the optimal market debt coupon for a given deposit coupon C_D such that $\partial v/\partial C_M = 0$. Plugging this constraint into Eq. (A.8), gives

$$\begin{aligned}&\frac{\partial v(C_D, C_M^*)}{\partial C_D} = \\ &\frac{1}{r}(1 - p_B)\left[\frac{\pi}{r-\pi} + \theta\left(1 - \frac{\partial V_B}{\partial C_D}\left(\frac{\partial V_B}{\partial C_M}\right)^{-1}\right) + (1-\omega)\left(\frac{\partial I^o}{\partial C_D} - \frac{\partial I^o}{\partial C_M}\right)\frac{\partial V_B}{\partial C_D}\left(\frac{\partial V_B}{\partial C_M}\right)^{-1}\right]\end{aligned} \tag{A.9}$$

Observe that

$$\frac{\partial V_B}{\partial C_D}\left(\frac{\partial V_B}{\partial C_M}\right)^{-1} = \frac{(1-\theta) + \omega\partial I^o/\partial C_D}{(1-\theta) + \omega\partial I^o/\partial C_M}. \tag{A.10}$$

The complication here is that V_B and I^o are co-determined. However, intuition and numerical checks tell us that the fair deposit premium is more sensitive to changes in deposits than in market debt, that is:

$$\frac{\partial I^o}{\partial C_D} > \frac{\partial I^o}{\partial C_M}.$$

As a result, the expression in Eq. (A.10) is larger than 1. This implies that the sign of the partial derivative of bank value with respect to C_D for an optimal C_M in Eq. (A.9) is ambiguous. That is, the bank can either add or destroy value by increasing deposits C_D. If the first case applies, it shows that a scenario with $V_B > V_A$ is suboptimal.

Increasing deposits when V_B is dominant, leads to more liquidity premium, tax, and deposit insurance subsidy benefits. On the other hand, increasing C_D also raises V_B, which increases the default boundary and default probability. This results in lower funding benefits and higher default costs.

When the above expression is positive, $V_A > V_B > V_R$ is suboptimal, as the marginal liquidity and deposit insurance subsidy benefits coming from deposits outweigh the marginal costs of having a higher insurance premium and a higher endogenous default boundary. From the numerical analysis, this is the case for most parameter values. However, for low values of π, or high values of σ, η, λ, ω, α or K, it is possible that the above expression is negative and it is actually suboptimal to increase deposits. For the exogenous parameter choices in this paper, this issue has been avoided.

Case 2b: $V_R > V_D = V_B > V_A$ In this case, the bank value is identical to case 2a and the insurance premium is given by:

$$I^o = \frac{r}{1-p_B}\left[(D+K)p_B - (1-\alpha)V_B\tilde{p}_B - K(p_B - \tilde{p}_B)\left(\frac{K}{(1-\alpha)V_B}\right)^{\eta}\right],$$

Using a similar argument as in case 2a, one can conclude that $V_B > V_A > V_R$ is suboptimal when the liquidity premium and subsidy benefits of issuing additional deposits outweigh the marginal deposit insurance cost.

Case 2c: $V_D = V_B > V_R > V_A$ Derivation and conclusion are equivalent to case 2a.

From case 1 one can conclude that $V_A > V_B$ is never optimal. Cases 2(a-c) show that $V_A < V_B$ is suboptimal only when the deposits are not too expensive as funds compared to subordinated market debt. However, in all the numerical scenarios considered, $V_A^* = V_B^*$.

A.1.8 Default probability and losses in default

Default probability

Let $\mathrm{PD}_T = \mathbb{P}(\tau < T)$ denote the probability that the bank defaults within time horizon $T \geq 0$. Unfortunately, there is no closed-form solution for this probability. Instead I numerically invert its Laplace transform for which a closed-form solution exists:

$$\int_0^\infty e^{-rT}\mathbb{P}(\tau < T)\,dT = \frac{1}{r}\mathbb{E}\left(e^{-r\tau}\right), \tag{A.11}$$

where the default state price $p_D = \mathbb{E}(e^{-r\tau})$ is defined in Eq. (A.2). In the absence of tail risk, a closed form solution for PD_T exists and is given by (see Ingersoll (1987)):

$$1-\Phi(k_1)+\left(\frac{V_D}{V}\right)^{2(r-\delta)\sigma^{-2}-1}\Phi(k_2),$$

where Φ represents the cumulatief distribution function of a standard normal random variable and

$$k_1 := \frac{\log(V/V_D)+(r-\delta-0.5\sigma^2)}{\sigma\sqrt{T}}, \quad k_2 := \frac{-\log(V/V_D)+(r-\delta-0.5\sigma^2)}{\sigma\sqrt{T}}.$$

Distribution of losses in default

Define the creditor loss function

$$\mathcal{L}_\tau := (D+M-((1-\alpha)V_\tau - K)^+)^+.$$

The probability that the bank defaults within a time horizon $T \geq 0$ and that the loss in default $\mathcal{L}_\tau$ is larger than some amount $y \geq 0$ is given by the probability $\mathbb{P}(\tau < T, \mathcal{L}_\tau \geq y)$. Again, there exists no closed-form expression for this probability, but only for its Laplace transform:

$$\begin{aligned}
&\int_0^\infty e^{-rT}\mathbb{P}(\tau < T \cap \mathcal{L}_\tau \geq y)dT = \frac{1}{r}\mathbb{E}\left[e^{-r\tau}\mathbb{1}_{\{\mathcal{L}_\tau \geq y\}}\right] \\
&= \frac{1}{r}\mathbb{1}_{\{D+M\geq y\}}\left(\mathbb{E}\left[e^{-r\tau}\mathbb{1}_{\{V_\tau < \frac{K}{1-\alpha}\}}\right] + \mathbb{E}\left[e^{-r\tau}\mathbb{1}_{\{\frac{K}{1-\alpha}\leq V_\tau < \frac{D+M+K-y}{1-\alpha}\}}\right]\right) \\
&= \frac{1}{r}\mathbb{1}_{\{D+M\geq y\}}\mathbb{E}\left[e^{-r\tau}\mathbb{1}_{\{V_\tau < \frac{D+M+K-y}{1-\alpha}\}}\right],
\end{aligned} \tag{A.12}$$

where the last expectation is determined as follows:

$$\mathbb{E}\left[e^{-r\tau}\mathbb{1}_{\{V_\tau < Z\}}\right] = \begin{cases} \left(\frac{Z}{V_D}\right)^\eta(\eta+1)(p_D-\tilde{p}_D), & \text{for } Z < V_D, \\ (\eta+1)(p_D-\tilde{p}_D), & \text{for } Z \geq V_D. \end{cases}$$

For current asset value V, the conditional value-at-risk is given by:

$$\mathrm{VaR}_T(q) = \inf\{x > 0 : \mathbb{P}(\mathcal{L}_\tau \geq x | \tau < T) \leq q\},$$

where Bayes' Rule is applied to compute the conditional probability:

$$\mathbb{P}(\mathcal{L}_\tau \geq x | \tau < T) = \frac{\mathbb{P}(\mathcal{L}_\tau \geq x \cap \tau < T)}{\mathbb{P}(\tau < T)}.$$

Numerical inversion Laplace transformation

I use the Gaver-Stehfest algorithm to numerically invert the Laplace transformations in Eq. (A.11) and Eq. (A.12). The algorithm, first described by Stehfest (1970), works as follows. Let $\hat{f}(r)$ be the Laplace transform of $f(T)$, that is:

$$\hat{f}(r) = \int_0^\infty e^{-rT} f(T) dT.$$

Function $f(T)$ can be approximated by $f_n^*(T)$ for large n:

$$f_n^*(T) = \sum_{k=1}^{n} w(k,n) \tilde{f}_k(T),$$

where

$$\tilde{f}_n(T) = \frac{\ln(2)}{T} \frac{(2n)!}{n!(n-1)!} \sum_{k=0}^{n} (-1)^k \binom{n}{k} \hat{f}\left((n+k)\frac{\ln(2)}{T}\right),$$

and extrapolation weights that speed up convergence are defined by

$$w(k,n) = (-1)^{n-k} \frac{k^n}{k!(n-k)!}.$$

The advantage of this method is that it does the inversion on the real line, rather than in the complex plane that is used in other methods. The main disadvantage of this method is that it requires high accuracy as both $\tilde{f}_n(T)$ and weights $w(k,n)$ involve alternating signs and factorials. In the numerical examples in this paper, the algorithm converges well for $n = 10$ and an accuracy of 100 digits.

A.2 Appendix to Chapter 2

A.2.1 Bank valuation

The following section presents the valuation of the bank's liabilities as determined by Sundaresan and Wang (2017).

Default state price and asset value in default

The bank defaults when the asset value hits default threshold value V_D. It is assumed that the asset starting value V lies above default threshold V_D, i.e., $V > V_D$. The default state price, which is the price of a security that pays one dollar if asset value V_t hits V_D for the first time, satisfies the following differential equation:

$$\frac{1}{2}\sigma_s^2 V^2 p_s'' + (r-\delta) V p_s' - r p_s = 0, \quad s \in \{H, L\}.$$

The general solution to this differential equation is $p_s = a_s V^{-\gamma_s} + b_s V^{-\gamma_s'}$, where $\gamma_s < 0 < \gamma_s'$ are the two roots of the following quadratic equation:

$$\frac{1}{2}\sigma_s^2 \gamma_s(\gamma_s - 1) + (r-\delta)\gamma_s = r.$$

Since $p_s(V_D) = 1$ and $\lim_{V\to\infty} p_s(V) = 0$, one can conclude that default state price $p_s = (V_D/V)^{\gamma_s}$. Note that $\gamma_L > \gamma_H$ for $\sigma_L < \sigma_H$.

Deposits

The bank pays the depositors coupon C_D per time unit dt. In case of bank default, the regulator covers the loss to depositors. Since it is assumed that the bank takes a liquidity premium π, the liability of deposits is $C_D = (r-\pi)D$. As a result, the market value of deposits is

$$D = \frac{C_D}{r-\pi},$$

which corresponds to the value of a perpetual bond with coupon C_D and interest rate $r - \pi$.

Market debt

The face value of market debt M is the sum of the expected coupons C_M until default and the proceeds in case of bank failure. As market debt is subordinated to deposits, the proceeds in default are equal to the remaining asset value in default after the regulator has received its share, if positive. This can be expressed as follows:

$$\begin{aligned} M_s &= \mathbb{E}\left[\int_0^\tau C_M e^{-ru} du\right] + \mathbb{E}\left[\max\{(1-\alpha)V_D - D, 0\} e^{-r\tau}\right] \\ &= \frac{C_M}{r}(1-p_s) + \mathbb{1}_{\{V_D \geq V_R\}}\left[(1-\alpha)V_D - D\right] p_s, \end{aligned}$$

where $\mathbb{1}_{\{\cdot\}}$ denotes the zero-one indicator function. This value corresponds to the present value of coupon payments until default and the expected discounted proceeds in default.

Total value

Total bank value is the sum of unlevered bank value V, the present value of the funding and deposit insurance benefits, minus the present value of the bankruptcy and deposit insurance costs. These components are derived below.

Tax benefits Assuming that interest payments are tax-deductible, tax benefits TB_s are equal to the present value of tax benefits until default. Note that unlike Sundaresan and Wang (2017), it is assumed in this paper that deposit insurance premium payments are not deductible from taxes.

$$TB_s = \mathbb{E}\left[\int_0^{\tau} \theta(C_D + C_M)e^{-ru}du\right] = \frac{\theta(C_D + C_M)}{r}(1 - p_s).$$

Liquidity premium benefits Liquidity premium benefits LB_s are equal to the present value of liquidity premium benefits until default.

$$LB_s = \mathbb{E}\left[\int_0^{\tau} \pi D e^{-ru}du\right] = \frac{\pi D}{r}(1 - p_s).$$

Bankrupty costs Bankruptcy costs BC_s are equal to the expected discounted value of αV_D at default.

$$BC_s = \alpha\mathbb{E}\left[V_D e^{-r\tau}\right] = \alpha V_D p_s.$$

Insurance benefits Deposit insurance benefits IB_s are equal to the expected payments in default to depositors by the regulator.

$$IB_s = \mathbb{E}\left[(D - (1-\alpha)V_A)^+ e^{-r\tau}\right] = D(1 - (1-\alpha)\kappa_s)^+ p_s.$$

This implies that when $\kappa_s > (1-\alpha)^{-1}$, the value of the bank in default is sufficiently high to reimburse depositors, so that $IB_s = 0$.

Insurance costs Equity holders pay a deposit insurance premium I per time interval dt to the regulator. The insurance costs IC_s are equal to the discounted payments to the regulator until default.

$$IC_s = \mathbb{E}\left[\int_0^{\tau} I e^{-ru}du\right] = \frac{I}{r}(1 - p_s).$$

Fair insurance premium For the deposit insurance to be fairly priced, the payments to the regulator must be equal to the expected payments of the regulator to depositors in default. Let I^o denote the fair insurance premium at $t = 0$ for which the insurance benefits and insurance costs are equal. This results in:

$$I_s^o = rD(1-(1-\alpha)\kappa_s)^+ \left(\frac{\kappa_s D}{V}\right)^{\gamma_s} \left(1 - \left(\frac{\kappa_s D}{V}\right)^{\gamma_s}\right)^{-1}. \tag{A.13}$$

Note that when $\kappa_s \geq (1-\alpha)^{-1}$, the depositors can be fully reimbursed by the regulator from the proceeds in default. As a result, the insurance premium payments are 0. Deposit insurance can be mispriced, so that equity holders only pay a fraction $\omega \in [0,1]$ of the fair insurance premium, that is, $I = \omega I_s^o$.

Total bank value The total bank value equals the sum of the unlevered bank value, funding benefits, insurance benefits, minus the expected bankruptcy costs and insurance costs:

$$\begin{aligned} v_s &= V + FB_s + LB_s + IB_s - BC_s - IC_s \\ &= V + \frac{\theta(C_D + C_M) + \pi D - I}{r}(1-p_s) - \alpha V_D p_s. \end{aligned}$$

Equity

Equity value is the difference between the levered bank value and the sum of the market value of deposits and subordinated market debt. Equivalently, equity value corresponds to the unlevered bank value, minus the net coupon payments to depositors and market debt holders and insurance premium payments until default, minus the bank value in default:

$$E_s = v_s - D - M_s = V - \frac{(1-\theta)(C_D + C_M) + I}{r}(1-p_s) - V_D p_s.$$

Endogenous default boundary

For a given risk level $s \in \{H, L\}$, the endogenous default boundary V_B^s is found by solving the smooth pasting condition:

$$\left.\frac{\partial E_s(V; V_B^s)}{\partial V}\right|_{V=V_B^s} = 0,$$

which results in

$$V_B^s = \frac{(1-\theta)(C_D + C_M) + I}{r} \frac{\gamma_s}{1+\gamma_s}.$$

As was shown by Sundaresan and Wang (2017), a capital structure with $V_A^s > V_B^s$ is never optimal in the baseline model, as the bank can increase its value by issuing more market debt without changing default boundary V_D:

$$\frac{\partial v_s}{\partial C_M} = \frac{\theta}{r}(1-p_s) > 0,$$

as it is assumed that the funding benefit of market debt θ is strictly positive. For most parameter settings, $V_B^s > V_A^s$ is also suboptimal, as the bank can increase its value by replacing some of its market debt by deposits that come with higher funding benefits. However, when the cost of issuing deposits is very high because of high asset risk in combination with high regulatory parameters ω and κ, issuing deposits might become very costly, so that the increased funding benefits do not outweigh the increased regulatory costs. Sundaresan and Wang (2017) show that there exists a $\tilde{\kappa}$ such that for all $\kappa \in (\tilde{\kappa}, (1-\alpha)^{-1})$, the optimal capital structure is unique and satisfies $V_B^s = V_A^s$. For all parameter combinations in this paper, $V_A^* = V_B^*$ holds for a bank that is restricted to a portfolio of low-risk assets or a bank that selects the high-risk portfolio.

First-best optimal capital structure

Absent any commitment constraint, it was shown by Sundaresan and Wang (2017) that the optimal value of a bank with risk profile $s \in \{H, L\}$ is given by:[3]

$$v_s = V\left[1 + \left(\frac{\theta}{1-\theta} + \frac{1}{\kappa_s}\frac{\pi}{r}\frac{\gamma_s}{1+\gamma_s}\right)(p_s^*)^{1/\gamma_s}\right],$$

where optimal default state price p_s^* is given by

$$p_s^* = \frac{1}{1+\gamma_s}\frac{\pi(1-\theta)\gamma_s + r\theta(1+\gamma_s)\kappa_s}{\pi(1-\theta)\gamma_s + r\theta(1+\gamma_s)\kappa_s + r\kappa_s\gamma_s[\omega(\kappa_s^{-1}-(1-\alpha))^+ + 1-\theta]}.$$

The optimal coupon values of deposits and market debt for risk profile $s \in \{H, L\}$ are given by:

$$C_{D,s}^* = (r-\pi)V(p_s^*)^{1/\gamma_s}\kappa_s^{-1}, \tag{A.14}$$

$$C_{M,s}^* = rV(p_s^*)^{1/\gamma_s}\left(\frac{1+\gamma_s}{\gamma_s}\frac{1}{1-\theta} - \frac{r-\pi}{r\kappa_s} - \frac{\omega}{1-\theta}(\kappa_s^{-1}-(1-\alpha))^+\frac{p_s^*}{1-p_s^*}\right). \tag{A.15}$$

A.2.2 Equity holders' risk-shifting incentives

Convexity of equity value

When equity holders can freely choose their default boundary and $V_D = V_B$, equity is convex in V:

$$\begin{aligned}\frac{\partial^2 E_s(V)}{\partial V^2} &= \frac{(1-\theta)(C_D+C_M)+I}{rV^2}\gamma_s(\gamma_s+1)\left(\frac{V_B}{V}\right)^{\gamma_s} - \frac{V_B}{V^2}\gamma_s(\gamma_s+1)\left(\frac{V_B}{V}\right)^{\gamma_s} \\ &= \frac{(1-\theta)(C_D+C_M)+I}{rV^2}\gamma_s\left(\frac{V_B}{V}\right)^{\gamma_s} \geq 0.\end{aligned}$$

[3] Note that the assumption that deposit insurance payments are not tax-deductible leads to a slight difference in the value of $C_{M,s}^*$ and p_s^* compared to Sundaresan and Wang (2017).

As a result, equity holders wish to increase risk in the absence of regulatory costs.

Concavity of total bank value

One can show that total bank value is a concave function of V, which implies that risk-taking reduces total bank value.

$$\begin{aligned}\frac{\partial^2 v_s(V)}{\partial V^2} &= -\frac{\theta(C_D+C_M)+\pi D-I}{rV^2}\left[1+\gamma_s(\gamma_s+1)\left(\frac{V_D}{V}\right)^{\gamma_s}\right]-\frac{1}{V^2}\alpha V_D\left[\gamma_s(\gamma_s+1)\left(\frac{V_D}{V}\right)^{\gamma_s}\right]\leq 0.\\ &= -\frac{1}{V^2}\left[\frac{\theta(C_D+C_M)+\pi D-I}{r}+\alpha V_D\right]\left[1+\gamma_s(\gamma_s+1)\left(\frac{V_D}{V}\right)^{\gamma_s}\right]\leq 0.\end{aligned}$$

Therefore, the value of a bank that selects low investment risk is higher than when it selects high risk. Alternatively, one can also see that when p_s increases because of an increase in σ_s, the bank's value decreases.

A.2.3 Formalization of risk-taking regions

I assume throughout this section that the $\kappa_s \leq (1-\alpha)^{-1}$, implying that the deposit insurance premium has a positive price.

Effects high-risk capital requirement on investment risk choice

To formalize the existence of $\kappa^*_{H,1}$ and $\kappa^*_{H,2}$ as described in Proposition 2.2, I proceed as follows. First, I show that the optimal value of a bank that takes high-risk v^*_H is lower than the optimal value of a bank that is restricted to the low-risk investment portfolio v^*_L when $\kappa_H = \kappa_L$. Then, I show that, under most parameter settings, v^*_H decreases in κ_H, while v^*_L is insensitive to changes in κ_H. Lastly, I show the conditions under which the difference in equity value E_H and E_L for first-best capital structure $\mathcal{C}^*$ is decreasing in κ_H. If this holds, it implies that the commitment constraint becomes less constraining for higher regulatory costs κ_H.

Optimal values restricted low-risk bank and high-risk bank For ease of notation, denote $\tilde{\omega} := (1-\theta)^{-1}\omega$. This adjustment is the result of the assumption that deposit insurance premium payments are not tax-deductible, in contrast to Sundaresan and Wang (2017). The authors show that, default state price p^*_s is increasing in asset volatility σ_s:

$$\begin{aligned}\frac{\partial (p^*_s)^{1/\gamma_s}}{\partial\sigma_s} &= -\frac{\partial (p^*_s)^{1/\gamma_s}}{\partial\gamma_s}\frac{\sigma_s\gamma_s^2(1+\gamma_s)}{0.5\sigma_s^2\gamma_s^2+r},\\ \frac{\partial (p^*_s)^{1/\gamma_s}}{\partial\gamma_s} &\geq \frac{(p^*_s)^{1/\gamma_s}}{(1+\gamma_s)^2}\frac{\pi(1-\theta)^2 r[\tilde{\omega}\alpha+(1-\tilde{\omega})(1-1/\kappa_s)]\gamma_s/\kappa_s}{\Psi[\Psi+r(1-\theta)[\tilde{\omega}\alpha+(1-\tilde{\omega})(1-1/\kappa_s)]\gamma_s]}>0,\end{aligned}$$

where $\Psi := r\theta(1+\gamma_s)+\pi(1-\theta)\gamma_s/\kappa_s$ and since

$$\tilde{\omega}\alpha+(1-\tilde{\omega})(1-1/\kappa_s) = \frac{\omega}{1-\theta}\left(\frac{1}{\kappa_s}-(1-\alpha)\right)+\left(1-\frac{1}{\kappa_s}\right)>0.$$

As a result, the value function of the low-risk bank will always be above the one of the high-risk bank:

$$\frac{\partial v_s^*}{\partial \sigma_s} = \left(\frac{\theta}{1-\theta} + \frac{1}{\kappa_s}\frac{\pi}{r}\frac{\gamma_s}{1+\gamma_s}\right)\frac{\partial}{\partial \sigma_s}(p_s^*)^{1/\gamma_s} + \frac{1}{(1+\gamma_s)^2}(p_s^*)^{1/\gamma_s}\frac{\partial \gamma_s}{\partial \sigma_s} < 0.$$

It follows that $v_H^*(\kappa_L) < v_L^*(\kappa_L)$.

Effect high-risk capital requirement on optimal value high-risk bank The derivative of above default state price with respect to capital requirement κ_s is

$$\frac{\partial p_s^*}{\partial \kappa_s} = -\frac{r\gamma_s}{1+\gamma_s}\frac{\pi(1-\theta)\gamma_s[1-\theta-\omega(1-\alpha)] + r\theta(1-\theta-\omega)(1+\gamma_s)}{\left[\pi(1-\theta)\gamma_s + r\theta(1+\gamma_s)\kappa_s + r\kappa_s\gamma_s(\omega(\alpha-1)+1-\theta) - r\gamma_s(1-\theta-\omega)\right]^2}.$$

This expression is negative when $\omega < \overline{\omega}$, where

$$\overline{\omega} := \underbrace{(1-\theta)}_{<1}\underbrace{\frac{\pi(1-\theta)\gamma_s + r\theta(1+\gamma_s)}{\pi(1-\theta)\gamma_s(1-\alpha) + r\theta(1+\gamma_s)}}_{>1}.$$

Using that

$$\frac{\partial (p_s^*)^{1/\gamma_s}}{\partial \kappa_s} = \frac{(p_s^*)^{1/\gamma_s}}{\gamma_s p_s^*}\frac{\partial p_s^*}{\partial \kappa_s},$$

the derivative of optimal bank value v_s^* with respect to capital requirement κ_s is given by:

$$\frac{\partial v_s^*}{\partial \kappa_s} = V(p_s^*)^{1/\gamma_s}\left[\left(\frac{\theta}{1-\theta} + \frac{1}{\kappa_s}\frac{\pi}{r}\frac{\gamma_s}{(1+\gamma_s)}\right)\frac{1}{\gamma_s p_s^*}\frac{\partial p_s}{\partial \kappa_s} - \frac{1}{\kappa_s^2}\frac{\pi}{r}\frac{\gamma_s}{1+\gamma_s}\right].$$

When $\omega < \overline{\omega}$, it is clear that this quantity is negative. In the opposite case, v_s^* may be increasing in κ_s. However, in the numerical analysis, this case does not occur.[4] Therefore, I focus on the case where optimal bank value v_H^* decreases in regulatory constraint κ_H. Note that the optimal value v_L^* of the restricted bank is not affected by changes in κ_H.

Effect high-risk capital requirement on commitment constraint For a given capital structure $\mathcal{C}$, the difference of equity value of the high-risk bank and the low-risk bank multiplied by risk-free rate r as a function of κ_H is given by:

$$\begin{aligned} r\Delta E(\kappa_H) &:= r\left[E_H(\kappa_H) - E_L(\kappa_H)\right] \\ &= (1-\theta)(C_D + C_M)(p_H - p_L) + \omega[I_L^o(1-p_L) - I_H^o(1-p_H)] + r(V_D^L p_L - V_D^H p_H). \end{aligned}$$

This quantity denotes the violation of the commitment constraint. That is, when this value is positive, the bank needs to deviate from the optimal capital structure to convince debt holders that it will not defer to a high-risk portfolio once debt is in place. Let $(C_{D,L}^*, C_{M,L}^*)$

[4]Note that in Sundaresan and Wang (2017), where deposit insurance premium payments are tax-deductible, this derivative is always negative.

denote the optimal capital structure of a bank that can commit to the low-risk portfolio. In that scenario, $V_A^* = V_B^*$ under reasonable parameter assumptions, as was discussed in Section A.2.1. However, when regulatory costs are set sufficiently low, the commitment constraint might be violated at the bank's privately optimal capital structure. Consider the effect of increasing κ_H on the commitment violation gap for a given capital structure $\mathcal{C}$, using Eq. (A.13):

$$\frac{\partial r\Delta E(\kappa_H)}{\partial \kappa_H} = \begin{cases} p_H\left[(1-\theta)(C_D+C_M)\frac{\gamma_H}{\kappa_H} - \frac{r}{r-\pi}C_D\left(\frac{\gamma_H}{\kappa_H}\omega + (1+\gamma_H)(1-\omega(1-\alpha))\right)\right], & \text{if } \kappa_H < \frac{1}{1-\alpha}, \\ p_H\left[(1-\theta)(C_D+C_M)\frac{\gamma_H}{\kappa_H} - \frac{r}{r-\pi}C_D(1+\gamma_H)\right], & \text{else.} \end{cases} \tag{A.16}$$

When this expression is negative, the difference between the equity value of a high-risk portfolio and of a low-risk portfolio becomes smaller for larger values of κ_H. In other words, when the capital charge of a high-risk portfolio increases, it becomes less attractive for the bank's equity holders to select a high-risk portfolio and be subject to the high capital requirement. Focusing on the case $\kappa_H < (1-\alpha)^{-1}$, the expression in Eq. (A.16) is negative when for a given C_M:

$$\frac{C_M}{C_D} < \frac{1}{1-\theta}\frac{r}{r-\pi}\left[\omega + (1-\omega(1-\alpha))\frac{\gamma_H+1}{\gamma_H}\kappa_H\right] - 1. \tag{A.17}$$

Assuming that $\kappa_L < (1-\alpha)^{-1}$, the ratio of the optimal coupons for a low-risk bank as defined in Eq. (A.14) and (A.15) equals:

$$\frac{C_{M,L}^*}{C_{D,L}^*} = \frac{r}{r-\pi}\frac{\kappa_L}{1-\theta}\left[\frac{1+\gamma_L}{\gamma_L} - \omega(1/\kappa_L - (1-\alpha))\frac{p_L}{1-p_L}\right] - 1.$$

Consider evaluating inequality (A.17) at the optimal coupons:

$$\frac{C_{M,L}^*}{C_{D,L}^*} < \frac{1}{1-\theta}\frac{r}{r-\pi}\left[\omega + (1-\omega(1-\alpha))\frac{\gamma_H+1}{\gamma_H}\kappa_H\right] - 1.$$

If this inequality holds, it implies that at the unconstrained first-best capital structure, the commitment constraint becomes less binding as κ_H increases. Plugging in the values for $\mathcal{C}_L^*$ and multiplying by $(1-\theta)(r-\pi)/r$ gives:

$$\kappa_L\left[\frac{1+\gamma_L}{\gamma_L} - \omega(1/\kappa_L - (1-\alpha))\frac{p_L}{1-p_L}\right] < \omega + (1-\omega(1-\alpha))\frac{\gamma_H+1}{\gamma_H}\kappa_H.$$

This inequality can be rewritten as

$$\kappa_H > \frac{\kappa_L\left[\frac{1+\gamma_L}{\gamma_L} + \omega(1-\alpha)\frac{p_L}{1-p_L}\right] - \omega\left[1 + \frac{p_L}{1-p_L}\right]}{1-\omega(1-\alpha)}\frac{\gamma_H}{\gamma_H+1}. \tag{A.18}$$

Note that for $\omega = 0$, inequality (A.18) simplifies to

$$\kappa_H > \kappa_L\frac{1+\gamma_L}{\gamma_L}\frac{\gamma_H}{\gamma_H+1},$$

which always holds since $\gamma_L > \gamma_H$. This implies that absent any deposit insurance premium payments, the commitment constraint is always decreasing in κ_H. The derivative of the right-hand side of inequality (A.18) with respect to ω is as follows:

$$\frac{\gamma_H}{\gamma_H+1}\frac{(1-p_L)^{-1}(\kappa_L(1-\alpha)-1)+\kappa_L(1-\alpha)\gamma_L^{-1}}{(1-\omega(1-\alpha))^2}.$$

The sign of the right-hand side is negative when

$$\kappa_L(1-\alpha) < \frac{\gamma_L}{\gamma_L+1-p_L}. \tag{A.19}$$

That is, when κ_L is sufficiently low, inequality (A.18) holds for $\omega \in [0,1]$. However, when inequality (A.19) does not hold, there is a point $\omega > 0$ for which the inequality no longer holds. This is the case when the deposit insurance premium is so substantial for the bank that increasing regulatory default threshold κ_H is not costly for the bad bank, as it lowers the deposit insurance payments. However, this scenario does not occur in the numerical analysis. This shows that when κ_H gets larger, the gap to close becomes smaller, so the bank has to deviate less from the optimal capital structure. In other words, as the regulatory cost increase, the incentive for equity holders to move to the high-risk portfolio becomes smaller. As a result, a smaller deviation from the optimal capital structure is necessary to convince debt holders that the bank will not deviate to the high-risk portfolio.

Risk-taking regions To identify the three risk-taking regions presented in Proposition 2.2, bring the observations together:

(i) Optimal bank value v_L^* as a function of κ_H is a straight line that is positioned above v_H^* for $\kappa_H \geq \kappa_L$.

(ii) Optimal bank value v_H^* is decreasing in κ_H.

(iii) Commitment constraint $E_L \geq E_H$ is becoming less constraining for larger values of κ_H.

Let $\tilde{v}_L^*(\kappa_H)$ be the optimal value of a bank that commits to the low-risk strategy as a function of κ_H. If $\tilde{v}_L^*(\kappa_L) < v_H^*(\kappa_L)$, then there exists a point $\kappa_{H,1}^*$ such that $\tilde{v}_L^*(\kappa_{H,1}^*) = v_H^*(\kappa_{H,1}^*)$. This condition is not always satisfied. For example, when ω is set sufficiently high, the higher deposit insurance premium payments corresponding to high asset risk lead to a lower bank value. When this is the case, $\kappa_{H,1}^*$ is set equal to κ_L, so that the risk-taking region is empty. As the commitment constraint is becoming less binding when κ_H increases, equity holders have to deviate less from the benchmark capital structure $\mathcal{C}_L^*$ to commit to low investment risk. As a result, the function $\tilde{v}_L^*(\kappa_H)$ is increasing in κ_H and eventually coincides with $v_L^*(\kappa_H)$. I define $\kappa_{H,2}^*$ the smallest value of κ_H for which the commitment constraint is not binding anymore.

Effects deposit insurance pricing on investment risk choice

To formalize the existence of threshold values ω_1^* and ω_2^* as described in Proposition 2.3, I proceed in a similar way as for κ_H. First, I show that the optimal value of a bank that takes high-risk v_H^* is lower than the optimal value of a bank that is restricted to the low-risk investment portfolio v_L^* when $\omega = 0$. Then, I show that v_H^* is decreasing in κ_H, while v_L^* is insensitive to changes in κ_H. Lastly, I show that commitment constraint violation $E_H \geq E_L$ decreases in κ_H.

Effects deposit insurance pricing on optimal value low-risk and high-risk bank Similarly, Sundaresan and Wang (2017) showed that the derivative of the default state price is increasing in $\tilde{\omega}$:

$$\frac{\partial p_s^*}{\partial \tilde{\omega}} = -\frac{r\gamma_s}{1+\gamma_s}\frac{(1-\theta)(\alpha-(\kappa_s-1)/\kappa_s)[r\theta(1+\gamma_s)+\pi\gamma_s/\kappa_s]}{[r\theta(1+\gamma_s)+\pi(1-\theta)\gamma_s/\kappa_s+r(1-\theta)(\tilde{\omega}\alpha+(1-\tilde{\omega})(\kappa_s-1)/\kappa_s)\gamma_s]^2} < 0,$$

and

$$\frac{\partial p_s^*}{\partial \omega} = \frac{\partial \tilde{\omega}}{\partial \omega}\frac{\partial p_s^*}{\partial \tilde{\omega}} = \frac{1}{1-\theta}\frac{\partial p_s^*}{\partial \tilde{\omega}} < 0, \quad \text{and} \quad \frac{\partial (p_s^*)^{1/\gamma_s}}{\partial \omega} = \frac{(p_s^*)^{1/\gamma_s}}{\gamma_s p_s^*}\frac{\partial p_s^*}{\partial \omega} < 0.$$

As a result,

$$\frac{1}{V}\frac{\partial v_s^*}{\partial \omega} = \left(\frac{\theta}{1-\theta} + \frac{1}{\kappa_s}\frac{\pi}{r}\frac{\gamma_s}{1+\gamma_s}\right)\frac{(p_s^*)^{1/\gamma_s}}{\gamma_s p_s^*}\frac{\partial p_s^*}{\partial \omega} < 0.$$

This shows that the optimal value of the bank is decreasing in ω, as the bank enjoys less subsidy benefits. The derivative of the value function with respect to γ_s is given by

$$\frac{1}{V}\frac{\partial v_s^*}{\partial \gamma_s} = \frac{1}{(1+\gamma_s)^2}(p_s^*)^{1/\gamma_s} - \left(\frac{\theta}{1-\theta} + \frac{1}{\kappa_s}\frac{\pi}{r}\frac{\gamma_s}{1+\gamma_s}\right)\ln(p_s^*)\frac{1}{\gamma_s^2} > 0.$$

This implies that the optimal value of a low-risk bank is higher than of a high-risk bank for any value $\omega \in [0,1]$ and $\kappa_H \geq \kappa_L$.

Effects deposit insurance pricing on commitment constraint For a given capital structure $\mathcal{C}$, the difference of equity value of the high-risk bank and the low-risk bank multiplied by r is given by as a function of deposit insurance pricing parameter ω is:

$$r\Delta E(\omega) := r[E_H(\omega) - E_L(\omega)].$$

Similar to Section A.2.3, I consider how the derivative of the commitment constraint moves at the unconstrained first-best capital structure $\mathcal{C}_L^*$ where $V_A^* = V_B^*$.

$$\begin{aligned}\frac{\partial r\Delta E(\omega)}{\partial \omega} &= I_L^o(1-p_L) - I_H^o(1-p_H)\\ &= \left[p_L(1-(1-\alpha)\kappa_L)^+ - p_H(1-(1-\alpha)\kappa_H)^+\right]\frac{r}{r-\pi}C_{D,L}^*.\end{aligned}$$

This derivative is negative when the present value of deposit insurance payments of a high-risk bank are higher than a low-risk bank. Assuming that $1-(1-\alpha)\kappa_s > 0$ for $s \in \{H, L\}$, this boils down to

$$\frac{p_L}{p_H} < \frac{1-(1-\alpha)\kappa_H}{1-(1-\alpha)\kappa_L}. \tag{A.20}$$

Note that when $\kappa_H = \kappa_L$, this inequality becomes

$$\left(\frac{\kappa_L D}{V}\right)^{\gamma_L - \gamma_H} < 1,$$

which always holds. However, when $\kappa_H = (1-\alpha)^{-1}$, the inequality does no longer hold. This implies that when κ_H is sufficiently large, the deposit insurance premiums of a high-risk bank are lower, as the obligation to depositors in case of bank failure is limited. In the numerical analysis, I focus on the case where inequality (A.20) holds.

Risk-taking regions To identify the three risk-taking regions presented in Proposition 2.3, bring the observations together:

(i) Optimal bank values v_L^* and v_H^* are decreasing in ω.

(ii) Optimal bank value v_L^* is positioned above v_H^* for all values of ω.

(iii) Commitment constraint $E_L \geq E_H$ is becoming less constraining for larger values ω.

Let $\tilde{v}_L^*(\omega)$ be the optimal value of a bank that commits to the low-risk strategy as a function of ω. If $\tilde{v}_L^*(\omega) < v_H^*(\omega)$, then there exists a point ω_1^* such that $\tilde{v}_L^*(\omega_1^*) = v_H^*(\omega_1^*)$. This condition is not always satisfied. In specific, when κ_H is set sufficiently high, there is still a cost of regulatory cost in terms of a higher capital requirement when choosing high investment risk. When this is the case, ω_1^* is set to 0 and the risk-shifting region is empty. As the commitment constraint is generally becoming less binding when ω increases, equity holders have to deviate less from the benchmark capital structure $\mathcal{C}_L^*$ to commit to low investment risk. As a result, the function $\tilde{v}_L^*(\omega)$ is increasing in ω and eventually coincides with $v_L^*(\omega)$. I define ω_2^* as the smallest value of ω for which the commitment constraint is not binding anymore.

A.2.4 Effects capital structure on risk-taking behavior

Keeping C_M constant, a change in C_D can either make V_A or V_B the dominant default threshold, depending on the relative magnitude of the following two quantities:

$$\frac{\partial V_A}{\partial C_D} = \frac{\kappa_L}{r-\pi}, \quad \text{and} \quad \frac{\partial V_B}{\partial C_D} = \frac{1}{r}\frac{\gamma_L}{1+\gamma_L}\left[(1-\theta) + \frac{\partial I}{\partial C_D}\right].$$

When $\partial V_A / \partial C_D > \partial V_B / \partial C_D$, deviating C_D upwards from its first-best optimal solution makes regulatory threshold V_A dominate. In the opposite case, V_B becomes the default threshold. I distinguish two cases to study how the commitment constraint moves with C_D.

Case i) $V_D = V_A$

The derivative of the commitment constraint with respect to C_D is given by:

$$r\frac{\partial \Delta E}{\partial C_D} = p_H(1+\gamma_H)\underbrace{\left[(1-\theta) - \frac{r}{r-\pi}[\kappa_H + (1-(1-\alpha)\kappa_H)\omega]\right]}_{=:A_1}$$

$$- p_L(1+\gamma_L)\underbrace{\left[(1-\theta) - \frac{r}{r-\pi}[\kappa_L + (1-(1-\alpha)\kappa_L)\omega]\right]}_{=:A_2} + (1-\theta)\frac{C_M}{C_D}(\gamma_H p_H - \gamma_L p_L).$$

Note that $A_1 \leq A_2 < 0$, since $\kappa_H \geq \kappa_L$. However, because $p_H > p_L$ but $\gamma_H < \gamma_L$, the sign of this derivative is ambiguous. In other words, from this expression it is not clear whether the bank should decrease or increase its deposit coupon when it wants to commit to the low-risk portfolio. However, numerical computations show that in general the negative terms dominate in this expression. As a result, equity holders commit to the low-risk portfolio by increasing deposits.

Case ii) $V_D = V_B$

The commitment constraint in the case that endogenous default boundary V_B is dominant is given by

$$\Delta E = r^{-1}(1-\theta)(C_D + C_M)(p_H - p_L) + \frac{\omega C_D[p_L(1-(1-\alpha)\kappa_L)^+ - p_H(1-(1-\alpha)\kappa_H)^+]}{(1-\theta)(r-\pi)} + (V_B^L p_L - V_B^H p_H).$$

Now take the derivative with respect to deposit coupon C_D:

$$\frac{\partial \Delta E}{\partial C_D} = \frac{1-\theta}{r}\underbrace{\left(\frac{1+\gamma_L - p_L}{1+\gamma_L} - \frac{1+\gamma_H - p_H}{1+\gamma_H}\right)}_{>0} + \frac{\omega}{1-\theta}\frac{1}{r-\pi}\left(\frac{p_L}{1-p_L}(1-(1-\alpha)\kappa_L)\frac{1+\gamma_L - p_L}{1+\gamma_L} - \frac{p_H}{1-p_H}(1-(1-\alpha)\kappa_H)\frac{1+\gamma_H - p_H}{1+\gamma_H}\right).$$

Again, the sign of this expression is ambiguous.

A.3 Appendix to Chapter 3

A.3.1 Computation of value functions

Value function after shock

Let $W(m) = W(m;\overline{m}^*)$ denote the value function after the shock. Note that the value function is independent of the bank's type, as the market learns the bank's type when the shock hits. The ordinary differential equation corresponding to the cash-flows dynamics is:

$$\rho W(m) = \mu W'(m) + 0.5\sigma^2 W''(m).$$

The characteristic roots $\overline{r}_1$ and $\overline{r}_2$ are given by characteristic equation

$$\rho - \mu r - 0.5\sigma^2 r^2 = 0 \implies \overline{r}_1 = \frac{-\mu - \sqrt{\mu^2 + 2\sigma^2\rho}}{\sigma^2}, \quad \overline{r}_2 = \frac{-\mu + \sqrt{\mu^2 + 2\sigma^2\rho}}{\sigma^2}.$$

As a result, the value function can be written as

$$W(m) = \begin{cases} \overline{A}_1 e^{\overline{r}_1(m-\overline{m}^*)} + \overline{A}_2 e^{\overline{r}_2(m-\overline{m}^*)}, & \text{for } m < \overline{m}^*, \\ m - \overline{m}^* + \overline{A}_1 + \overline{A}_2, & \text{for } m \geq \overline{m}^*. \end{cases}$$

The coefficients $\overline{A}_1$ and $\overline{A}_2$ are pinned down by smooth pasting and high-contact conditions:

$$W'(\overline{m}^*) = 1, \quad W''(\overline{m}^*) = 0,$$

which results in

$$\overline{A}_1 = \frac{\overline{r}_2^2}{\overline{r}_1\overline{r}_2(\overline{r}_2 - \overline{r}_1)}, \quad \overline{A}_2 = \frac{-\overline{r}_1^2}{\overline{r}_1\overline{r}_2(\overline{r}_2 - \overline{r}_1)}.$$

Furthermore, the optimal dividend boundary is pinned down by value matching at 0:

$$\overline{m}^* = \frac{2}{\overline{r}_2 - \overline{r}_1} \log\left(-\frac{\overline{r}_1}{\overline{r}_2}\right). \tag{A.21}$$

Note that at this optimal boundary, $W(\overline{m}^*) = \overline{A}_1 + \overline{A}_2 = \mu/\rho$.

Value function bad bank before shock

We will now compute the value function of a bad bank before the arrival of the liquidity shock for a given dividend policy m_B. We will distinguish three cases that depend on the relative position of the dividend policy before and after the shock.

Case i) $m_B - f \in (0, \overline{m}^*)$
The bank defaults when the bank's cash reserves are smaller than the shock, i.e. $m < f$. In this

region, the ordinary differential equation is:

$$\rho V_B(m) = \mu V_B'(m) + 0.5\sigma^2 V_B''(m) - \lambda V_B(m),$$

so that the solution can be written as

$$V_B(m) = \sum_{i=1}^{2} A_i^B e^{r_i(m-m_B)},$$

where r_1 and r_2 are the solution to characteristic equation

$$(\rho+\lambda) - \mu r - 0.5\sigma^2 r^2 = 0 \implies r_1 = \frac{-\mu - \sqrt{\mu^2 + 2\sigma^2(\rho+\lambda)}}{\sigma^2}, \quad r_2 = \frac{-\mu + \sqrt{\mu^2 + 2\sigma^2(\rho+\lambda)}}{\sigma^2}.$$

For the region $m \in [f, m_B]$ the ordinary differential equation is

$$\rho V_B(m) = \mu V_B'(m) + 0.5\sigma^2 V_B''(m) + \lambda(W(m-f) - V_B(m)).$$

The homogeneous solution can be written as

$$V_B^h(m) = \sum_{i=1}^{2} B_i^B e^{r_i(m-m_B)},$$

To find the particular solution, plug in conjecture $\sum_{i=1}^{2} \alpha_i \overline{A}_i e^{\overline{r}_i(m-f)}$ in the ODE:

$$\sum_{i=1}^{2} (\rho+\lambda)\alpha_i \overline{A}_i e^{\overline{r}_i(m-f)} = \sum_{i=1}^{2} \mu\alpha_i \overline{r}_i \overline{A}_i e^{\overline{r}_i(m-f)} + 0.5\sigma^2 \alpha_i r_i^2 \overline{A}_i e^{\overline{r}_i(m-f)} + \lambda \overline{A}_i e^{\overline{r}_i(m-f)},$$

where α_i, $i \in \{1,2\}$ can be simplified as follows:

$$(\rho + \lambda - \mu\overline{r}_i - 0.5\sigma^2\overline{r}_i^2)\alpha_i = \lambda \implies \alpha_i = 1.$$

Bringing this together:

$$V_B(m) = V_B(m; m_B) = \begin{cases} \sum_{i=1}^{2} A_i^B e^{r_i(m-m_B)}, & \text{for } m < f, \\ \sum_{i=1}^{2} B_i^B e^{r_i(m-m_B)} + W(m-f), & \text{for } m \in [f, m_B), \\ \sum_{i=1}^{2} B_i^B + W(m_B - f) + m - m_B, & \text{for } m \geq m_B. \end{cases} \tag{A.22}$$

The coefficients A_i^B and B_i^B are pinned down by the following boundary equations:

- Value matching at $m = 0$: $\lim_{m\downarrow 0} V_B(m) = 0$;
- Value matching at $m = f$: $\lim_{m\uparrow f} V_B(m) = \lim_{m\downarrow f} V_B(m)$;
- Smooth pasting at $m = f$: $\lim_{m\uparrow f} V_B'(m) = \lim_{m\downarrow f} V_B'(m)$;
- Smooth pasting at $m = m_B$: $\lim_{m\uparrow m_B} V_B'(m) = 1$.

Denote $\mathbf{A^B} = \begin{bmatrix} A_1^B & A_2^B \end{bmatrix}^\top$ and $\mathbf{B^B} = \begin{bmatrix} B_1^B & B_2^B \end{bmatrix}^\top$. These boundary equations can be summarized into the following system of equations:

$$\begin{bmatrix} \mathbf{A^B} \\ \mathbf{B^B} \end{bmatrix} = (M_1^B)^{-1} v_1^B,$$

where

$$M_1^B := \begin{bmatrix} e^{-r_1 m_B} & e^{-r_2 m_B} & 0 & 0 \\ e^{r_1(f-m_B)} & e^{r_2(f-m_B)} & -e^{r_1(f-m_B)} & -e^{r_2(f-m_B)} \\ r_1 e^{r_1(f-m_B)} & r_2 e^{r_2(f-m_B)} & -r_1 e^{r_1(f-m_B)} & -r_2 e^{r_2(f-m_B)} \\ 0 & 0 & r_1 & r_2 \end{bmatrix}, \quad v_1^B := \begin{bmatrix} 0 \\ 0 \\ W'(0) \\ 1 - W'(m_B - f) \end{bmatrix}.$$

Case ii) $m_B - f \geq \overline{m}^*$
In the region $m < f$, the ordinary differential equation and solution is the same as in case i).
In the region $m \in [f, f + \overline{m}^*)$, the ordinary differential equation is again given by

$$(\rho + \lambda) V_B(m) = \mu V_B'(m) + 0.5\sigma^2 V_B''(m) + \lambda W(m - f).$$

In the region $m \in [\overline{m}^* + f, m_B)$, the ordinary differential equation is given by

$$(\rho + \lambda) V_B(m) = \mu V_B'(m) + 0.5\sigma^2 V_B''(m) + \lambda \left(m - f - \overline{m}^* + \frac{\mu}{\rho} \right).$$

Conjecture the following solution to the particular solution: $V_B^p(m) = \beta_B + \gamma m$, and plug this into the ordinary differential equation:

$$(\rho + \lambda)(\beta_B + \gamma m) = \mu\gamma + \lambda \left(m - f - \overline{m}^* + \frac{\mu}{\rho} \right).$$

Solving for β_B and γ gives

$$(\rho + \lambda)\gamma = \lambda \implies \gamma = \frac{\lambda}{\rho + \lambda},$$
$$(\rho + \lambda)\beta_B = \mu\gamma + \lambda \left(-f - \overline{m}^* + \frac{\mu}{\rho} \right) \implies \beta_B = \gamma \left(\frac{\mu}{\rho + \lambda} + \frac{\mu}{\rho} - f - \overline{m}^* \right).$$

Bringing all of this together the following value function:

$$V_B(m) = \begin{cases} \sum_{i=1}^2 A_i^B e^{r_i(m - m_B)}, & \text{for } m \in [0, f), \\ \sum_{i=1}^2 B_i^B e^{r_i(m - m_B)} + W(m - f), & \text{for } m \in [f, f + \overline{m}^*], \\ \sum_{i=1}^2 C_i^B e^{r_i(m - m_B)} + \beta_B + \gamma m, & \text{for } m \in [f + \overline{m}^*, m_B), \\ \sum_{i=1}^2 C_i^B + \beta_B + (\gamma - 1) m_B + m, & \text{for } m \geq m_B. \end{cases}$$

The coefficients A_i^B, B_i^B, C_i^B, for $i \in \{1, 2\}$ are solved by the following boundary conditions:

- Value matching at $m = 0$: $\lim_{m \downarrow 0} V_B(m) = 0$;
- Value matching at $m = f$: $\lim_{m \downarrow f} V_B(m) = \lim_{m \uparrow f} V_B(m)$;
- Smooth pasting at $m = f$: $\lim_{m \downarrow f} V_B'(m) = \lim_{m \uparrow f} V_B'(m)$;

- Value matching at $m = f + \overline{m}^*$: $\lim_{m \downarrow f+\overline{m}^*} V_B(m) = \lim_{m \uparrow f+\overline{m}^*} V_B(m)$;
- Smooth pasting at $m = f + \overline{m}^*$: $\lim_{m \downarrow f+\overline{m}^*} V_B'(m) = \lim_{m \uparrow f+\overline{m}^*} V_B'(m)$;
- Smooth pasting at $m = m_B$: $\lim_{m \uparrow m_B} V_B'(m) = 1$.

Denote $\mathbf{A^B} = \begin{bmatrix} A_1^B & A_2^B \end{bmatrix}^\top$, $\mathbf{B^B} = \begin{bmatrix} B_1^B & B_2^B \end{bmatrix}^\top$ and $\mathbf{C^B} = \begin{bmatrix} C_1^B & C_2^B \end{bmatrix}^\top$. The system of equations can then be summarized as follows:

$$\begin{bmatrix} \mathbf{A^B} \\ \mathbf{B^B} \\ \mathbf{C^B} \end{bmatrix} = (M_2^B)^{-1} v_2^B, \quad \text{where } v_2^B := \begin{bmatrix} 0 \\ 0 \\ W'(0) \\ \frac{\mu}{\rho+\lambda}(\gamma - 1) \\ \gamma - 1 \\ 1 - \gamma \end{bmatrix},$$

and $M_2^B :=$

$$\begin{bmatrix} e^{-r_1 m_B} & e^{-r_2 m_B} & 0 & 0 & 0 & 0 \\ e^{r_1(f-m_B)} & e^{r_2(f-m_B)} & -e^{r_1(f-m_B)} & -e^{r_2(f-m_B)} & 0 & 0 \\ r_1 e^{r_1(f-m_B)} & r_2 e^{r_2(f-m_B)} & -r_1 e^{r_1(f-m_B)} & -r_2 e^{r_2(f-m_B)} & 0 & 0 \\ 0 & 0 & e^{r_1(f+\overline{m}^*-m_B)} & e^{r_2(f+\overline{m}^*-m_B)} & -e^{r_1(f+\overline{m}^*-m_B)} & -e^{r_2(f+\overline{m}^*-m_B)} \\ 0 & 0 & r_1 e^{r_1(f+\overline{m}^*-m_B)} & r_2 e^{r_2(f+\overline{m}^*-m_B)} & -r_1 e^{r_1(f+\overline{m}^*-m_B)} & -r_2 e^{r_2(f+\overline{m}^*-m_B)} \\ 0 & 0 & 0 & 0 & r_1 & r_2 \end{bmatrix}.$$

Case iii) $m_B - f \leq 0$
In this case, the bad bank defaults as soon as the shock arrives. Although this is an unrealistic case, we will add the derivations of its value function for the sake of complexity. The ordinary differential equation of said case is:

$$(\rho + \lambda) V_B(m) = \mu V_B'(m) + 0.5\sigma^2 V_B''(m),$$

so that

$$V_B(m) = \begin{cases} \sum_{i=1}^2 A_i^B e^{r_i(m-m_B)}, & \text{for } m < m_B, \\ \sum_{i=1}^2 A_i^B + m - m_B, & \text{for } m \geq m_B. \end{cases}$$

The coefficients A_1^B and A_2^B are determined as follows:

$$\begin{bmatrix} A_1^B \\ A_2^B \end{bmatrix} = (M_3^B)^{-1} v_3^B, \quad M_3^B := \begin{bmatrix} e^{-r_1 m_B} & e^{-r_2 m_B} \\ r_1 & r_2 \end{bmatrix}, \quad v_3^B := \begin{bmatrix} 0 \\ 1 \end{bmatrix}.$$

Value function good bank before shock

Case i) $m_G \leq \overline{m}^*$

$$V_G(m) = \begin{cases} \sum_{i=1}^{2} A_i^G e^{r_i(m-m_G)} + W(m), & \text{for } m \in [0, m_G), \\ \sum_{i=1}^{2} A_i^G + W(m_G) + m - m_G, & \text{for } m \geq m_G. \end{cases} \tag{A.23}$$

where A_1^G and A_2^G are pinned down by

- Value matching at $m = 0$: $\lim_{m \downarrow 0} V_G(m) = 0$;
- Smooth pasting at $m = m_G$: $\lim_{m \downarrow m_G} V_G'(m) = 1$.

which gives us

$$\begin{bmatrix} A_1^G \\ A_2^G \end{bmatrix} = (M_1^G)^{-1} v_1^G, \quad M_1^G := \begin{bmatrix} e^{-r_1 m_G} & e^{-r_2 m_G} \\ r_1 & r_2 \end{bmatrix}, \quad v_1^G := \begin{bmatrix} 0 \\ 1 - W'(m_G) \end{bmatrix}.$$

Case ii) $m_G > \overline{m}^*$

Suppose now that the good bank pays out later than what is optimal,

$$V_G(m) = \begin{cases} \sum_{i=1}^{2} A_i^G e^{r_i(m-m_G)} + W(m), & \text{for } m \in [0, \overline{m}^*), \\ \sum_{i=1}^{2} B_i^G e^{r_i(m-m_G)} + \beta_G + \gamma m, & \text{for } m \in [\overline{m}^*, m_G), \\ \sum_{i=1}^{2} B_i^G + \beta_G + (\gamma - 1) m_G + m, & \text{for } m \geq m_G. \end{cases}$$

where $\gamma = \lambda / (\rho + \lambda)$ and

$$(\rho + \lambda)\beta_G = \mu\gamma + \lambda\left(\frac{\mu}{\rho} - \overline{m}^*\right) \implies \beta_G = \gamma\left(\frac{\mu}{\rho + \lambda} + \frac{\mu}{\rho} - \overline{m}^*\right).$$

The coefficients are pinned down by the following conditions

- Value matching at $m = 0$: $\lim_{m \downarrow 0} V_G(m) = 0$;
- Value matching at $m = \overline{m}^*$: $\lim_{m \downarrow \overline{m}^*} V_G(m) = \lim_{m \uparrow \overline{m}^*} V_G(m)$;
- Smooth pasting at $m = \overline{m}^*$: $\lim_{m \downarrow \overline{m}^*} V_G'(m) = \lim_{m \uparrow \overline{m}^*} V_G'(m)$;
- Smooth pasting at $m = m_G$: $\lim_{m \uparrow m_G} = 1$.

This can be summarized by the following system of equations:

$$\begin{bmatrix} \mathbf{A^G} \\ \mathbf{B^G} \end{bmatrix} = (M_2^G)^{-1} v_2^G,$$

where

$$M_2^G := \begin{bmatrix} e^{-r_1 m_G} & e^{-r_2 m_G} & 0 & 0 \\ e^{r_1(\overline{m}^* - m_G)} & e^{r_2(\overline{m}^* - m_G)} & -e^{r_1(\overline{m}^* - m_G)} & -e^{r_2(\overline{m}^* - m_G)} \\ r_1 e^{r_1(\overline{m}^* - m_G)} & r_2 e^{r_2(\overline{m}^* - m_G)} & -r_1 e^{r_1(\overline{m}^* - m_G)} & -r_2 e^{r_2(\overline{m}^* - m_G)} \\ 0 & 0 & r_1 & r_2 \end{bmatrix}, \quad v_2^G := \begin{bmatrix} 0 \\ \frac{\mu}{\rho+\lambda}(\gamma - 1) \\ \gamma - 1 \\ 1 - \gamma \end{bmatrix}.$$

Full information case

In the full information case, the optimal cash target m_G^* of the good bank simply equals the after-shock threshold given in Eq. (A.21). The optimal cash target m_B^* is determined by the high-contact condition around the payout threshold m_B:

$$\lim_{m \downarrow m_B^*} V_B''(m) = 0.$$

In general, there exists no closed-form solution for the optimal payout level m_B^*. In the case where the dividend threshold is smaller than shock size f, the bank is wiped out when the shock arrives. In this scenario, there exists a closed form solution for m_B^*:

$$m_B^* = \frac{2}{r_2 - r_1} \log\left(-\frac{r_1}{r_2}\right). \tag{A.24}$$

One can show that this value is smaller than m_G^*. This implies that shareholders hoard less cash to hedge against the Brownian liquidation risk in the presence of tail risk.

Furthermore, one can observe that the intrinsic value of the bank at optimal boundary m_G^* can be determined as follows:

$$(\rho+\lambda)V_G(m_G^*) = \mu V_G'(m_G^*) + 0.5\sigma^2 V_G''(m_G^*) + \lambda W(m_G^*),$$
$$(\rho+\lambda)V_G(m_G^*) = \mu + \lambda W(m_G^*) \implies V_G(m_G^*) = \frac{\mu}{\rho+\lambda} + \frac{\lambda}{\rho+\lambda} W(m_G^*),$$

and analogously for the bad bank

$$(\rho+\lambda)V_B(m_B^*) = \mu V_B'(m_B^*) + 0.5\sigma^2 V_B''(m_B^*) + \lambda W(m_B^* - f),$$
$$(\rho+\lambda)V_B(m_B^*) = \mu + \lambda W(m_B^* - f) \implies V_B(m_B^*) = \frac{\mu}{\rho+\lambda} + \frac{\lambda}{\rho+\lambda} W(m_B^* - f).$$

Optimal cash target in the presence of asymmetric information

We will first look at the optimal cash target of a good bank that is being mimicked by a bad bank. The objective function of the good bank becomes:

$$k\left[\alpha V_G(m; m_D) + (1-\alpha) V_B(m; m_D)\right] + (1-k) V_G(m; m_D)$$
$$= \left[1 - (1-\alpha)k\right] V_G(m; m_D) + (1-\alpha) k V_B(m; m_D)$$

The optimal barrier $m_{G,p}^*$ is the solution to the following high contact condition:

$$\left[1 - (1-\alpha)k\right] \left.\frac{\partial^2 V_G(m; m_{G,p}^*)}{\partial m^2}\right|_{m=m_{G,p}^*} + (1-\alpha) k \left.\frac{\partial^2 V_B(m; m_{G,p}^*)}{\partial m^2}\right|_{m=m_{G,p}^*} = 0.$$

Similarly, the best pooling equilibrium strategy for the bad bank $m^*_{B,p}$ is the solution to:

$$k\alpha \left. \frac{\partial^2 V_G(m;m^*_{B,p})}{\partial m^2} \right|_{m=m^*_{B,p}} + (1-k\alpha) \left. \frac{\partial^2 V_B(m;m^*_{B,p})}{\partial m^2} \right|_{m=m^*_{B,p}} = 0.$$

We will now study the optimal cash target of a good bank that is considered to be bad. The objective function of the good bank becomes:

$$kV_B(m;m_D) + (1-k)V_G(m;m_D).$$

The optimal barrier $m^*_{G,B}$ is the solution to the following high contact condition:

$$(1-k) \left. \frac{\partial^2 V_G(m;m^*_{G,B})}{\partial m^2} \right|_{m=m^*_{G,B}} + k \left. \frac{\partial^2 V_B(m;m^*_{G,B})}{\partial m^2} \right|_{m=m^*_{G,B}} = 0.$$

A.3.2 Default probability

In this section we present the methodology used to find the bank's default probability. We first approximate the default probabilities after the liquidity shock has materialized and extend the numerical procedure to the setting before arrival of the shock.

Default probability after shock

Let $\overline{K}(m,t,T)$ be the probability that the bank did not default before time horizon T for a current time $t < T$ and a cash reserve m. It is assumed that after the shock, the bank plays its optimal dividend strategy $\overline{m}^*$ and denote the default time

$$\overline{K}(m,t,T) = \mathbb{P}(\tau^L > T \mid M^L_t = m).$$

For the ease of notation, we drop the argument T. Following Klimenko and Moreno–Bromberg (2016), one can show that the survival probability $\overline{K}(m,t)$ solves the following boundary problem described in Eq. (A.25) - (A.28). Note that the presence of a time dimension results in an additional partial derivative with respect to time. Furthermore, the survival probability is not discounted, so the term $\rho\overline{K}(m,t)$ is not showing up in the partial derivative.

$$\frac{\partial \overline{K}(m,t)}{\partial t} + \frac{1}{2}\sigma^2 \frac{\partial^2 \overline{K}(m,t)}{\partial m^2} + \mu \frac{\partial \overline{K}(m,t)}{\partial m} = 0, \tag{A.25}$$

$$\overline{K}(0,t) = 0, \quad \forall t \geq 0, \tag{A.26}$$

$$\overline{K}(m,T) = 1, \quad \forall m > 0, \tag{A.27}$$

$$\left. \frac{\partial \overline{K}(m,t)}{\partial m} \right|_{m=\overline{m}^*} = 0. \tag{A.28}$$

Boundary condition (A.26) states that the probability of survival after having been liquidated is zero. Furthermore, boundary condition (A.27) says that the bank has survived until $t = T$

for all positive values of m. Lastly, Neumann condition (A.28) guarantees that the survival probability does not change anymore beyond $m > \overline{m}^*$, since the cash reserves do not increase beyond this level. Because of the time dimension in the above boundary system, there is no closed-form solution to this system. Instead, we solve it numerically using the Crank-Nicolson finite-difference method, see Crank and Nicolson (1947).

Computations of default probability before shock

Let $K_\ell(m,t,T)$ be the probability that the bank of type ℓ did not dfault before time horizon T for a current time $t < T$ and cash reserve m, before arrival of the liquidity shock. For the good bank, $K_G(m,t,T)$ is solved exactly as in $\overline{K}(m,t,T)$ but now with payout threshold m_G rather than $\overline{m}^*$. For the bad bank that is subject to the liquidity shock, the boundary system before arrival of the liquidity shock is given by:

$$\begin{aligned}
&\frac{\partial K_B(m,t)}{\partial t} + \frac{1}{2}\sigma^2 \frac{\partial^2 K_B(m,t)}{\partial m^2} + \mu \frac{\partial K_B(m,t)}{\partial m} = \lambda\left[K_B(m,t) - \overline{K}(m-f,t)\right], \qquad \text{(A.29)}\\
&K_B(0,t) = 0, \quad \forall t \geq 0,\\
&K_B(m,T) = 1, \quad \forall m > 0,\\
&\left.\frac{\partial K_B(m,t)}{\partial m}\right|_{m=m_B} = 0.
\end{aligned}$$

Eq. (A.29) incorporates the jump of the liquidity reserves. We distinguish several cases.
Case i) $m_B - f \in (0, \overline{m}^*)$
In this scenario, the partial differential equation is given by:

$$\begin{aligned}
&\frac{\partial K_B(m,t)}{\partial t} + \frac{1}{2}\sigma^2 \frac{\partial^2 K_B(m,t)}{\partial m^2} + \mu \frac{\partial K_B(m,t)}{\partial m} - \lambda K_B(m,t) = 0, && m < f,\\
&\frac{\partial K_B(m,t)}{\partial t} + \frac{1}{2}\sigma^2 \frac{\partial^2 K_B(m,t)}{\partial m^2} + \mu \frac{\partial K_B(m,t)}{\partial m} - \lambda\left[K_B(m,t) - \overline{K}(m-f,t)\right], && m \in [f, m_B].
\end{aligned}$$

Before applying the Crank Nicolson method, one discretizes the grid separately on the domains $(0,T)\times(0,f)$ and $(0,T)\times(f,m_B)$.

Case ii) $m_B - f \geq \overline{m}^*$
In this case, we differentiate three regions:

$$\begin{aligned}
&\frac{\partial K_B(m,t)}{\partial t} + \frac{1}{2}\sigma^2 \frac{\partial^2 K_B(m,t)}{\partial m^2} + \mu \frac{\partial K_B(m,t)}{\partial m} - \lambda K_B(m,t) = 0, && m < f,\\
&\frac{\partial K_B(m,t)}{\partial t} + \frac{1}{2}\sigma^2 \frac{\partial^2 K_B(m,t)}{\partial m^2} + \mu \frac{\partial K_B(m,t)}{\partial m} - \lambda\left[K_B(m,t) - \overline{K}(m-f,t)\right], && m \in [f, \overline{m}^*],\\
&\frac{\partial K_B(m,t)}{\partial t} + \frac{1}{2}\sigma^2 \frac{\partial^2 K_B(m,t)}{\partial m^2} + \mu \frac{\partial K_B(m,t)}{\partial m} - \lambda\left[K_B(m,t) - \overline{K}(\overline{m}^*-f,t)\right], && m > \overline{m}^*,
\end{aligned}$$

Case iii) $m_B - f \leq 0$

The boundary system looks as follows:

$$\frac{\partial K_B(m,t)}{\partial t} + \frac{1}{2}\sigma^2 \frac{\partial^2 K_B(m,t)}{\partial m^2} + \mu \frac{\partial K_B(m,t)}{\partial m} - \lambda K_B(m,t) = 0.$$

To conclude, the default probability PD_ℓ^T is given by $1 - K_\ell(m, 0, T)$.

A.3.3 Single-crossing

The bank's objective is to maximize the following function:

$$V_{\ell,\tilde{\ell}}(m) = kV_{\tilde{\ell}}(m) + (1-k)V_\ell(m),$$

where ℓ represents the bank's true type and $\tilde{\ell}$ the bank's perceived type. The single crossing condition states that lowering the dividend payout threshold can be considered a valid signal from the good bank when lowering dividend boundary m_D is less costly for the good bank than for the bad bank. This can be formalized as follows:

$$\frac{V_{G,G}(m) - V_{G,B}(m)}{\partial V_{G,\tilde{\ell}}/\partial m_D} > \frac{V_{B,G}(m) - V_{B,B}(m)}{\partial V_{B,\tilde{\ell}}/\partial m_D}. \tag{A.30}$$

Note that,

$$V_{G,G}(m) - V_{G,B}(m) = k(V_G(m) - V_B(m)),$$
$$V_{B,G}(m) - V_{B,B}(m) = k(V_G(m) - V_B(m)).$$

Furthermore

$$\frac{\partial V_{G,\tilde{\ell}}(m)}{\partial m_D} = k\frac{\partial V_{\tilde{\ell}}(m)}{\partial m_D} + (1-k)\frac{\partial V_G(m)}{\partial m_D},$$
$$\frac{\partial V_{B,\tilde{\ell}}(m)}{\partial m_D} = k\frac{\partial V_{\tilde{\ell}}(m)}{\partial m_D} + (1-k)\frac{\partial V_B(m)}{\partial m_D}.$$

Therefore, condition (A.30) can be simplified to

$$\frac{\partial V_G(m)}{\partial m_D} < \frac{\partial V_B(m)}{\partial m_D}.$$

We will show in the remainder of this section when this condition holds.

Derivative value function bad bank w.r.t. payout threshold

In this section we will compute the derivative of V_B with respect to m_D. First define the following quantities:

$$\Delta := \Delta(m_D) = r_2 e^{-m_D r_1} - r_1 e^{-m_D r_2} > 0, \quad \forall m_D \geq 0, \tag{A.31}$$
$$\Delta' := \Delta'(m_D) = r_1 r_2 \left(e^{-m_D r_2} - e^{-m_D r_1}\right) \geq (>)0, \quad \forall m_D \geq (>)0.$$

Case i) $m_D - f \in (0, \overline{m}^*)$, $m \in (f, m_D)$:
In this case, the value of the bad bank equals (see Eq. (A.22)):

$$V_B(m; m_D) = \sum_{i=1}^{2} B_i^B e^{r_i(m-m_D)} + W(m-f).$$

One can show after many algebraic manipulations that

$$\begin{bmatrix} B_1^B \\ B_2^B \end{bmatrix} = \frac{1}{\Delta} \begin{bmatrix} r_2 & -e^{-m_D r_2} \\ -r_1 & e^{-m_D r_1} \end{bmatrix} \begin{bmatrix} e^{-f r_1} - e^{-f r_2} & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} (r_2 - r_1)^{-1} W'(0) \\ 1 - W'(m_D - f) \end{bmatrix}.$$

So that

$$\begin{aligned} V_B &= \frac{1}{\Delta} \begin{bmatrix} e^{r_1(m-m_D)} \\ e^{r_2(m-m_D)} \end{bmatrix}^\top \begin{bmatrix} r_2 & -e^{-m_D r_2} \\ -r_1 & e^{-m_D r_1} \end{bmatrix} \begin{bmatrix} e^{-r_1 f} - e^{-r_2 f} & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} (r_2 - r_1)^{-1} W'(0) \\ 1 - W'(m_D - f) \end{bmatrix} + W(m-f) \\ &= \frac{n_B}{\Delta} + W(m-f), \end{aligned}$$

where n_B is defined by

$$\begin{aligned} n_B := n_B(m_D) = &\frac{W'(0)}{r_2 - r_1} \left(e^{-r_1 f} - e^{-r_2 f}\right) \left(r_2 e^{r_1(m-m_D)} - r_1 e^{r_2(m-m_D)}\right) \\ &+ \left(1 - W'(m_D - f)\right) e^{-m_D(r_1+r_2)} \left(e^{r_2 m} - e^{r_1 m}\right). \end{aligned}$$

and whose derivative with respect to m_D is given by:

$$\begin{aligned} n_B' = \frac{\partial n_B(m_D)}{\partial m_D} = &W'(0) \frac{r_1 r_2}{r_2 - r_1} (e^{-r_1 f} - e^{-r_2 f})(e^{r_2(m-m_D)} - e^{r_1(m-m_D)}) \\ &+ e^{-m_D(r_1+r_2)} (e^{r_2 m} - e^{r_1 m}) \left(-(r_1 + r_2)(1 - W'(m_D - f) - W''(m_D - f)\right). \end{aligned}$$

The derivative of V_B is then given by

$$\begin{aligned} &\frac{\partial V_B(m)}{\partial m_D} = \frac{1}{\Delta^2} (n_B' \Delta - \Delta' n_B) \\ &= \frac{1}{\Delta^2} \Bigg(\frac{W'(0)}{r_2 - r_1} \left(e^{-r_1 f} - e^{-r_2 f}\right) \left[r_1 (r_2 \Delta + \Delta') e^{r_2(m-m_D)} - r_2 (r_1 \Delta + \Delta') e^{-r_1(m-m_D)}\right] \\ &- (e^{r_2 m} - e^{r_1 m}) e^{-m_D(r_1+r_2)} \left[((r_1 + r_2)\Delta + \Delta')(1 - W'(m_D - f)) + W''(m_D - f)\Delta\right] \Bigg). \end{aligned}$$

where one can do the following simplifications

$$\begin{aligned} &\left[r_1 (r_2 \Delta + \Delta') e^{r_2(m-m_D)} - r_2 (r_1 \Delta + \Delta') e^{-r_1(m-m_D)}\right] = r_1 r_2 e^{-m_D(r_1+r_2)} (r_2 - r_1)(e^{r_2 m} - e^{r_1 m}), \\ &(r_1 + r_2)\Delta + \Delta' = r_2^2 e^{-m_D r_1} - r_1^2 e^{-m_D r_2}. \end{aligned}$$

Define the following quantities

$$\begin{aligned} &\Gamma := \Gamma(m_D) = (r_1 + r_2)\Delta + \Delta' = r_2^2 e^{-r_1 m_D} - r_1^2 e^{-r_2 m_D}, \qquad \text{(A.32)} \\ &\Gamma' = -r_1 r_2 \Delta, \end{aligned}$$

so that

$$\frac{\partial V_B}{\partial m_D} = \frac{e^{-m_D(r_1+r_2)}(e^{r_2 m} - e^{r_1 m})}{\Delta^2} \Big(W'(0)r_1 r_2(e^{-r_1 f} - e^{-r_2 f}) - (1 - W'(m_D - f))\Gamma - W''(m_D - f)\Delta\Big). \tag{A.33}$$

Case ii) $m \le f$, $m_D - f < \overline{m}^*$:
In this scenario, one can show that the value function equals

$$\begin{aligned} V_B(m) &= \frac{1}{\Delta}(e^{r_2 m} - e^{r_1 m})e^{-m_D(r_1+r_2)} \begin{bmatrix} r_2 e^{-r_2(f-m_D)} - r_1 e^{-r_1(f-m_D)} \\ 1 \end{bmatrix}^\top \begin{bmatrix} W'(0)(r_2 - r_1)^{-1} \\ 1 - W'(m_D - f) \end{bmatrix} \\ &= \frac{\tilde{n}_B}{\Delta}(e^{r_2 m} - e^{r_1 m}), \end{aligned}$$

where

$$\tilde{n}_B := \tilde{n}_B(m_D) = \left(\frac{W'(0)}{r_2 - r_1}[r_2 e^{-r_2(f-m_D)} - r_1 e^{-r_1(f-m_D)}] + 1 - W'(m_D - f)\right) e^{-m_D(r_1+r_2)}$$

The derivative of interest is

$$\frac{\partial V_B(m)}{\partial m_D} = \frac{1}{\Delta^2}(\tilde{n}_B'\Delta - \Delta'\tilde{n}_B)(e^{r_2 m} - e^{r_1 m}),$$

where

$$\begin{aligned} &\tilde{n}_B'\Delta - \Delta'\tilde{n}_B \\ &\quad = e^{-m_D(r_1+r_2)}\Big((W'(0)r_1 r_2(e^{-r_1 f} - e^{-r_2 f}) - (1 - W'(m_D - f))\Gamma - W''(m_D - f)\Delta\Big). \end{aligned}$$

This corresponds to Eq. (A.33).

Derivative value function good bank w.r.t. payout threshold

For the high type the value function from Eq. (A.23) for $m \in [0, m_D)]$ can be rewritten as:

$$\begin{aligned} V_G(m; m_D) &= \frac{1}{\Delta}\begin{bmatrix} e^{r_1(m-m_D)} \\ e^{r_2(m-m_D)} \end{bmatrix}^\top \begin{bmatrix} r_2 & -e^{-r_2 m_D} \\ -r_1 & e^{-r_1 m_D} \end{bmatrix} \begin{bmatrix} 0 \\ 1 - W'(m_D) \end{bmatrix} + W(m) \\ &= \frac{1}{\Delta}e^{-m_D(r_1+r_2)}(e^{r_2 m} - e^{r_1 m})(1 - W'(m_D)) + W(m), \end{aligned}$$

so that its derivative is given by

$$\frac{\partial V_G}{\partial m_D} = \frac{e^{-m_D(r_1+r_2)}(e^{r_2 m} - e^{r_1 m})}{\Delta^2}\big(-(1 - W'(m_D))\Gamma - W''(m_D)\Delta\big).$$

Conditions for single-crossing to hold

For distortion to be more costly for the low type, it must be the case that

$$\frac{\partial V_G}{\partial m_D} < \frac{\partial V_B}{\partial m_D} \iff$$
$$(W'(m_D) - W'(m_D - f))\Gamma < \Delta(W''(m_D) - W''(m_D - f)) + W'(0)r_1 r_2(e^{-r_1 f} - e^{-r_2 f}). \quad \text{(A.34)}$$

Note that for $m_D = \overline{m}_G^*$, $\partial V_G(m)/\partial m_D = 0$, since $W'(\overline{m}_G^*) = 1$ and $W''(\overline{m}_G^*) = 0$. As a result, the condition simplifies to $\partial V_B/\partial m_D > 0$.

Uniqueness

Rewriting Eq.(A.34) as

$$(W'(m_D) - W'(m_D - f))\Gamma - \Delta(W''(m_D) - W''(m_D - f)) < W'(0)r_1 r_2(e^{-r_1 f} - e^{-r_2 f})$$

the right hand side is constant with respect to m_D. If the left hand side is monotonic in m_D on the relevant range, there is at most one level of m_D for which the inequality holds with equality, defining a region where it holds and one where it does not. First, define the following function

$$h_1(m_D) := e^{\bar{r}_1(m_D - \bar{m}^*)}(1 - e^{-\bar{r}_1 f}),$$
$$h_2(m_D) := e^{\bar{r}_2(m_D - \bar{m}^*)}(1 - e^{-\bar{r}_2 f}).$$

Taking out the common constant in the after value functions $\frac{1}{\bar{r}_2 - \bar{r}_1} = \frac{\sigma^2}{2\sqrt{\bar{\Omega}}}$, the brackets on the left hand side can be rewritten as respectively:

$$\bar{r}_2 e^{\bar{r}_1(m_D - \bar{m}^*)} - \bar{r}_1 e^{\bar{r}_2(m_D - \bar{m}^*)} - \bar{r}_2 e^{\bar{r}_1(m_D - f - \bar{m}^*)} + \bar{r}_1 e^{\bar{r}_2(m_D - f - \bar{m}^*)} = \bar{r}_2 h_1(m_D) - \bar{r}_1 h_2(m_D),$$
$$\bar{r}_2 \bar{r}_1 \left(e^{\bar{r}_1(m_D - \bar{m}^*)} - e^{\bar{r}_2(m_D - \bar{m}^*)} - e^{\bar{r}_1(m_D - f - \bar{m}^*)} + e^{\bar{r}_2(m_D - f - \bar{m}^*)}\right) = \bar{r}_1 \bar{r}_2 [h_1(m_D) - h_2(m_D)],$$

and the left hand side can be summarized as

$$LHS = \frac{\sigma^2}{2\sqrt{\bar{\Omega}}} \{[\bar{r}_2 h_1(m_D) - \bar{r}_1 h_2(m_D)]\Gamma - \Delta \bar{r}_1 \bar{r}_2 [h_1(m_D) - h_2(m_D)]\}.$$

Taking a derivative with respect to m_D yields

$$\begin{aligned}\frac{\partial LHS}{\partial m_D} &= \frac{\sigma^2}{2\sqrt{\bar{\Omega}}} \Big\{ [\bar{r}_1 h_2(m_D) - \bar{r}_2 h_1(m_D)] r_1 r_2 \Delta + \bar{r}_1 \bar{r}_2 [h_1(m_D) - h_2(m_D)]\Gamma \\ &\quad - \Delta' \bar{r}_1 \bar{r}_2 [h_1(m_D) - h_2(m_D)] - \Delta \bar{r}_1 \bar{r}_2 [\bar{r}_1 h_1(m_D) - \bar{r}_2 h_2(m_D)] \Big\} \\ &= \bar{r}_1 \bar{r}_2 \frac{\sigma^2}{2\sqrt{\bar{\Omega}}} \Big\{ -\frac{r_1 r_2}{\bar{r}_1 \bar{r}_2} [\bar{r}_2 h_1(m_D) - \bar{r}_1 h_2(m_D)]\Delta \\ &\quad + (\Gamma - \Delta')[h_1(m_D) - h_2(m_D)] - \Delta[\bar{r}_1 h_1(m_D) - \bar{r}_2 h_2(m_D)] \Big\}\end{aligned}$$

$$= \frac{\rho}{\sqrt{\bar{\Omega}}}\Delta\frac{\rho+\lambda}{\rho}\bigg\{[\bar{r}_2 h_1(m_D) - \bar{r}_1 h_2(m_D)] + \frac{\rho}{\rho+\lambda}[\bar{r}_1 h_1(m_D) - \bar{r}_2 h_2(m_D)]$$
$$+ 2\frac{\mu}{\sigma^2}\frac{\rho}{\rho+\lambda}[h_1(m_D) - h_2(m_D)]\bigg\}.$$

using that $\Gamma - \Delta' = (r_1 + r_2)\Delta = -\frac{2\mu}{\sigma^2}\Delta$, $\frac{r_1 r_2}{\bar{r}_1\bar{r}_2} = \frac{\rho+\lambda}{\rho}$ and $\bar{r}_1\bar{r}_2 = -2\frac{\rho}{\sigma^2}$. Collecting $h_i(m_D)$, $\forall i \in \{1,2\}$ terms in the first line of the bracket yields

$$\left(\bar{r}_2 + \frac{\rho}{\rho+\lambda}\bar{r}_1\right)h_1(m_D) - \left(\bar{r}_1 + \frac{\rho}{\rho+\lambda}\bar{r}_2\right)h_2(m_D)$$
$$= \frac{1}{\sigma^2}\bigg\{-\mu\left(1+\frac{\rho}{\rho+\lambda}\right)[h_1(m_D) - h_2(m_D)] + \sqrt{\bar{\Omega}}\frac{\lambda}{\rho+\lambda}[h_1(m_D) + h_2(m_D)]\bigg\},$$

which allows the following simplification of the derivative

$$\frac{\partial LHS}{\partial m_D} = \frac{\rho}{\sqrt{\bar{\Omega}}}\Delta\frac{\rho+\lambda}{\rho\sigma^2}\bigg\{\sqrt{\bar{\Omega}}\frac{\lambda}{\rho+\lambda}[h_1(m_D) + h_2(m_D)]$$
$$-\mu\left(1+\frac{\rho}{\rho+\lambda} - 2\frac{\rho}{\rho+\lambda}\right)[h_1(m_D) - h_2(m_D)]\bigg\}$$
$$= \frac{\lambda}{\sqrt{\bar{\Omega}}\sigma^2}\Delta\bigg\{\sqrt{\bar{\Omega}}[h_1(m_D) + h_2(m_D)] - \mu[h_1(m_D) - h_2(m_D)]\bigg\}$$
$$= \frac{\lambda}{\sqrt{\bar{\Omega}}\sigma^2}\Delta\bigg\{\left(\sqrt{\bar{\Omega}} - \mu\right)h_1(m_D) + \left(\sqrt{\bar{\Omega}} + \mu\right)h_2(m_D)\bigg\}.$$

Since both the constant $\rho\bar{\Omega}^{-1/2}$ and Δ are positive for all values of m_D, the sign of the derivative is determined by the bracket where both $\left(\sqrt{\bar{\Omega}} + \mu\right) \geq \left(\sqrt{\bar{\Omega}} - \mu\right) \geq 0$. The signs of the h-functions are mostly contrasting with $h_1(m_D) = e^{\bar{r}_1(m_D - \bar{m}^*)}(1 - e^{-\bar{r}_1 f}) \leq 0$ and $h_2(m_D) = e^{\bar{r}_2(m_D - \bar{m}^*)}(1 - e^{-\bar{r}_2 f}) \geq 0$ because $e^{-\bar{r}_1 f} \geq 1 \geq e^{-\bar{r}_2 f}$, with the exception being at $f = 0$ where the inequalities hold with equality and both functions are zero. For the range of $m_D \in (f, \bar{m}^*)$ a second set of relevant inequalities is $e^{\bar{r}_1(m_D - \bar{m}^*)} \geq 1 \geq e^{\bar{r}_2(m_D - \bar{m}^*)}$ where equality holds at $m_D = \bar{m}^*$. The derivative of the bracket is increasing in m_D as both $h_1'(m_D) = r_1 h_1(m_D) \geq 0$ and $h_2'(m_D) = r_2 h_2(m_D) \geq 0$, so if $\frac{\partial LHS}{\partial m_D}\Big|_{m_D = \bar{m}^*} < 0$ the derivative is negative over the full range. For $f > 0$ this is indeed the case as

$$\frac{\partial LHS}{\partial m_D}\bigg|_{m_D = \bar{m}^*}\left(\frac{\lambda}{\sqrt{\bar{\Omega}}\sigma^2}\Delta\right)^{-1} = \left(\sqrt{\bar{\Omega}} - \mu\right)(1 - e^{-\bar{r}_1 f}) + \left(\sqrt{\bar{\Omega}} + \mu\right)(1 - e^{-\bar{r}_2 f}),$$

which is zero at $f = 0$ and decreasing in f which will be shown next. To establish the second point notice that

$$\frac{\partial^2 LHS}{\partial m_D \partial f}\bigg|_{m_D = \bar{m}^*}\left(\frac{\lambda}{\sqrt{\bar{\Omega}}\sigma^2}\Delta\right)^{-1} = \left(\sqrt{\bar{\Omega}} - \mu\right)\bar{r}_1 e^{-\bar{r}_1 f} + \left(\sqrt{\bar{\Omega}} + \mu\right)\bar{r}_2 e^{-\bar{r}_2 f}$$
$$= e^{-\bar{r}_2 f}\left[\left(\sqrt{\bar{\Omega}} - \mu\right)\bar{r}_1 e^{2\frac{\sqrt{\bar{\Omega}}}{\sigma^2}f} + \bar{r}_2\left(\sqrt{\bar{\Omega}} + \mu\right)\right].$$

If the bracket in the last expression is negative, higher f means lower $\frac{\partial LHS}{\partial m_D}\Big|_{m_D=\bar{m}^*}$ since $e^{-\bar{r}_2 f} > 0$. Because $\frac{\partial LHS}{\partial m_D}\Big|_{m_D=\bar{m}^*}$ is zero at $f = 0$ it must be negative for $f > 0$. Focusing on the square bracket, its derivative with respect to f is trivially negative as

$$\underbrace{\bar{r}_1}_{<0}\underbrace{\left(\sqrt{\bar{\Omega}}-\mu\right)2\frac{\sqrt{\bar{\Omega}}}{\sigma^2}e^{2\frac{\sqrt{\bar{\Omega}}}{\sigma^2}f}}_{>0} < 0.$$

At $f = 0$ the value of the square bracket is zero since

$$\begin{aligned}
&\left(\sqrt{\bar{\Omega}}-\mu\right)\bar{r}_1+\bar{r}_2\left(\sqrt{\bar{\Omega}}+\mu\right)=0 \iff \bar{r}_2\left(\sqrt{\bar{\Omega}}+\mu\right)<-\left(\sqrt{\bar{\Omega}}-\mu\right)\bar{r}_1\\
\iff &\frac{1}{\sigma^2}\left(\sqrt{\bar{\Omega}}+\mu\right)\left(-\mu+\sqrt{\bar{\Omega}}\right)=\frac{1}{\sigma^2}\left(\sqrt{\bar{\Omega}}-\mu\right)\left(\mu+\sqrt{\bar{\Omega}}\right)\\
\iff &\left(\mu+\sqrt{\bar{\Omega}}\right)\left(\sqrt{\bar{\Omega}}-\mu\right)=\left(\sqrt{\bar{\Omega}}-\mu\right)\left(\mu+\sqrt{\bar{\Omega}}\right),
\end{aligned}$$

so for $f > 0$ the bracket is negative, which concludes the proof.

Existence

Define the following function

$$g(m_D)=\Gamma[W'(m_D)-W'(m_D-f)]-\Delta[W''(m_D)-W''(m_D-f)]+W'(0)\Delta'(f)$$

Evaluated at $m_D = f$

$$g(f)=\Gamma(f)[W'(f)-W'(0)]-\Delta(f)[W''(f)-W''(0)]+W'(0)\Delta'(f)=A(f)-B(f),$$

where

$$\begin{aligned}
A(f) &:= \Gamma(f)W'(f)-\Delta(f)W''(f),\\
B(f) &:= \Gamma(f)W'(0)-\Delta(f)W''(0)-W'(0)\Delta'(f).
\end{aligned}$$

Using that $\Gamma(f)-\Delta'(f)=(r_1+r_2)\Delta(f)$ and $r_1+r_2=\overline{r}_1+\overline{r}_2$, we show that $B(f)=0$:

$$\begin{aligned}
B(f) &= \Delta(f)\left[(r_1+r_2)W'(0)-W''(0)\right]\\
&= \frac{\Delta(f)}{\overline{r}_2-\overline{r}_1}\left[e^{-\overline{r}_1\overline{m}^*}\overline{r}_2(r_1+r_2-\overline{r}_1)+e^{-\overline{r}_2\overline{m}^*}\overline{r}_1(\overline{r}_2-r_1-r_2)\right]\\
&= \frac{\Delta(f)}{\overline{r}_2-\overline{r}_1}\left[\overline{r}_2^2e^{-\overline{r}_1\overline{m}^*}-\overline{r}_1^2e^{-\overline{r}_2\overline{m}^*}\right]=0.
\end{aligned}$$

We will show that $A(0)=0$:

$$\begin{aligned}
A(0) &= \Gamma(0)W'(0)-\Delta(0)W''(0)=(r_2^2-r_1^2)W'(0)-(r_2-r_1)W''(0)\\
&= (r_2-r_1)\left[(r_1+r_2)W'(0)-W''(0)\right]=0.
\end{aligned}$$

The derivative of $A(f)$ with respect to f is positive:

$$
\begin{aligned}
\frac{\partial A}{\partial f} &= \Gamma'(f)W'(f) + \Gamma(f)W''(f) - \Delta'(f)W''(f) - \Delta(f)W'''(f) \\
&= -r_1 r_2 \Delta(f) W'(f) + (\Gamma(f) - \Delta'(f))W''(f) - \Delta(f)W'''(f) \\
&= \Delta(f)[W''(f)(r_1 + r_2) - W'(f)r_1 r_2 - W'''(f)] \\
&= \frac{1}{\bar{r}_2 - \bar{r}_1}\left[e^{\bar{r}_1(f-\bar{m}^*)}\bar{r}_2(r_1 - \bar{r}_1)(\bar{r}_1 - r_2) - e^{\bar{r}_2(f-\bar{m}^*)}\bar{r}_1(r_2 - \bar{r}_2)(\bar{r}_2 - r_1)\right] \\
&= \frac{(r_1 - \bar{r}_1)(\bar{r}_1 - r_2)}{\bar{r}_2 - \bar{r}_1}\left[e^{\bar{r}_1(f-\bar{m}^*)}\bar{r}_2 - e^{\bar{r}_2(f-\bar{m}^*)}\bar{r}_1\right] > 0.
\end{aligned}
$$

Since $A(0) = 0$, and the derivative with respect to f is positive, we know that $A(f) > 0$ for $f > 0$.

<u>Evaluated at $m_D = \overline{m}^*$</u>

$$
g(\overline{m}^*) = (1 - W'(\overline{m}^* - f))\Gamma(\overline{m}^*) + \Delta(\overline{m}^*)W''(\overline{m}^* - f) + W'(0)\Delta'(f)
$$

Again $g(\overline{m}^*)|_{f=0} = 0$. The derivative is

$$
\begin{aligned}
\frac{\partial g(\overline{m}^*)}{\partial f} &= \Gamma(\overline{m}^*)W''(\overline{m}^* - f)) - \Delta(\overline{m}^*)W'''(\overline{m}^* - f) + W'(0)\Delta''(f) \\
&= \frac{\bar{r}_1\bar{r}_2}{\bar{r}_2 - \bar{r}_1}\Big\{(e^{-\bar{r}_1 f} - e^{-\bar{r}_2 f})\Gamma(\overline{m}^*) - \Delta(\overline{m}^*)(\bar{r}_1 e^{-\bar{r}_1 f} - \bar{r}_2 e^{-\bar{r}_2 f}) \\
&\qquad - \frac{\rho+\lambda}{\rho}(\bar{r}_2 e^{-\bar{r}_1\overline{m}^*} - \bar{r}_1 e^{-\bar{r}_2\overline{m}^*})(r_2 e^{-r_2 f} - r_1 e^{-r_1 f})\Big\} \\
&= -\frac{\bar{r}_1\bar{r}_2}{\bar{r}_2 - \bar{r}_1}\Big\{(e^{-\bar{r}_2 f} - e^{-\bar{r}_1 f})\Gamma(\overline{m}^*) + \Delta(\overline{m}^*)(\bar{r}_1 e^{-\bar{r}_1 f} - \bar{r}_2 e^{-\bar{r}_2 f}) \\
&\qquad + \frac{\rho+\lambda}{\rho}\Delta(\overline{m}^*)(r_2 e^{-r_2 f} - r_1 e^{-r_1 f})\Big\}
\end{aligned}
$$

Plugging in these quantities gives

$$
\begin{aligned}
g(\overline{m}^*) &= \left(1 - \frac{1}{\overline{r}_2 - \overline{r}_1}\left[\overline{r}_2 e^{-\overline{r}_1 f} - \overline{r}_1 e^{-\overline{r}_2 f}\right]\right)\Gamma(\overline{m}^*) + \Delta(\overline{m}^*)\frac{\overline{r}_1\overline{r}_2}{\overline{r}_2 - \overline{r}_1}\left[e^{-\overline{r}_1 f} - e^{-\overline{r}_2 f}\right] \\
&\quad + \frac{1}{\overline{r}_2 - \overline{r}_1}\left[\overline{r}_2 e^{-\overline{r}_1\overline{m}^*} - \overline{r}_1 e^{-\overline{r}_2\overline{m}^*}\right]\Delta'(f) \\
(\bar{r}_2 - \bar{r}_1)g(\overline{m}^*) &= \underbrace{\left(\overline{r}_2 - \overline{r}_1 - \overline{\Delta}(f)\right)\Gamma(\overline{m}^*)}_{<0}\underbrace{-\Delta(\overline{m}^*)\overline{\Delta}'(f)}_{<0} + \underbrace{\overline{\Delta}(\overline{m}^*)\Delta'(f)}_{>0}.
\end{aligned}
$$

Note that $\Gamma(\overline{m}^*) > 0$, since $\Gamma(m^*) = 0$, $\Gamma' > 0$ and $\overline{m}^* > m^*$.

$$
\Delta(x) - \overline{\Delta}(x) = r_2 e^{-r_1 x} - \overline{r}_2 e^{-\overline{r}_1 x} - r_1 e^{-r_2 x} + \overline{r}_1 e^{-\overline{r}_2 x}
$$

This expression is 0 for $x = 0$. Take the derivative:

$$
\Delta'(x) - \overline{\Delta}'(x) = -r_1 r_2 e^{-r_1 x} + \overline{r}_1\overline{r}_2 e^{-\overline{r}_1 x} + r_1 r_2 e^{-r_2 x} - \overline{r}_1\overline{r}_2 e^{-\overline{r}_2 x}
$$

$$= \frac{2(\rho+\lambda)}{\sigma^2}\left[e^{-r_2 x} - e^{-r_1 x}\right] - \frac{2\rho}{\sigma^2}\left[e^{-\overline{r}_2 x} - e^{-\overline{r}_1 x}\right] < 0.$$

This expression is negative because $e^{-r_2 x} < e^{-\overline{r}_2 x}$, $e^{-r_1 x} > e^{-\overline{r}_1 x}$, so that $e^{-r_2 x} - e^{-r_1 x} < e^{-\overline{r}_2 x} - e^{-\overline{r}_1 x} < 0$.

A.3.4 Reverse signaling

In this section we will consider the case where the good bank signals its quality by increasing its dividend policy. In this scenario, the single-crossing condition becomes:

$$\frac{\partial V_G(m; m_D)}{\partial m_D} > \frac{\partial V_B(m; m_D)}{\partial m_D}.$$

This condition implies that the cost of increasing m_D is lower for the good bank than for the bad bank.

Derivative value function good bank with respect to payout level

After some algebraic steps, one can show that the value function of the good bank for $m \in [m_G^*, m_D)$ is given by:

$$V_G(m; m_D) = \frac{1-\gamma}{(r_2 - r_1)\Delta}\begin{bmatrix} e^{r_1(m-m_G)} \\ e^{r_2(m-m_G)} \end{bmatrix}^\top \begin{bmatrix} r_2 & r_2 & e^{-m_D r_2} \\ -r_1 & -r_1 & -e^{-m_D r_1} \end{bmatrix}$$
$$\times \operatorname{diag}\left(\begin{bmatrix} r_2 e^{-m_G^* r_1} - r_1 e^{-m_G^* r_2} \\ e^{-m_G^* r_2} - e^{-m_G^* r_1} \\ r_1 - r_2 \end{bmatrix}\right)\begin{bmatrix} \frac{\mu}{\rho+\lambda} \\ 1 \\ 1 \end{bmatrix} + \beta_G + \gamma m.$$

This can be written as

$$V_G(m; m_D) = \frac{n_G}{(r_2 - r_1)\Delta} + \beta_G + \gamma m,$$

where

$$\begin{aligned} n_G &:= n_G(m_D) \\ &= C_G\left[r_2 e^{r_1(m-m_D)} - r_1 e^{r_2(m-m_D)}\right] + (1-\gamma)(e^{r_1 m} - e^{r_2 m})e^{-(r_1+r_2)m_D}(r_1 - r_2), \\ n_G' &:= n_G'(m_D) \\ &= r_1 r_2 (e^{r_2(m-m_D)} - e^{r_1(m-m_D)})C_G + (1-\gamma)(e^{r_1 m} - e^{r_2 m})(r_1 + r_2)(r_1 - r_2)e^{-(r_1+r_2)m_D}, \end{aligned}$$

and

$$\begin{aligned} C_G &:= (1-\gamma)\left[\left(\frac{\mu r_2}{\rho+\lambda} - 1\right)e^{-\overline{m}^* r_1} - \left(\frac{\mu r_1}{\rho+\lambda} - 1\right)e^{-\overline{m}^* r_2}\right] \\ &= \frac{1}{2}\sigma^2\frac{1-\gamma}{\rho+\lambda}\left[r_2^2 e^{-\overline{m}^* r_1} - r_1^2 e^{-\overline{m}^* r_2}\right] = \frac{1}{2}\sigma^2\frac{\rho}{(\rho+\lambda)^2}\Gamma(\overline{m}^*). \end{aligned}$$

Now consider

$$\frac{\partial V_G(m;m_D)}{\partial m_D}=\frac{1}{(r_2-r_1)\Delta^2}(n_G'\Delta-\Delta' n_G),$$

where

$$n_G'\Delta-\Delta' n_G=(r_2-r_1)e^{-m_G(r_1+r_2)}(e^{r_2m}-e^{r_1m})\left[r_1r_2C_G-(1-\gamma)\Gamma\right].$$

Putting everything together gives the following expression for the derivative

$$\frac{\partial V_G(m;m_D)}{\partial m_G}=\frac{e^{-m_D(r_1+r_2)}(e^{r_2m}-e^{r_1m})}{\Delta^2}\left[r_1r_2C_G-(1-\gamma)\Gamma\right].$$

Observe that

$$r_1r_2C_G=-\frac{2\rho}{\sigma^2}\frac{1}{2}\sigma^2\frac{\rho}{(\rho+\lambda)^2}\Gamma(\overline{m}^*)=-\left(\frac{\rho}{\rho+\lambda}\right)^2\Gamma(\overline{m}^*).$$

Derivative value function bad bank with respect to payout level

The derivative of $V_B(m;m_D)$ with respect to m_D in the case that $m_D-f<\overline{m}^*$, is given by Eq. (A.33). In the case that $m_D-f>\overline{m}^*$, the value function for $m\in[f,m_D)$ is given by

$$\begin{aligned}V_B(m;m_D)=&\frac{1}{\Delta(r_2-r_1)}\begin{bmatrix}e^{r_1(m-m_D)}\\ e^{r_2(m-m_D)}\end{bmatrix}^\top\begin{bmatrix}-r_2 & r_2 & -r_2 & e^{-m_Dr_2}\\ r_1 & -r_1 & r_1 & -e^{-m_Dr_1}\end{bmatrix}\\ &\times\operatorname{diag}\left(\begin{bmatrix}e^{-fr_2}-e^{-fr_1}\\ r_1e^{-r_2(\overline{m}^*+f)}-r_2e^{-r_1(\overline{m}^*+f)}\\ e^{-r_2(\overline{m}^*+f)}-e^{-r_1(\overline{m}^*+f)}\\ r_1-r_2\end{bmatrix}\right)\begin{bmatrix}W'(0)\\ \frac{\mu}{\rho+\lambda}(\gamma-1)\\ \gamma-1\\ 1-\gamma\end{bmatrix}+\beta_B+\gamma m.\end{aligned}$$

So we can write the value function as

$$V_B(m;m_D)=\frac{n_B(m_D)}{\Delta(r_2-r_1)}+\beta_B+\gamma m,$$

where

$$n_B(m_D)=C_B\left[r_2e^{r_1(m-m_D)}-r_1e^{r_2(m-m_D)}\right]+(1-\gamma)(r_2-r_1)(e^{r_2m}-e^{r_1m})e^{-(r_1+r_2)m_D},$$

and

$$\begin{aligned}C_B&:=W'(0)(e^{-fr_1}-e^{-fr_2})+(1-\gamma)\left(\left[\frac{\mu r_2}{\rho+\lambda}-1\right]e^{-r_1(\overline{m}^*+f)}-\left[\frac{\mu r_1}{\rho+\lambda}-1\right]e^{-r_2(\overline{m}^*+f)}\right)\\ &=W'(0)(e^{-fr_1}-e^{-fr_2})+\frac{1}{2}\sigma^2\frac{\rho}{(\rho+\lambda)^2}\Gamma(\overline{m}^*+f).\end{aligned}$$

The derivative of n_B with respect to m_D is

$$n_B'=C_Br_1r_2\left[e^{r_2(m-m_D)}-e^{r_1(m-m_D)}\right]-(1-\gamma)(r_2-r_1)(r_1+r_2)(e^{r_2m}-e^{r_1m})e^{-(r_1+r_2)m_D}.$$

Then the derivative of $V_B(m)$ with respect to m_D is

$$\frac{\partial V_B(m;m_D)}{\partial m_D} = \frac{1}{(r_2-r_1)\Delta^2}(n_B'\Delta - \Delta' n_B).$$

where the term in brackets is

$$n_B'\Delta - \Delta' n_B = (r_2-r_1)e^{-m_D(r_1+r_2)}(e^{r_2 m} - e^{r_1 m})\left[C_B r_1 r_2 - (1-\gamma)\Gamma\right].$$

Then we get

$$\frac{\partial V_B(m;m_D)}{\partial m_D} = \frac{e^{-m_D(r_1+r_2)}(e^{r_2 m} - e^{r_1 m})}{\Delta^2}\left[C_B r_1 r_2 - (1-\gamma)\Gamma\right].$$

Single crossing condition

When $m_D - f > \overline{m}^*$:

$$\frac{\partial V_G(m;m_D)}{\partial m_D} - \frac{\partial V_B(m;m_D)}{\partial m_D} = \frac{e^{-m_D(r_1+r_2)}(e^{r_2 m} - e^{r_1 m})}{\Delta^2} r_1 r_2 (C_G - C_B).$$

where

$$\begin{aligned} r_1 r_2 (C_G - C_B) &= W'(0) r_1 r_2 (e^{-f r_1} - e^{-f r_2}) + \left(\frac{\rho}{\rho+\lambda}\right)^2 [\Gamma(\overline{m}^* + f) - \Gamma(\overline{m}^*)] \\ &= -\Delta'(f) W'(0) + \left(\frac{\rho}{\rho+\lambda}\right)^2 [\Gamma(\overline{m}^* + f) - \Gamma(\overline{m}^*)]. \end{aligned}$$

Note that the first term $-\Delta'(f)W'(0) < 0$ and the remaining term is positive, since $\Gamma'(x) = -r_1 r_2 \Delta(x) > 0$ for $x > 0$. For all m_D for which this expression is positive, increasing payout threshold can be used as a signaling device.

Separating equilibrium

The incentive compatibility constraint of the bad bank in this scenario becomes

$$V_{B,B}^{FI}(\tilde{m}^S; m_B^*) \geq V_{B,G}(\tilde{m}^S; \tilde{m}^S). \tag{A.35}$$

When this condition does not hold at $\tilde{m}^S = m_G^*$, the good bank will have to deviate from its privately optimal strategy m_G^* by choosing a higher payout boundary. The ICC of the good bank is

$$V_{G,G}(\tilde{m}^S; \tilde{m}^S) \geq V_{G,B}(\tilde{m}^S; m_B^*). \tag{A.36}$$

For $\tilde{m}^S$ to be a PBE, it is sufficient that the good bank does not have an incentive to defect to a different strategy under the pessimistic belief that the good bank is a bad bank instead. The corresponding condition becomes:

$$V_{G,G}(\tilde{m}^S; \tilde{m}^S) \geq V_{G,B}(\tilde{m}^S; m_{G,B}^*). \tag{A.37}$$

A separating equilibrium exists when there is a $\tilde{m}^S$ for which the three conditions Eq. (A.35), (A.36) and (A.37) are jointly satisfied.

Pooling equilibrium

The incentive compatibility constraint of the bad bank:

$$V_{B,p}(\tilde{m}^P;\tilde{m}^P) \geq V_{B,B}(\tilde{m}^P;m_B^*).$$

Restriction that the value of the good bank in the pooling equilibrium is larger than in the least-cost separating equilibrium:

$$V_{G,p}(\tilde{m}^P;\tilde{m}^P) \geq \mathbb{1}_{\{m_G^* \geq \overline{m}^S\}} V_{G,G}(\tilde{m}^P;m_G^*) + \mathbb{1}_{\{m_G^* < \overline{m}^S\}} V_{G,G}(m^P;\overline{m}^S).$$

where $\overline{m}^S$ is now the solution to the ICC of the bad bank.

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