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Catastrophe Bonds and Reinsurance: The Competitive Effect of Information-Insensitive Triggers

Silke Finken
Christian Laux

Abstract

We identify a new benefit of index or parametric triggers. Asymmetric information between reinsurers on an insurer's risk affects competition in the reinsurance market: reinsurers are subject to adverse selection, since only high-risk insurers may find it optimal to change reinsurers. The result is high reinsurance premiums and cross-subsidization of high-risk insurers by low-risk insurers. A contract with a parametric or index trigger (such as a catastrophe bond) is insensitive to information asymmetry and therefore alters the equilibrium in the reinsurance market. Provided that basis risk is not too high, the introduction of contracts with parametric or index triggers provides low-risk insurers with an alternative to reinsurance contracts, and therefore leads to less cross-subsidization in the reinsurance market.

Introduction

Catastrophic events, such as hurricanes and earthquakes, are one of the main risks that insurers and reinsurers face. These hazards can result in huge losses and financing problems. For a long time reinsurance contracts have been the only way to hedge against these losses. However, since the early 1990s, new risk transfer instruments have emerged as an alternative to traditional reinsurance contracts. The emergence of

Silke Finken is at DZ Bank, Frankfurt, Germany. Christian Laux is at Goethe-University Frankfurt am Main, CFS, and ECGI. The authors can be contacted via e-mail: silke@finken.eu and laux@finance.uni-frankfurt.de. We are grateful to two anonymous referees for their valuable comments and suggestions. We also thank David Cummins, Neil Doherty, Kenneth Froot, Harald Glembocki, Marcel Grandi, Howard Kunreuther, and Morton Lane, as well as seminar participants of the 2006 NBER Insurance Project Meeting, the CFS Conference on "Risk Transfer Between (Re-)Insurers, Banks and Markets," and the meetings of the European Financial Management Association, the European Group of Risk and Insurance Economists, the German Finance Association, and the Global Finance Conference for their helpful comments. Silke Finken gratefully acknowledges financial support from the German Research Foundation through the Graduate Program "Finance and Monetary Economics" at the Goethe-University Frankfurt am Main. The views expressed in the article are those of the authors and should not be attributed to the DZ Bank.

the new instruments came along with the availability of new triggers that determine the contract's payoff. Traditional reinsurance contracts' payoffs are based on the policyholder's realized loss (indemnity payment or indemnity trigger). As an alternative, new risk transfer instruments have evolved where the payoff is often based on index or parametric triggers. A prominent example for such contracts are catastrophe (cat) bonds.

One of the characteristics of index triggers is that the contract's payoff is largely, and in the case of a parametric trigger, completely, independent of the insurer's realized loss. For that reason, a main advantage of index or parametric triggers is their positive effect on moral hazard (e.g., Niehaus and Mann, 1992; Doherty, 1997). We provide a new argument in favor of such triggers: information-insensitive triggers help to overcome the potential problems of adverse selection in the reinsurance market due to asymmetric information between reinsurers about an insurer's risk.

Asymmetric Information in the Reinsurance Market

Reinsurers typically have a close and long-term relation to their insurers. In the course of the business relation, reinsurers acquire information that helps to assess the insurer's risk and to price nonproportional reinsurance policies.[1] For example, they obtain inside information about an insurer's business model, underwriting and reserving policy, book of business, internal decision processes, ability to screen policies (applicants), and efficiency in claims settlement. A large part of this information is "soft" and cannot easily and credibly be conveyed to third parties.

Obtaining information can help to overcome problems of asymmetric information between insurers and reinsurers. Thus, the inside information is an important source of value for the relation between an insurer and its reinsurer. However, there is also a potential dark side. A reinsurer's inside information locks insurers into their relationship with their current reinsurer, which gives the reinsurer a competitive advantage when competing against outside reinsurers for the renewal of the reinsurance business. This issue is particularly important, as reinsurance contracts are short term in nature, although reinsurance is typically characterized by long-term relationships between insurers and reinsurers.

Structure and Trigger of Cat Bonds

Since the 1990s, cat bonds have evolved as an alternative to standard reinsurance contracts. From 1997 to 2006, a total of 89 cat bonds were issued worldwide, 41 by insurers and 43 by reinsurers. And 2006 was a record year in the history of cat bonds, with 20 issuances (Guy Carpenter, 2007.)

Cat bonds are similar to regular bonds, but they have an additional forgiveness provision. If an insurer issues a cat bond, the investors pay the principal amount to a "special-purpose vehicle" (SPV), which acts as a clearing institution. If the trigger

[1]With proportional reinsurance, the reinsurer assumes the same proportion of the insurer's liabilities, premiums, and losses. Most catastrophe reinsurance business in the United States or Bermuda involves nonproportional, excess of loss reinsurance contracts, where the reinsurer pays for losses in excess of a deductible up to the policy limit.

is set off, then the interest payment or a fraction of the principal is forgiven and transferred to the insurer. In exchange for bearing this risk, investors receive a higher promised interest on their cat bond, which is financed through a premium that the insurer pays to the SPV.

An important characteristic of cat bonds is the chosen trigger. Although indemnity triggers are a potential alternative, cat bonds often use index or parametric triggers. For example, Guy Carpenter (2007) report that of the 20 issuances in 2006, only 2 used an indemnity trigger. Examples for index or parametric triggers are the estimated industrywide loss after a catastrophic event, certain parameters of a catastrophic event (e.g., the magnitude and location of an earthquake or hurricane), or the loss predicted by a model of a catastrophic event and an insurer's exposure.

We focus on cat bonds because they are the most prominent example of risk-transfer instruments with index triggers. However, cat bonds are not the only products with index triggers. Other risk-transfer instruments with index triggers include index loss warranty contracts and catastrophe options.

We discuss the role of information-insensitive triggers to overcome the potential problems of asymmetric information between reinsurers in the simplest setting possible. An insurer faces a large cost of financial distress after a catastrophic event. To reduce the expected costs of financial distress, the insurer hedges the risk. The insurer can obtain indemnity-based reinsurance from the current reinsurer (incumbent or insider) or from another reinsurer (outsider). Alternatively, the insurer can also issue a cat bond with a parametric trigger. The insurer and the insider know whether the insurer's expected loss is high or low, but outsiders do not have this information. Because of the information disadvantage, an outsider fears that low-risk insurers will stay with their current reinsurer and that only high-risk insurers will be willing to switch.

An outsider can offer contracts to separate different types of insurers to overcome the adverse selection problem. However, separating contracts are not a perfect substitute for the information advantage of an inside reinsurer. The reason is that retention is costly: if it were not, then it could not be used to separate types in the first place. Examples for such costs include costs of capital to cover the potential losses, reduced underwriting capacity, and a lower credit rating. Therefore, a low-risk insurer is willing to accept a premium that exceeds the fair premium for higher coverage. The insider can offer to fully insure the low-risk insurer at a premium that extracts the low-risk insurer's benefit of avoiding the retention. If this benefit is so high that this premium would exceed the pooling premium, then offering pooling contracts also becomes attractive for the outsider. Of course, the outsider fears that the insider always tries to undercut its offer, leaving only high-risk types that will accept the outsider's offer. This adverse selection problem results in strategies with rents to the insider and cross-subsidization of high-risk insurers by low-risk insurers.

The value of a cat bond with a parametric trigger is independent of the insurer's expected loss. Therefore, the adverse selection problem does not arise. Instead, there is basis risk, which stems from an imperfect correlation between the cat bond's payoff with the insurer's loss. Because of basis risk, the payment from the cat bond may not completely match the insurer's loss, leaving the insurer exposed to potentially large uncovered losses. The insurer will issue the cat bond if the reinsurance premium loading exceeds the expected costs of financial distress from basis risk. Akin to the separating contract, this alternative places an upper bound on the reinsurance premium that an insider can demand.

If the insurer's exposure to basis risk is lower than the required retention of the separating contract, then the availability of cat bonds reduces the premiums aimed at attracting a low-risk type. At the same time, the expected premium for a high-risk type increases. Therefore, the introduction of cat bonds helps to restore the competitive position of low-risk insurers: the profitability of low-risk insurers increases whereas the profitability of high-risk insurers decreases.

We note that even though cat bonds can be an important alternative for insurers in our model, their benefit resides in constraining the power of insiders. For this role to be effective, it is not necessary for the cat bonds to actually be used. Indeed, in our stylized model, cat bonds are not used in equilibrium. The reason is that because of basis risk, an informed reinsurer can adjust the premium so that it is not optimal for an insurer to choose the cat bond. We do not want to overstress this point, as there are other potential reasons for why cat bonds may be used (e.g., moral hazard, counterparty risk, etc.). But the observation that cat bonds can be useful even when not used is interesting for another reason. Cat bonds were initially praised as important innovations. However, the absolute level of coverage obtained through cat bonds is small, and the growth rate has increased only recently. This low level of usage may seem to contradict the perception of cat bonds as important instruments. Our article shows that this conclusion may be unwarranted.

Our discussion of the role of cat bonds is in line with Froot (2001). He argues that cat bonds reduce barriers to entry and that therefore the reinsurance market has become more contested, thus decreasing premiums for traditional reinsurance. In our model the source of reinsurers' market power is asymmetric information between reinsurers. Cat bonds with information-insensitive triggers can reduce the cost of entry because they are not subject to adverse selection. However, although the market power of insiders is constrained, because of basis risk it is not eliminated.

Basis risk is sometimes viewed as a major obstacle to using index or parametric triggers. This concern is also important for our model where the competitive effect is greatly diminished in the presence of large basis risk. However, Cummins, Lalonde, and Phillips (2002, 2004) show that for cat losses from hurricanes in Florida, basis risk is unlikely to deter insurers from the possibility of using cat bonds to hedge their exposure. Harrington, Mann, and Niehaus (1995) empirically analyze the hedging effectiveness of different loss indexes that are based on contracts that the Chicago Board of Trade has introduced or considered introducing. Their results suggest that futures with index triggers can be effectively used to hedge catastrophe risks.

The article proceeds as follows. We discuss the related literature in the next section. We then outline the model. Because we solve the model backward, we start our analysis with the second period, where reinsurers are asymmetrically informed. We first examine the main problem of asymmetric information between reinsurers for full reinsurance before we extend the analysis by allowing for partial reinsurance to separate types. We then introduce cat bonds with information-insensitive triggers to analyze their effect on reinsurance premiums. As a final step, we discuss the first period, when reinsurers are symmetrically informed. In the remaining sections we examine the robustness of the model and possible extensions, discuss the empirical implications, and conclude.

RELATED LITERATURE

Intertemporal learning about a policyholder's risk type plays an important role in insurance and has received considerable interest in the literature. Closest to our setting are the contributions by Kunreuther and Pauly (1985) and Nilssen (2000) who analyze the effect of asymmetric information about customers' types. Customers know their types, and insurers (reinsurers in our model) obtain information about the risk characteristics of their customers. This information is not available for outsiders. Like us, they focus on short-term contracts. Kunreuther and Pauly (1985) show that asymmetric information about customers creates an information lock-in that allows insiders to earn an information rent on their current customers. They only consider "price policies" that do not allow for a separation of types. Nilssen (2000) extends their model by introducing Rothschild and Stiglitz (1976) type "price-quantity policies." He assumes that first-period contracts are publicly observable so that first-period pooling is a prerequisite for information lock-in. Nilssen shows that in a multiperiod setting, pooling equilibria are possible. Therefore, information lock-in can also arise in his setting. By assuming that insurers and reinsurers have symmetric information in the first period, we take the first-period pooling equilibrium as given and focus our analysis on the effect of separating contracts on the information lock-in in the second period. We extend both models by introducing contracts with type-independent payoffs. We analyze the effect of these contracts on the second-period information lock-in and compare it to separating contracts.

There is also a large strand of literature that analyzes long-term contracting and intertemporal learning about policyholders (see, e.g., Cooper and Hayes, 1987, Dionne and Doherty, 1994, Jean-Baptiste and Santomero, 2000, and Dionne, Doherty, and Fobaron, 2000 for a survey.) Long-term contracts allow for an improved risk sharing, but if policyholders cannot commit to the long-term contract and are free to switch, then the benefits of improved risk sharing are limited (Cooper and Hayes, 1987). In this case, information lock-in can be beneficial, since information lock-in is a partial substitute for commitment by the policyholders. If first-period contracts are not observable by outsiders, information lock-in can arise even when separating contracts are used in the first period. However, such a contract may be renegotiated. Dionne and Doherty (1994) allow for renegotiation and derive the optimal long-term contract with pooling in the first period. In our model the issue of renegotiation does not arise because no information is available in the first period that could be revealed through the choice of contract. Moreover, contracts are short term; i.e., there is no commitment.

The literature that discusses long-term contracts focuses on hard information that can be part of a contract. In contrast, we assume that a large part of the information that is learned during the course of the business relation is soft and thus not contractible. The difference in focus seems to be quite natural given the different settings that are underlying these articles and our article. In the case of an insurer and a household, the insurer's information is indeed largely limited to the claims history as the relation is arm's length.

In the case of short-term contracts, information lock-in results in a rent that the insider gains at the expense of low-risk insurers. Because of competition, the first-period premium reflects the expected future rent. Thus, insurers make an expected loss on their policyholders in the first period and an expected profit in the second period (lowballing). With long-term contracts and commitment by the insurer (but possibly with renegotiation), insurers make profits in the first period but expected losses in the second period (highballing). Therefore, the different models yield different predictions about the pricing pattern of insurance policies. However, the empirical evidence is mixed. For example, Cox and Ge (2004) analyze long-term care insurance and find empirical evidence for lowballing. Dionne and Doherty (1994) find that some automobile insurers in California use policies that are consistent with highballing.

Our setting is also closely related to the literature on relationship lending and information lock-in in banking as developed by Sharpe (1990), Rajan (1992), and von Thadden (2004). We apply this setting to the reinsurance market and introduce separating contracts and cat bonds with a trigger that is information insensitive to the quality of insurers. In Rajan's (1992) model bonds can be used to avoid information lock-in. However, there is an interesting difference to cat bonds, which we analyze in the present article. A bond's payoff depends on the issuing firm's payoff; i.e., in the insurance terminology, the bond uses an indemnity trigger. Therefore, the bond does not reduce the information lock-in when bank debt is used in the first period: when new debt is raised, bondholders are subject to the same adverse selection problem as an outside bank. Instead, the bond has to be used in the first period as an alternative to a bank. As arm's length investors, such as bondholders, do not obtain private information, they cannot extract an information rent when new debt is issued. In contrast, the payoff of a cat bond with an information-insensitive trigger does not depend on the issuer's type. Therefore, it is not subject to adverse selection and its availability helps to constrain the insider's rent from information lock-in. To do so, the cat bond does not need to be actually used, either in the first or in the second period.

There are many studies that discuss the potential costs and benefits of cat bonds. Whereas in our article the benefit of cat bonds arises even when they are not used, these articles provide rationales for why cat bonds may be used. One group focuses on the benefits of using index and parametric triggers to reduce moral hazard (Niehaus and Mann, 1992; Doherty, 1997; Doherty and Richter, 2002), the benefit of which has to be compared to the costs of basis risk. Another strand argues that large catastrophic losses are costly to reinsure because of intermediaries' high cost of raising and holding capital (Jaffee and Russell, 1997; Froot, 1999, 2001; Niehaus, 2002; Lakdawalla and Zanjani, 2006), giving rise to counterparty risk. Our article complements these studies by identifying a new benefit of cat bonds with index or parametric triggers, which is based on adverse selection in the presence of asymmetric information between reinsurers. Gibson, Habib, and Ziegler (2007) compare the information-gathering incentives of traders in financial markets (cat bonds) with the incentives of reinsurers. Thus, they endogenize the information acquisition incentives. However, their model is quite different from ours as they want to explain a potential benefit of reinsurance over the financial market. To make their case as strong as possible, they assume that (incumbent) reinsurers have no informational benefit over arm's length investors in cat bonds and that both types of contracts use identical triggers. In contrast, we focus on a potential benefit of an index or parametric trigger when an incumbent reinsurer has an information advantage over an outsider.

THE MODEL

We consider a model with two periods and two different types of insurers. In each period, a catastrophic event can result in large losses for insurers. To avoid the costs of incurring the losses, insurers can hedge the potential loss, using reinsurance or a cat bond.

Catastrophic Losses and Insurers' Types

In each period, a catastrophic event occurs with probability θ, which may result in an "excess loss" X. Insurers differ in their exposure to the catastrophic event. We model this difference in exposure as a probability with which they incur the loss X conditional on the catastrophic event. There are two types of insurers: high risk and low risk. Given a catastrophic event, a high-risk insurer incurs the loss with probability p_h whereas the probability is p_l for a low-risk insurer, with $p_h > p_l$. The proportion of low-risk insurers is q. If there is no catastrophic event, insurers incur no loss. Although catastrophic events are independently distributed in the two periods, several insurers may be affected by the same catastrophic event. We normalize the risk-free interest rate between the two periods at zero.

Risk Transfer: Motive and Alternatives

A large catastrophic loss, if borne by the insurer, would result in high costs above and beyond the direct loss X. These costs stem from problems of financial distress, the high costs of raising new capital after the catastrophic event, reduced underwriting capacity, and a downgraded credit rating, as well as distorted incentives of the insurer and adverse reactions of policyholders. Moreover, insurers have intangible capital from their investment in building a book of business and establishing a reputation for high service quality. This intangible capital gives rise to quasi-rents that can be partially lost in the case of financial difficulties. We refer to these frictional costs of bearing large losses as (indirect) bankruptcy costs B. Because of these bankruptcy costs, insurers want to hedge a catastrophic loss.

Insurers can obtain either a reinsurance contract or a cat bond. Reinsurance contracts are short term in nature. Therefore, in our two-period model we assume that only one-period reinsurance contracts are available. Although reinsurance contracts are usually 1-year contracts, we point out that the need to renew reinsurance contracts is central to our analysis.

A reinsurance contract pays if the insurer incurs the loss. The insurer may completely transfer the excess loss X ("full reinsurance") or retain the fraction α and cover only the fraction $(1 - \alpha)$ of the excess loss X ("partial reinsurance"). In contrast, as we discuss in the section titled "Cat Bonds," the cat bond pays X conditional on the realization of an index or parametric trigger.

If the insurer's loss is fully covered by reinsurance or by the cat bond's payoff, then no bankruptcy costs B occur. If there is only partial coverage (e.g., because of a retention in the reinsurance contract), then the frictional costs are lower, but they cannot be completely avoided. We assume that the bankruptcy costs are linear in the loss that the insurer retains: if a catastrophic loss occurs and the insurer retained the fraction α of the loss, the bankruptcy costs are αB; thus, we also assume that, when X increases, the bankruptcy costs B also increase linearly in X so that $\partial B/\partial X > 0$ and $\partial^2 B/\partial X^2 = 0$.

Information

Reinsurers' ability to price reinsurance claims depends on their knowledge of an insurer's book of business, underwriting and reserving policy, and business model related to growth, screening, and claim s settlement. As we noted earlier, reinsurance markets are characterized by a close relation between insurers and reinsurers. In the course of the business relation, reinsurers obtain an information advantage over outside reinsurers who have not done any business with the insurers. This information advantage may stem not only from the catastrophe risk business but also from other reinsurance businesses that the relation involves. Alternatively, asymmetric information may stem from different capabilities to evaluate an insurer's expected loss. We capture this information asymmetry in reinsurance markets by assuming that an insurer's loss probability is not observable by outside reinsurers. However, a reinsurance company with which the insurer has done business learns the insurer's type $p_i \in \{p_l, p_h\}$. We assume that the insider obtains the same information as the insurer after the first period to make the model analytically tractable when we consider separating contracts. An outside reinsurer does not obtain any additional information but knows that a reinsurer who has done business with an insurer in the first period knows the insurer's loss probability. The degree of information asymmetry between the insider and the outsider is reflected in the difference between the probabilities, $p_h - p_l$. Thus, a lower degree of information asymmetry due to imperfect information of the insider or some learning by outsiders is akin to reducing $p_h - p_l$.

To focus on the information asymmetry between reinsurers in the second period, we make the simplifying assumption that there is no asymmetric information in the first period.

Competition between Reinsurers and Timeline

In the following analysis, we focus on the decision of a representative insurer. In each period, the insurer wants to hedge the potential loss from a catastrophic event. We assume that the insurer's shareholders are risk neutral. Therefore, the only hedging motive is to avoid the bankruptcy costs. Investors who offer coverage, i.e., reinsurers' shareholders and cat bond investors, are also risk neutral.

Reinsurers simultaneously offer reinsurance contracts for the insurer to choose from. Each contract specifies the required retention α and the premium K. In addition, cat bonds with an index or parametric trigger are available at a fair premium that is equal to the expected payment to the insurer.

In the first period, there is Bertrand competition between reinsurers. As we will show below, it is optimal for the insurer to obtain reinsurance with full coverage at the lowest premium offered. We assume that the insurer randomly picks a contract from the group of reinsurers that demand the lowest premium. If a loss occurs, the reinsurer indemnifies it. During the first period, the insurer and its reinsurer observe the insurer's risk, $p_i \in \{p_l, p_h\}$. Thus, there will be one inside reinsurer (insider or incumbent) who knows the insurer's type in the second period.

In the second period, the incumbent and outside reinsurers again offer the insurer menus of contracts. We assume that there is one outsider who makes zero expected profits in equilibrium. The insurer chooses between the offered reinsurance contracts and the cat bond to minimize the total costs of risk, which equals the sum of the premium, the expected loss that is not covered, and the resulting expected bankruptcy costs. The insurer stays with the incumbent if it is indifferent. At the end of the period, the chosen contract makes the promised payment in the case of a catastrophic event.

We solve the model backward. We first consider the second stage where asymmetrically informed reinsurers compete for reinsurance business because the equilibrium in the second period determines the pricing strategy of reinsurers in the first period. To derive the equilibrium in the second period, we proceed in three steps. As a benchmark case, we first derive the equilibrium with full reinsurance of the excess loss. Equivalently, as in Kunreuther and Pauly (1985), reinsurers offer "price policies." Adverse selection reduces competition in the reinsurance market and allows the insider to earn a rent. We then allow for Rothschild and Stiglitz (1976) type "price-quantity policies" so that separating contracts are possible. Separating contracts constrain the market power of insiders but may not completely eliminate the adverse selection problem. Our final step is to introduce cat bonds. These contracts have an effect similar to separating contracts on competition in reinsurance markets. However, the mechanisms differ: information-insensitive trigger rather than screening. Cat bonds can further constrain the market power of an incumbent reinsurer.

It is interesting to note that if reinsurers cannot observe an insurer's quantity decision, i.e., the total reinsurance coverage obtained in the market, then screening by means of the retention is not possible. In this case, full reinsurance is not just a reference case, but the relevant case.[2] If separating contracts are not available, cat bonds are even more important.

SECOND PERIOD: ASYMMETRICALLY INFORMED REINSURERS

Reinsurance Equilibrium With Full Reinsurance (Price Policies)

Here, we assume that only full coverage of the excess loss is available and that the expected bankruptcy costs are so high that it is optimal for a low-risk insurer to obtain coverage even if the premium equals K_h. The insider and the outsider simultaneously quote the premiums at which they are willing to offer reinsurance. As the insider

[2]See the discussion and references in Kunreuther and Pauly (1985). Jaynes (1978) and Hellwig (1988) discuss the case where insurers can choose whether or not to share information about their customers.

knows whether the expected loss is $\theta p_l X$ or $\theta p_h X$, the insider can offer different premiums to both types, $K^{in}(l)$ and $K^{in}(h)$. The outsider cannot distinguish between a low-risk and a high-risk insurer and demands a type-independent premium K^{out}. We define $K_l \equiv \theta p_l X$, $K_h \equiv \theta p_h X$, and $K_{pool} \equiv ((1-q)p_h + qp_l)\theta X$ as the fair premiums for a low-risk type and a high-risk type and the pooling premium, respectively.

The outsider must fear that for a given premium, only a high-risk type changes the reinsurer because the insider can retain low-risk types by making a more attractive offer. Suppose that the outsider demands the pooling premium, i.e., $K^{\text{out}} = K_{pool}$. At this premium, a reinsurer expects to break even if both types accept the contract. In this case, it is optimal for the insider to choose $K^{\text{in}}(l) = K^{\text{out}}$ and $K^{\text{in}}(h) = K_h$. The high-risk type will then accept the outsider's offer but a low-risk type will remain with the insider. (Recall that we assume that the insurer chooses the insider if indifferent. Alternatively, the insider must choose $K^{\text{in}}(l)$ slightly below K^{out}.) The outsider foresees that only a high-risk insurer will accept the contract. To break even, the outsider must set $K^{\text{out}} = K_h$. Again, it is optimal for the incumbent to choose $K^{\text{in}}(l) = K^{\text{out}}$, which is now equal to K_h. But this offer cannot be an equilibrium either, because now the outsider can make a profit by offering reinsurance at a premium $K_{pool} < K^{\text{out}} < K_h$, which, given $K^{\text{in}}(l) = K_h$, will be chosen by both types of insurers. The following lemma directly follows from the discussion.

Lemma 1: *There exists no equilibrium in pure strategies.*

With asymmetric information, there exists only a mixed equilibrium in which the insider and the outsider randomize over the premiums that they will demand. The low-risk insurer chooses the insider whenever $K^{\text{in}}(l) \leq K^{\text{out}}$. In this case, the outsider is left with the high-risk type and makes a loss if $K^{\text{out}} < K_h$. If $K^{\text{in}}(l) > K^{\text{out}}$, then both types of insurers choose the outsider's contract and the expected indemnity payment equals K_{pool}. Therefore, K_{pool} places a lower bound on K^{out}, whereas $K^{\text{out}} = K_h$ constitutes an upper bound at which the outsider's profit from selling to a high-risk type is zero.

Proposition 1: *The following mixed strategies constitute a Nash equilibrium:*

(i) *The insurer chooses the contract with the lowest premium and stays with the insider if indifferent.*

(ii) *The insider chooses $K^{\text{in}}(h) = K_h$ for a high-risk type and $K^{\text{in}}(l) \in [K_{pool}, K_h]$ with density*

$$\omega(K) = \frac{K_{pool} - K_l}{q(K - K_l)^2} \tag{1}$$

for a low-risk type.

(iii) *The outsider chooses $K^{\text{out}} \in [K_{pool}, K_h]$ where $K^{\text{out}} = K_h$ has a point mass of $(1-q)$ and $K^{\text{out}} \in [K_{pool}, K_h)$ has density*

$$\phi(K) = q\,\omega(K). \tag{2}$$

We derive the equilibrium in the Appendix.

When choosing $K^{\text{out}} = K_h$, the outsider will never sell to a low-risk insurer, so the outsider's expected profit is zero. By reducing K^{out}, the outsider might also sell to a low-risk insurer at a profit, but at the same time the outsider will make an expected loss if it does not succeed in underbidding the insider. The insider's mixed strategy has the property that the outsider is indifferent between any $K^{\text{out}} \in [K_{pool}, K_h]$.

The insider's information advantage allows the insider to earn a rent. If the insider chooses $K^{\text{in}}(l) = K_{pool}$, then the low-risk insurer always stays with the insider and the rent is $K_{pool} - K_l$. Increasing $K^{\text{in}}(l)$ increases the expected profit from a low-risk insurer but reduces the probability of selling reinsurance to a low-risk type, because now the outsider's premium may be lower. The outsider's mixed strategy has the property that the insider is indifferent between any $K^{\text{in}}(l) \in [K_{pool}, K_h]$. Thus, the expected rent from a low-risk insurer equals $K_{pool} - K_l$.

The outsider must be compensated for situations in which only a high-risk type accepts the offer and $K^{\text{out}} < K_h$. The outsider's expected profit from a low-risk type is derived in the Appendix and is given by

$$E[\Pi^{\text{out}} \mid l] = (K_h - K_l)\frac{(1-q)^2}{q}\left[\frac{q}{1-q} + \ln(1-q)\right]. \tag{3}$$

The expected profit compensates the outsider for the expected loss from a high-risk type, $E[\Pi^{\text{out}} \mid h]$, and can be interpreted as the level of (expected) cross subsidization of types. In equilibrium, the outsider's *ex ante* expected profit is zero and $qE[\Pi^{\text{out}} \mid l] + (1-q)E[\Pi^{\text{out}} \mid h] = 0$. Thus, $E[\Pi^{\text{out}} \mid h] = -[q/(1-q)]E[\Pi^{\text{out}} \mid l]$.

A low-risk insurer buys reinsurance either from the insider or from the outsider and the expected premium is

$$E[\min\{K^{\text{in}}(l), K^{\text{out}}\}] = K_l + E[\Pi^{\text{in}} \mid l] + E[\Pi^{\text{out}} \mid l] > K_l. \tag{4}$$

The expected premium for a low-risk type consists of three components: the expected indemnity payment, K_l; the (expected) rent to the insider, $E[\Pi^{\text{in}} \mid l] = (K_{pool} - K_l)$; and the level of (expected) cross-subsidization, $E[\Pi^{\text{out}} \mid l]$. Thus, a low-risk type expects to pay a premium that exceeds the pooling premium.

A high-risk insurer obtains reinsurance at an expected premium

$$E[K^{\text{out}}] = K_h + E[\Pi^{\text{out}} \mid h] = K_h - \frac{q}{1-q}E[\Pi^{\text{out}} \mid l] < K_h. \tag{5}$$

The difference between the expected premiums in (5) and (4) is given by $K_h - K_l - E[\Pi^{\text{in}} \mid l] - \frac{1}{1-q}E[\Pi^{\text{out}} \mid l] > 0$ and decreasing in the insider's rent and the level of cross-subsidization.

Although a low-risk insurer's expected premium is lower than a high-risk insurer's expected premium, the difference in the expected losses, $K_h - K_l$, exceeds the difference in the expected premiums. The spread between the difference in the expected losses and the difference in the expected premiums equals the insider's rent and the level of cross-subsidization:

$$E[\Pi^{\text{in}}\,|\,l] + \frac{1}{1-q}E[\Pi^{\text{out}}\,|\,l] = (K_h - K_l)\frac{1-q}{q}\left[q + \frac{q}{1-q} + \ln(1-q)\right]. \tag{6}$$

Separating Contracts (Price-Quantity Policies)

We now allow the outsider to offer Rothschild and Stiglitz (1976) type price-quantity policies. A retention can be used to separate low-risk and high-risk insurers. For example, the insurer may retain a fraction $\alpha > 0$ of the excess loss X and only buy reinsurance coverage for the fraction $1 - \alpha$. The outsider can now separate risk types by offering two types of contracts, $(\alpha_h, K_h(\alpha_h))$ and $(\alpha_l, K_l(\alpha_l))$. The high-risk insurer is offered full coverage with $\alpha_h = 0$ and $K_h(\alpha_h) = K_h$, and the low-risk insurer is offered partial reinsurance at a fair premium. Separation of types implies that the retention is sufficiently high so that a high-risk type will not choose this contract. Thus, the cost saving for a high-risk type must not exceed the expected bankruptcy costs when choosing $(\alpha_l, K_l(\alpha_l))$ instead of $(0, K_h)$, i.e., $(1-\alpha_l)(K_h - K_l) \le \theta p_h \alpha_l B$. The lowest α_l that satisfies this condition is $\hat{\alpha}_l \equiv (K_h - K_l)/(\theta p_h B + K_h - K_l)$ and the fair premium is $\hat{K}_l \equiv (1-\hat{\alpha}_l)K_l$.

If a low-risk insurer chooses the contract $(\hat{\alpha}_l, \hat{K}_l)$, it has to bear expected bankruptcy costs of $\hat{B}_l \equiv \hat{\alpha}_l \theta p_l B$. It is straightforward to check that the low-risk type's incentive compatibility and participation constraints are satisfied. Thus, it is optimal for the low-risk insurer to choose the separating contract $(\hat{\alpha}_l, \hat{K}_l)$ rather than full reinsurance at a premium K_h or no reinsurance.

Because the insider knows the insurer's type, it can continue to offer full coverage at the premium $K^{\text{in}}(l)$. However, the separating contract places an upper bound on the reinsurance premium that a low-risk insurer will accept. To be attractive for the low-risk insurer, the premium for full reinsurance must not exceed the fair premium by more than the expected bankruptcy costs when choosing the separating contract, i.e., $K^{\text{in}}(l) - K_l \le \hat{B}_l$. The insider makes zero profit if the low-risk insurer does not buy reinsurance from it. Thus, the insider will never demand a premium that exceeds $K_l^{\max} \equiv K_l + \hat{B}_l$. The highest premium that the insider can demand in the reinsurance equilibrium with separating contracts is lower than the highest premium without separating contracts, K_h, since $K_l^{\max} < K_h$. This condition directly follows from the low-risk insurer's incentive compatibility constraint.

We first consider the case in which $K_l^{\max}$ is so low that the insider is not able to demand a premium that exceeds the pooling premium, K_{pool}. This case arises if

$$K_l^{\max} \le K_{pool}. \tag{7}$$

Proposition 2: *For $K_l^{\max} \le K_{pool}$, the following pure strategies constitute a Nash equilibrium:*

(i) The insurer chooses the contract that minimizes the expected costs of a catastrophic loss.
(ii) The insider sets $K^{\text{in}}(h) = K_h$ and $K^{\text{in}}(l) = K_l^{\max}$.
(iii) The outsider offers two contracts, $(\hat{\alpha}_l, \hat{K}_l)$ and $(0, \hat{K}_h)$.

If (7) holds, then the insider chooses the premium $K_l^{\max}$ for a low-risk type, which is lower or equal to the pooling premium. For the outsider, there is no better alternative to offering the separating contracts. The reinsurance market is stable. Insurers do not change their reinsurer, as the insider's offer is more attractive for the low-risk insurer and high-risk insurers are indifferent. When changing the reinsurer, a low-risk insurer would have to accept a higher retention to reveal its type. Because of the costs of bearing losses, the insurer stays with the informed reinsurer.

If (7) is violated, it is no longer optimal for the outsider to offer only the separating contracts in Proposition 2. Consider the strategies in Proposition 2 and assume that $K_l^{\max} > K_{pool}$. For $K^{\text{in}}(l) = K_l^{\max} > K_{pool}$, it is optimal for the outsider to offer a contract with full reinsurance at a premium just below $K^{\text{in}}(l)$. This contract will be accepted by both types, and the outsider makes a positive expected profit. Of course, it is then no longer optimal for the insider to choose $K^{\text{in}}(l) = K_l^{\max}$.

The following proposition states the new equilibrium:

Proposition 3: *For $K_l^{\max} > K_{pool}$ the following mixed strategies constitute a Nash equilibrium:*

(i) The insurer chooses the contract that minimizes the expected costs of a catastrophic loss given its type.

(ii) The insider chooses $K^{\text{in}}(h) = K_h$ and $K^{\text{in}}(l) \in [K_{pool}, K_l^{\max}]$ where $K^{\text{in}}(l) = K_l^{\max}$ is chosen with probability

$$\frac{1-q}{q}\left[\frac{K_h - K_l}{\hat{B}_l} - 1\right] \tag{8}$$

and $K^{\text{in}}(l) \in [K_{pool}, K_l^{\max})$ with density (1) in Proposition 1.

(iii) The outsider offers two contracts, $(\hat{\alpha}_l, \hat{K}_l)$ and full reinsurance with $K^{\text{out}} \in \{[K_{pool}, K_l^{\max}), K_h\}$ where $K^{\text{out}} = K_h$ is chosen with probability

$$(1-q)\frac{K_h - K_l}{\hat{B}_l} \tag{9}$$

and $K^{\text{out}} \in [K_{pool}, K_l^{\max})$ with density (2) in Proposition 1.

We derive the equilibrium in the Appendix.

The equilibrium strategies are similar to those in Proposition 1 with $K_l^{\max}$ as a new upper bound on the insider's bid. The insider no longer chooses $K^{\text{in}}(l) \in (K_l^{\max}, K_h]$ because a low-risk insurer would then choose the separating contract $(\hat{\alpha}_l, \hat{K}_l)$; the probability mass over this region shifts to $K^{\text{in}}(l) = K_l^{\max}$. As a consequence, the outsider will also offer no contracts in this region because these contracts will only be accepted by a high-risk insurer; the probability mass shifts to $K^{\text{out}} = K_h$.

For $K_l^{\max} > K_{pool}$, the insider can still guarantee itself an expected rent of $K_{pool} - K_l$ from a low-risk type. To understand why the insider is still able to capture the same rent as without a separating contract, we recall that a higher premium does not result in a higher profit, because the likelihood that the outsider will underbid the offer also increases, and in equilibrium the insider's expected profit does not change.

We are interested in taking a closer look at the bidding strategy of the outsider. The separating contract $(\hat{\alpha}_l, \hat{K}_l)$ is not prone to adverse selection, but it is also not successful in attracting low-risk insurers, which are offered full reinsurance by the insider. Since the insider earns a rent on low-risk insurers, the outsider tries to lure low-risk insurers away from the insider by offering contracts with a lower retention than the separating contract $(\hat{\alpha}_l, \hat{K}_l)$. Of course, these contracts are also attractive for high-risk insurers and to continue to separate types, the outsider has to make an attractive offer also to high-risk insurers. Indeed, as we show in the proof to Proposition 3, when trying to attract a low-risk insurer away from the incumbent reinsurer, it is optimal for the outsider to choose a retention of zero and offer full reinsurance at a premium $K^{out} \in [K_{pool}, K_l^{max})$ to both types. Although these contracts are also chosen by high-risk insurers, the outsider is still better off because separating types in a way that is still attractive for a low-risk insurer relative to the insider's offer involves even higher costs.

The reason for the mixed equilibrium in Proposition 3 is directly related to the reason for the mixed equilibrium in Proposition 1. The only difference is that the separating contract in Proposition 3 puts a new upper bound, K_l^{max}, on the insider's bidding strategy. This new upper bound displaces bids by the outsider in the region K_l^{max} to K_h. Formally, the outsider puts less probability mass on premiums $K^{out} < K_h$ with which it tries to attract a low-risk insurer. Thus, the probability that low-risk insurers change their reinsurer and the level of cross-subsidization are lower than without separating contracts.

The probability of choosing $K^{out} < K_h$ is related to the degree of information asymmetry, as measured by the heterogeneity of types, $p_h - p_l$, and the average riskiness of types, as measured by the fraction of low-risk types in the economy, q. The probability that an outsider tries to underbid the insider's offer for a low-risk insurer is decreasing in the degree of information asymmetry and increasing in the average quality of insurers in the economy.[3]

For $K_l^{max} \leq K_{pool}$, the outsider continues to offer separating contracts but no longer tries to compete with the insider to attract a low-risk insurer by offering higher coverage (full reinsurance) at a rate below K_h. Thus, a high-risk insurer pays the fair premium and the required cross-subsidization is zero. The insider's information rent now equals $\hat{B}_l$. Clearly, the rent decreases when the expected bankruptcy costs that are associated with the low-risk type's separating contract decrease.

[3]Using $\Pr(K^{out} = K_h) = (1-q)[K_h - K_l]/\hat{B}_l$ (from Proposition 3), $K_h - K_l = (p_h - p_l)\theta X$, and the definition of $\hat{B}_l$, we obtain $\Pr(K^{out} < K_h) = 1 - \Pr(K^{out} = K_h) = 1 - (1-q)[p_h B + (p_h - p_l)X]/p_l B$. It is straightforward to check that $\Pr(K^{out} < K_h)$ is decreasing in p_h, increasing in p_l, and increasing in q.

The spread between the difference in expected losses and the difference in expected premiums is again given by $\Delta \equiv E[\Pi^{\text{in}} \mid l] + \frac{1}{1-q} E[\Pi^{\text{out}} \mid l]$, with

$$\Delta = \begin{cases} \hat{B}_l & \text{for } K_l^{\max} \leq K_{pool} \\ (K_h - K_l)\dfrac{1-q}{q}\left[q + \dfrac{1}{1-q} + \ln(1-q) - \dfrac{K_h - K_l}{\hat{B}_l} + \ln \dfrac{K_h - K_l}{\hat{B}_l}\right] & \text{for } K_l^{\max} > K_{pool}. \end{cases} \tag{10}$$

The first line is straightforward, given pure bidding strategies. A high-risk type always has to pay K_h, and the low-risk type has to pay $K_l^{\max}$. We derive the second line in the Appendix. It is analogous to the case with full reinsurance. The only difference is that $K_l^{\max}$ replaces K_h as the upper bound for the insider's bids. For $K_l^{\max} = K_h$, the spread is equivalent to (6). However, as $K_l^{\max}$ is strictly lower than K_h, the expected distortion due to the insider's rent and cross-subsidization of types is also strictly lower.

We derive the following comparative statics result in the Appendix.

Proposition 4: *Holding insurers' types, p_i, constant, increasing expected losses from catastrophic events go along with (i) an increasing rent that an insider can extract from low-risk insurers (for $K_l^{\max} < K_{pool}$) and (ii) an increasing level of cross-subsidization of types (for $K_l^{\max} \geq K_{pool}$).*

Because of asymmetric information, the level of pricing distortions in reinsurance contracts increases in the probability θ of a catastrophic event and the potential loss X. Thus, increasing expected losses of catastrophic events provide low-risk insurers with incentives to search for new alternatives to transfer catastrophe risk.

Cat Bonds

Cat bonds with an index or parametric trigger have emerged as a capital-market-based alternative to reinsurance. If the trigger is set off, then the insurer receives X. An important characteristic of the cat bond is the trigger's correlation with the insurer's loss. The higher the correlation, the lower the basis risk. We assume that given a catastrophic event, the cat bond "pays" the amount X with probability p_T. Thus, the probability does not depend on an individual insurer's type. The fair premium equals $\theta p_T X$, which is the expected loss for investors in the cat bond and the cat bond's expected payoff to the insurer. To determine the level of basis risk, we define the joint probability that the trigger is set off and that an insurer of type $i \in \{l, h\}$ incurs a loss as p_T^i, with $p_T^i \in [p_T p_i, \min\{p_i, p_T\}]$. Thus, $p_T^i = p_T p_i$ corresponds to the case of zero correlation, and an increasing p_T^i reflects an increasing correlation between the trigger and the insurer's loss. Unless the cat bond's payoff and the insurer's loss are perfectly correlated and $p_i = p_T^i$, the insurer must bear basis risk $B_i^{risk} \equiv (p_i - p_T^i)\theta B$. (For ease of exposition, we assume that $p_i > p_T^i$.) We note that we define basis risk as the expected bankruptcy costs that stem from the possibility that the cat bond's payoff does not perfectly match the insurer's loss.

With a cat bond, an insurer receives the coverage at a fair premium but must bear basis risk. The basis risk is akin to the expected bankruptcy costs of a retention with a separating contract. As with the availability of a separating contract, the availability of a cat bond can have important implications for competition in the reinsurance market.

We first consider the case of full reinsurance. The low-risk insurer will only choose the reinsurance contract if the premium $K = \min\{K^{\text{in}}(l), K^{\text{out}}\}$ does not exceed the fair premium K_l by more than the basis risk B_l^{risk}, i.e., if $K - K_l \leq B_l^{risk}$. Hence, the availability of a cat bond places an upper bound on the reinsurance premium that a low-risk type will accept, just as does the separating contract. Thus, the cat bond has the same effect on the competition in reinsurance as does the separating contract. Therefore, if we replace $\hat{B}_l$ and $K_l^{\max}$ with B_l^{risk} and $K_{cat}^{\max} \equiv K_l + B_l^{risk}$, the analysis in the previous subsection also holds for cat bonds.

Therefore, an interesting (empirical) question is which alternative, the separating contract or the cat bond, constrains the insider more. If $K_{cat}^{\max} < K_l^{\max}$, then cat bonds reduce the hold-up and adverse selection problem inherent in the reinsurance relationship. The condition holds if $B_l^{risk} < \hat{B}_l$.

Given the importance of the level of $\hat{B}_l$ and B_l^{risk}, we take a closer look at their determinants. The expected bankruptcy costs from the retention in the separating contract are $\hat{B}_l = \frac{(p_h - p_l)X}{p_h B + (p_h - p_l)X}\theta p_l B$, and the expected bankruptcy costs when using the cat bond are $B_l^{risk} = (p_l - p_T^l)\theta B$. Thus, $B_l^{risk} < \hat{B}_l$ if

$$(1 - \beta) < \frac{(\gamma - 1)X}{\gamma B + (\gamma - 1)X}, \tag{11}$$

where $\beta \equiv \frac{p_T^l}{p_l}$ and $\gamma \equiv \frac{p_h}{p_l}$. The parameter β can be interpreted as a measure for the "quality" of the cat bond's trigger. The higher β, the lower is the level of basis risk. For $\beta = 1$, the cat bond is always triggered when the insurer incurs a catastrophic loss and there is no basis risk. The parameter γ is a measure of the asymmetric information in the market; for $\gamma = 1$ there is no difference in types and thus no asymmetric information. The left-hand side is decreasing in β whereas the right-hand side is increasing in γ. Therefore, we can state the following lemma.

Lemma 2: *Cat bonds are more likely to constrain the maximum premium that a low-risk insurer has to pay in the reinsurance market if the cat bond's trigger quality β and the degree of information asymmetry γ are high.*

The lemma suggests that cat bonds are likely to become increasingly important in increasing the contestability in the reinsurance market as more precise indexes are developed, which, e.g., might be based on postal codes or use improved loss models.

In the following, we assume that $B_l^{risk} < \hat{B}_l$ so that the availability of cat bonds is a viable alternative for an insurer and thus constrains the premium that a low-risk insurer has to pay. The distortion in expected premiums between a high-risk and a low-risk type is now given by

$$\Delta_c = \begin{cases} B_l^{risk} & \text{for } K_{cat}^{\max} \le K_{pool} \\ (K_h - K_l)\dfrac{1-q}{q}\left[q + \dfrac{1}{1-q} + \ln(1-q) - \dfrac{K_h - K_l}{B_l^{risk}} + \ln\dfrac{K_h - K_l}{B_l^{risk}}\right] & \text{for } K_{cat}^{\max} > K_{pool}. \end{cases} \tag{12}$$

Proposition 5: *If $B_l^{risk} < \hat{B}_l$, the introduction of cat bonds increases the difference in expected premiums that a high-risk and a low-risk insurer have to pay. Holding insurers' types, p_i, constant, the effect is more pronounced when catastrophic events are more likely and the cat bond's trigger quality is high.*

We prove the proposition in the Appendix.

FIRST PERIOD: SYMMETRICALLY INFORMED REINSURERS

We are now able to analyze the first period. In the first period, all reinsurers have the same information and will therefore place identical bids, taking into account the second-period equilibrium. Since all reinsurers can become insiders when winning the bid in the first period, Bertrand competition will drive down the first-period premium, which then internalizes the insider's second-period rent. Bertrand competition implies perfect competition, no financing constraints for the reinsurers, and full internalization of insider profits. The first-period premium K_1 is then

$$K_1 = \begin{cases} K_{pool} - q(\bar{K}^{\max} - K_l) & \text{for } \bar{K}^{\max} \le K_{pool} \\ K_{pool} - q(K_{pool} - K_l) & \text{for } \bar{K}^{\max} > K_{pool}, \end{cases} \tag{13}$$

with $\bar{K}^{\max} \equiv \min\{K_l^{\max}, K_{cat}^{\max}\}$.

The reinsurance premium in the first period equals the expected indemnity payment net of the expected future rent that the reinsurer will be able to extract from the inside information that the business generates. The cross-subsidization does not affect first-period premiums because it is a pure redistribution between insurers. For $\bar{K}^{\max} \le K_{pool}$, the expected future rent is increasing in q. For $\bar{K}^{\max} > K_{pool}$, the expected future rent has a maximum at $q = 0.5$ since $q(K_{pool} - K_l) = q(1-q)(K_h - K_l)$: increasing q has a positive effect, since it increases the probability of a low-risk type, but also a negative effect, because it reduces the pooling premium. The rent also depends on the difference between the expected losses of a high-risk type and a low-risk type, $K_h - K_l$. This difference depends on the degree of information asymmetry. The higher the information asymmetry, the more valuable is the inside information and the higher is the rent that the insider can extract.

Instead of buying reinsurance, the insurer may choose a cat bond in the first period.

Lemma 3: *Given the premiums in (13), the insurer strictly prefers the reinsurance contract to the cat bond in the first period.*

The lemma follows directly from the observation that insurers receive a fair premium in the first period that takes into account the rent extracted in the second period. In contrast, the cat bond involves basis risk.

The analysis of the first period might suggest that cat bonds are irrelevant, since insurers are compensated for the future extraction of information rents by lower premiums in the first period. However, this presumption is not correct. The benefit of using cat bonds in the second period remains: low-risk insurers benefit from the availability of cat bonds in the second period, no matter how large the discount was in the first period. Moreover, the availability of cat bonds can have a spillover effect and impact reinsurance premiums at times when cat bonds are not considered as an alternative. The link is that future rents impact the current premium and cat bonds may impact future rents.

ROBUSTNESS AND EXTENSIONS

Multiple Insiders

We now consider the case in which the insurer can obtain reinsurance from multiple reinsurers in the first period. In the absence of monitoring costs and with symmetric information by insiders, Bertrand competition between the insiders will drive down the premiums demanded from a low-risk type to the fair premium K_l. The cat bond will then have no effect on the premiums because competition between insiders eliminates the lock-in from asymmetric information. However, this argument hinges critically on the assumption that both insiders will have the same information. If they have asymmetric information, the situation is similar to the one with an informed insider and an uninformed outsider. In the presence of even a low monitoring cost and unequal access to information, insiders may still be able to extract information rents (Rajan, 1991, 1992).

Multiple Outsiders

Multiple Outsiders and Full Reinsurance. Our proof of the reinsurance equilibrium with asymmetrically informed reinsurers and full reinsurance is related to Engelbrecht-Wiggans, Milgrom, and Weber (1983) who derive a bidding equilibrium with one informed bidder and multiple uninformed bidders. What their study shows is that what matters for the equilibrium outcome is the distribution of the maximum bids made by uninformed bidders who each make zero expected profits in equilibrium. The distribution of the maximum bids made by uninformed bidders is equivalent to the distribution of a single bidder who is assumed to make zero profits. Thus, although the bidding strategy of each uninformed bidder depends on the number of uninformed bidders, the informed bidder's expected profit and the expected allocation (i.e., whether the informed or an uninformed bidder wins) are not affected.

Multiple Outsiders and Separating Contracts. With separating contracts, we have to distinguish two cases. First, when $\bar{K}^{\max} \leq K_{pool}$, nothing changes if we introduce multiple outsiders: all outsiders offer separating contracts and Proposition 2 continues to hold. Second, when $\bar{K}^{\max} > K_{pool}$, the setting is similar to the case with full reinsurance with the notable exception that outsiders can now offer partial reinsurance. Given the bidding strategies in Proposition 3, outsiders cannot use separating contracts to increase the expected share of low-risk insurers that they attract from the insider. The reason is that any contract (with full or partial reinsurance) that can potentially attract a low-risk type is also preferred to K_h by a high-risk type. Thus, again, the presence of multiple outsiders does not affect the competition between the insider and outsiders, which is the focus of our analysis. However, outsiders may now use separating contracts to reduce their expected share of high-risk insurers at the expense of other uninformed outsiders as in Rothschild and Stiglitz (1976). Deriving the outsiders' optimal strategies for this case is beyond the scope of this article.[4]

Counterparty Risk

Counterparty risk can be important for catastrophe reinsurance. Indemnity-based reinsurance contracts are usually not funded, and the reinsurer may default after a catastrophic event. In contrast, because of the initial provision of the principal amount, default risk can be eliminated for a cat bond. Here, we discuss the implications of this difference between the two instruments.

To simplify the exposition, we assume that the reinsurer's default probability p_C is independent of the insurer's type, that no payment is made in the case of default, and that default involves no cost for the reinsurer. Thus, with probability p_C the insurer is not reimbursed for its loss, and it receives X with probability $1 - p_C$. Default risk by the reinsurer has a similar effect for an insurer as a retention, with the notable difference that default affects both types of insurers. In the case of full reinsurance, the fair premiums with default are $(1 - p_C)K_l$, $(1 - p_C)K_h$, and $(1 - p_C)K_{pool}$ and the possibility of nonperformance results in expected bankruptcy costs of $p_C\theta p_i B$ for a type i insurer.

Introducing counterparty risk does not change the qualitative results in the case in which no cat bond is available. However, cat bonds now have an additional advantage relative to reinsurance contracts. For that reason they are more likely to affect the reinsurance market. Indeed, they may now be chosen in equilibrium if the expected bankruptcy costs due to nonperformance of reinsurance are sufficiently high. However, cat bonds may also still be inefficient and merely constrain the pricing of reinsurance contracts. If $p_C\theta p_l B < B_l^{risk}$, then the counterparty risk is lower than the basis risk so that reinsurance is efficient for a low-risk insurer. In the simplest setting, the cat bond is also inefficient for a high-risk insurer, i.e., $p_C\theta p_h B < B_h^{risk}$. In the presence of cat bonds, a low-risk type will not pay a reinsurance premium that exceeds $(1 - p_C)K_l + B_l^{risk} - p_C\theta p_l B$.

Frictional Cost of Capital and Transaction Costs

Capital market frictions are a major reason for counterparty risk (and, indeed, for the use of reinsurance in the first place). The cost of raising and holding capital can differ substantially for a reinsurer and an SPV that issues the cat bond. The SPV is a focused insurer whose only purpose it is to write one reinsurance contract. In contrast, a general insurer engages in many different activities and has many different risks on the balance sheet. An SPV helps to segregate the claims of different policyholders, thus minimizing the risk that funds may be diverted to other uses. Thereby the SPV can considerably reduce the cost of raising and holding capital and increases the

[4]Rosenthal and Weiss (1984) derive a mixed-strategy equilibrium with asymmetric information between the bidder and the seller for symmetrically informed bidders.

insurer's confidence that the funds will be available when needed. These benefits are particularly pronounced when low-frequency and high-severity risks are involved and there is a high correlation of losses between policyholders, as in the case of catastrophe risk.

Explicitly taking into account transaction costs changes the equilibrium boundary conditions but not the qualitative results. The transaction costs may differ because of differences in the frictional cost of capital or the cost of setting up an SPV. In the following we will assume fixed transaction costs of c_{re} for the reinsurance contract and c_{cat} for the cat bond. Given c_{re}, the breakeven premium for full reinsurance is $K_i + c_{re}$ for an insurer of type *i*.

Without cat bonds, the reinsurance premiums are increased by c_{re}, and the insider's profit and the cross-subsidization remain unchanged, since the higher premium just covers the transaction costs. However, cat bonds now have an additional advantage relative to reinsurance contracts if $c_{cat} < c_{re}$. A low-risk insurer will not pay more than $K_l + B_l^{risk} + c_{cat} = K_{cat}^{\max} + c_{cat}$. Without the cat bond, this limit is given by $K_l^{\max} + c_{re}$. Thus, the cat bond affects competition if $K_{cat}^{\max} < K_l^{\max} + c_{re} - c_{cat}$. For $c_{re} - c_{cat} > 0$, the transaction costs make it more likely that the cat bond reduces rents in the reinsurance market. Moreover, lower transaction costs may be a reason for using the cat bond despite basis risk: if $c_{re} - c_{cat} > B_l^{risk}$, it is optimal for a low-risk insurer to choose the cat bond.

EMPIRICAL IMPLICATIONS

We show that cat bonds can play an important role for the pricing of reinsurance contracts. Practitioners and academics (e.g., Froot, 2001) argue that cat bonds reduce barriers to entry and that therefore the reinsurance market has become more contested. We formalize this idea in a setting with asymmetric information between reinsurers. Asymmetric information is an important source of market power because the fear of adverse selection has an anticompetitive effect on the pricing of reinsurance contracts. Tracing the origin of market power to asymmetric information has several interesting implications.

When losses from catastrophic events are low, the reinsurance market is stable and reinsurers' ability to extract rents from their information advantage is limited. However, as expected losses from catastrophic events increase, the likelihood that insurers will switch their reinsurer, the insider's expected rent, and the level of cross-subsidization increase. This is the setting in which the availability of cat bonds can be important. The potential effect of cat bonds on competition in the reinsurance market has important implications for insurers. Most notably, the competitive effect differs substantially for different types of insurers. Although the availability of cat bonds with index or parametric triggers reduces the reinsurance premium for low-risk types, it increases the reinsurance premium to be paid by high-risk types.

The reinsurance premium is a cost to insurers that affects their underwriting business. Cross-subsidization and the insider's rent undermine a low-risk insurer's competitive advantage when it competes with a high-risk insurer for underwriting business. Thus, since the pricing of reinsurance becomes more sensitive to an insurer's risk, the introduction of cat bonds helps to restore the competitive position of low-risk insurers. As a consequence, the profitability of low-risk insurers increases whereas the profitability of high-risk insurers decreases. The price effect allows low-risk insurers to bid more aggressively in the primary market. Therefore, low-risk insurers are likely to grow faster than high-risk insurers. The increased sensitivity of reinsurance premiums to an insurer's risk also increases insurers' incentives to maintain low risk, which will reduce the average risk of insurers.

The effect of cat bonds on individual insurers cannot be measured directly. In our model, we define "high risk" and "low risk" as relative to an insurer's expected type, where the expectation is determined by all publicly available information. Therefore, we cannot distinguish between high-risk and low-risk insurers based on publicly available information. Alternatively, empirical studies may focus on the heterogeneity of insurers' profitability and growth: when cat bonds are available and affect reinsurance premiums, the difference (heterogeneity) in profitability and growth between insurers increases.

Cat bonds are most likely to affect reinsurance premiums if the degree of asymmetric information and the quality of the cat bond's trigger are high. Asymmetric information is likely to be higher for insurers that are incorporated in countries where accounting information is less informative about an insurer's risk. Moreover, mutual insurers are more opaque than are stock insurers, for which more public information is available. Therefore, asymmetric information is likely to be a greater problem for mutual insurers than for stock insurers. The level of basis risk is lower for insurers that have a high concentration of exposure in regions with a high risk of catastrophic events, so that the correlation between the individual insurers' losses and the parametric trigger is high. Examples for well-specified and regionally concentrated perils include Californian and Japanese earthquakes, as well as U.S. East Coast hurricanes, and Japanese typhoons.

Therefore, we predict that

- The introduction of cat bonds is more likely to increase the heterogeneity of insurers' profitability and growth for insurers with a high concentration of their risk in California and Japan, and on the East Coast in the United States; for mutual insurers than for stock insurers; and, to the extent that U.S. accounting information is more informative than Japanese accounting information, for Japanese insurers than for U.S. insurers.
- The effect on the heterogeneity of insurers' profitability and growth is increasing in the probability of catastrophic events and decreasing in the level of basis risk.

In our basic model insurers do not use cat bonds unless counterparty risk, transaction costs, monitoring costs, or moral-hazard problems are sufficiently high. The result is interesting as it shows that a potential benefit of cat bonds arises from their availability, not from their use. Therefore, cat bonds may be very important even when they are rarely used.

CONCLUSION

In this article, we show that cat bonds can play an important role in the pricing of reinsurance contracts when there is asymmetric information between inside and outside reinsurers about an insurer's risk. Thereby, we carve out a novel benefit of cat bonds that arises even in the absence of counterparty risk, transaction costs, monitoring costs, or moral-hazard problems. An interesting observation is that the benefit arises solely because of the potential availability of cat bonds.

The existence of information-insensitive cat bonds can reduce the asymmetric-information and lock-in problems in a reinsurance relationship and discipline the rent extraction from insider information. The reason is that for sufficiently small basis risk, the availability of cat bonds places an upper bound on the maximum premium that a low-risk insurer is willing to pay for reinsurance. As a consequence, the degree of cross-subsidization from the low-risk types to the high-risk types decreases. If the basis risk is sufficiently low, the level of cross-subsidization is zero and the insider's information rent is reduced. Our primary findings on the competitive effect of cat bonds are robust to a number of extensions.

APPENDIX

Proof of Proposition 1

To prove the proposition, we draw on the work of von Thadden (2004) and Engelbrecht-Wiggans, Milgrom, and Weber (1983) who analyze related settings.

First, we show that the interval $K \in [K_{pool}, K_h]$ is the optimal support for the randomization strategies. For any bid below the pooling premium, the outsider's participation constraint is violated, so the minimum premium will be K_{pool}. Therefore, it also cannot be optimal for the insider to offer a lower premium to the low-risk type because raising the premium to the pooling premium increases profits. The upper bound K_h follows from the zero-profit constraint for offering a contract to a high-risk type.[5]

Second, we derive the optimal strategies. Let $\Phi(K)$ denote the cumulative density function (CDF) of the outsider's mixed equilibrium strategy for the choice of K^{out}, and let $\Omega(K)$ denote the insider's CDF for the choice of $K^{\text{in}}(l)$. Given K^{out}, the outsider's expected profit is $\Pi^{\text{out}}(K^{\text{out}}) = (1 - \Omega(K^{\text{out}}))(K^{\text{out}} - K_{pool}) + \Omega(K^{\text{out}})(1 - q)$ $(K^{\text{out}} - K_h)$. With probability $(1 - \Omega(K^{\text{out}}))$, $K^{\text{out}} < K^{\text{in}}(l)$ so that both types of insurers accept the offer and the expected net payoff is $K^{\text{out}} - K_{pool} \geq 0$. With probability $\Omega(K^{\text{out}})$, $K^{\text{out}} \geq K^{\text{in}}(l)$ so that a low-risk type stays with the insider and the outsider will only sell the reinsurance contract if the insurer has high risk, which occurs with probability $(1 - q)$ and results in an expected net payoff of $K^{\text{out}} - K_h \leq 0$. In equilibrium, the outsider makes an expected profit of zero. Moreover, in the mixed-strategy equilibrium the outsider must be indifferent between different premiums. Hence, $\Pi^{\text{out}}(K^{\text{out}}) = 0$ for all $K^{\text{out}} \in [K_{pool}, K_h]$. From $(1 - \Omega(K^{\text{out}}))(K^{\text{out}} - K_{pool}) = -\Omega(K^{\text{out}})(1 - q)(K^{\text{out}} - K_h)$ and $K_{pool} = qK_l + (1 - q)K_h$ it follows that the insider's CDF is $\Omega(K) = [K - K_{pool}]/[q(K - K_l)]$ for $K \in [K_{pool}, K_h]$.

Given the outsider's mixed strategy $\Phi(K)$, the insider's expected profit is $\Pi^{\text{in}}(K^{\text{in}}(l)) = q[1 - \Phi(K^{\text{in}}(l))](K^{\text{in}}(l) - K_l)$ for $K^{\text{in}}(l) \in [K_{pool}, K_h)$ and $\Pi^{\text{in}}(K^{\text{in}}(l)) =$

[5]With Bertrand competition between outside reinsurers, the upper bound converges to K_h. See von Thadden (2004) or Engelbrecht-Wiggans, Milgrom, and Weber (1983).

$q\Pr(K^{\text{out}} = K_h)(K_h - K_l)$ for $K^{\text{in}}(l) = K_h$. For $K^{\text{in}}(l) = K_{pool}$, the low-risk type will always stay with the insider who makes an expected profit of $\Pi^{\text{in}}(K_{pool}) = K_{pool} - K_l$. In a mixed-strategy equilibrium the insider must be indifferent between different $K^{\text{in}}(l)$ given the outsider's strategy. Therefore, it must be the case that $\Pi^{\text{in}}(K^{\text{in}}(l)) = \Pi^{\text{in}}(K_{pool})$ for all $K^{\text{in}} \in [K_{pool}, K_h]$: the outsider's equilibrium strategy must satisfy $\Phi(K) = [K - K_{pool}]/[K - K_l] = q\Omega(K)$ for $K \in [K_{pool}, K_h)$ and $\Phi(K) = 1$ for $K = K_h$.

The densities of the reinsurers' strategies can now be derived by differentiating the CDFs with respect to K, which yields (1) and (2). □

Equation (3)

Assume that the insurer is a low-risk type. Given the premium K, the outsider's expected profit is $\Pi^{\text{out}}(K, l) = (1 - \Omega(K))(K - K_l) = [(1 - q)/q](K_h - K)$, where $\Omega(K)$ is defined in the proof of Proposition 1. Taking the expectation over the choice of K yields $E[\Pi^{\text{out}} | l] = \int_{K_{pool}}^{K_h} \Pi^{\text{out}}(K,l)\phi(K)dK = \frac{(1-q)}{q}(K_{pool} - K_l)\int_{K_{pool}}^{K_h}(K_h - K)\frac{1}{(K-K_l)^2}dK$.

Integration by parts yields

$$E[\Pi^{\text{out}} | l] = \frac{1-q}{q}(K_{pool} - K_l)\left[\left[-\frac{K_h - K}{K - K_l}\right]_{K_{pool}}^{K_h} - \int_{K_{pool}}^{K_h} \frac{1}{K - K_l}dK\right],$$

and using $K_{pool} = qK_l + (1 - q)K_h$, we obtain (3). □

Proof of Proposition 3

We show that the mixed strategies in Proposition 3 constitute a Nash equilibrium.

We first consider the insider's strategy, taking the outsider's and the insurer's strategies as given. $K^{\text{in}}(h) = K_h$ is optimal since $K^{\text{in}}(h) < K_h$ results in an expected loss, and $K^{\text{in}}(h) > K_h$ yields the same expected payoff as $K^{\text{in}}(h) = K_h$, which is zero given the outsider's strategy. $K^{\text{in}}(l) > K_l^{\max}$ is never optimal since a low-risk type will not choose this offer given the separating contract $(\hat{\alpha}_l, \hat{K}_l)$; $K^{\text{in}}(l) < K_{pool}$ is also never optimal since the rent can be increased by increasing $K^{\text{in}}(l)$. Hence, $K^{\text{in}}(l) \in [K_{pool}, K_l^{\max}]$. Given the outsider's strategy $\Phi(K) = [K - K_{pool}]/[K - K_l]$ for $K \in [K_{pool}, K_l^{\max})$, the insider's expected profit is $\Pi^{\text{in}}(K^{\text{in}}(l)) = q[1 - \Phi(K^{\text{in}}(l))](K^{\text{in}}(l) - K_l) = q(K_{pool} - K_l)$ and thus independent of the own offer for any $K^{\text{in}}(l) \in [K_{pool}, K_l^{\max}]$. Therefore, the insider's mixed strategy in the proposition is a best response.

We now consider the outsider's strategy. The separating contract $(\hat{\alpha}_l, \hat{K}_l)$ is weakly optimal as it is not chosen in equilibrium and as it does not negatively affect the outsider's profit. When offering full reinsurance, it is never optimal for the outsider to choose $K \neq K^{\text{out}} \in \{[K_{pool}, K_l^{\max}), K_h\}$: for $K < K_{pool}$, both types accept the contract and the expected indemnity payment exceeds the premium; for $K_l^{\max} \leq K^{\text{out}} < K_h$, only the high-risk type accepts the contract at a premium below the expected indemnity payment. For $K^{\text{out}} = K_h$, $\Pi^{\text{out}}(K^{\text{out}}) = 0$; and for

$K^{out} \in [K_{pool}, K_l^{max})$, $\Pi^{out}(K^{out}) = (1 - \Omega(K^{out}))q(K^{out} - K_l) - (1-q)(K_h - K^{out}) = 0$ given the insider's strategy, $\Omega(K) = [K - K_{pool}]/[q(K - K_l)]$. As a final step we show that it is not optimal for the outsider to replace a full reinsurance offer at a premium $K^{out} \in [K_{pool}, K_l^{max})$ by a set of separating contracts $(\alpha_l^{out}, K_l^{out})$ and K_h^{out} so that (i) a high-risk type chooses K_h^{out} and (ii) a low-risk type is indifferent between K^{out} and $(\alpha_l^{out}, K_l^{out})$. We note that (ii) implies that the probability of attracting a low-risk type is the same for K^{out} and $(\alpha_l^{out}, K_l^{out})$. If it is possible to find a pair of contracts $(\alpha_l^{out}, K_l^{out})$ and K_h^{out} that satisfy (i) and (ii) and for which the outsider is better off than with K^{out}, the outsider can bid more aggressively for a low-risk insurer. However, as we will show, the outsider will be worse off replacing $K^{out} \in [K_{pool}, K_l^{max})$ with separating contracts. Given $(\alpha_l^{out}, K_l^{out})$ and K_h^{out}, the outsider's expected profit is $\Pi_{sep}^{out}(K^{out}) = (1 - \Omega(K^{out}))q(K_l^{out} - (1 - \alpha_l^{out})K_l) - (1-q)(K_h - K_h^{out})$. Thus, a separating contract is optimal if $\Pi_{sep}^{out}(K^{out}) - \Pi^{out}(K^{out}) = (1 - \Omega(K^{out}))q(K_l^{out} + \alpha_l^{out}K_l - K^{out}) - (1 - q)(K^{out} - K_h^{out}) > 0$. (i) requires that $K_l^{out} + \alpha_l^{out}K_h + \alpha_l^{out}\theta p_h B \geq K_h^{out}$, which is binding in equilibrium so that $K_l^{out} + \alpha_l^{out}K_h + \alpha_l^{out}\theta p_h B = K_h^{out}$. (ii) requires that $K_l^{out} + \alpha_l^{out}K_l + \alpha_l^{out}\theta p_l B = K^{out}$. Substituting α_l^{out}, K_l^{out}, and K_h^{out} from (i) and (ii) into $\Pi_{sep}^{out}(K^{out}) - \Pi^{out}(K^{out})$ yields $\Pi_{sep}^{out}(K^{out}) - \Pi^{out}(K^{out}) = -(1 - \Omega(K^{out}))q(\alpha_l^{out}\theta p_l B) + (1-q)\alpha_l^{out}(K_h - K_l + \theta p_h B - \theta p_l B)$. The first term on the right-hand side of the equation represents the negative effect of a separating contract: the expected bankruptcy costs imposed by the retention have to be borne by the outsider to make a low-risk type indifferent. The second term on the right-hand side represents the positive effect of a separating contract: the premium paid by a high-risk type can be increased so that the loss on a high-risk type decreases. The separating contract is optimal if $-(1 - \Omega(K^{out}))q\theta p_l B + (1-q)(K_h - K_l + \theta p_h B - \theta p_l B) > 0$. The left-hand side of the inequality is strictly increasing in $\Omega(K^{out})$, which is strictly increasing in $K^{out} \in [K_{pool}, K_l^{max})$, and $\lim_{K^{out} \to K_l^{max}}(\Pi_{sep}^{out}(K^{out}) - \Pi^{out}(K^{out})) = -\frac{1-q}{q}[\frac{K_h - K_l}{\hat{B}_l} - 1]q\theta p_l B + (1-q)(K_h - K_l + \theta p_h B - \theta p_l B)$. If we substitute $\hat{B}_l \equiv \hat{\alpha}_l \theta p_l B$ and $\hat{\alpha}_l \equiv (K_h - K_l)/(\theta p_h B + K_h - K_l)$, we obtain $\lim_{K^{out} \to K_l^{max}}(\Pi_{sep}^{out}(K^{out}) - \Pi^{out}(K^{out})) = 0$ so that it is not optimal to replace full reinsurance at a premium of $K^{out} \in [K_{pool}, K_l^{max})$ with separating contracts. Indeed, the outsider is strictly better off by offering full reinsurance. Therefore, the outsider's mixed strategy in Proposition 3 is a best response. $\square$

Equation (10)

To derive $\Delta \equiv E[\Pi^{in} | l] + \frac{1}{1-q} E[\Pi^{out} | l]$ for $K_l^{max} > K_{pool}$, we first derive $E[\Pi^{out} | l]$. It is derived in the same way as (3) with the only difference that K_h is replaced by K_l^{max} in the integral. Thus, integration by parts now yields $E[\Pi^{out} | l] = \frac{1-q}{q}(K_{pool} - K_l)[[-\frac{K_h - K}{K - K_l}]_{K_{pool}}^{K_l^{max}} - \int_{K_{pool}}^{K_l^{max}} \frac{1}{K - K_l} dK]$. Using $K_{pool} = qK_l + (1-q)K_h$ and $K_l^{max} = K_l + \hat{B}_l$, we obtain $E[\Pi^{out} | l] = \frac{(1-q)^2}{q}(K_h - K_l)[\frac{q}{(1-q)} - \frac{K_h - K_l}{\hat{B}_l} + 1 + \ln(1 - q) + \ln\frac{K_h - K_l}{\hat{B}_l}]$.

Substituting $E[\Pi^{out} | l]$ and $E[\Pi^{in} | l] = K_{pool} - K_l = (1-q)(K_h - K_l)$ in $E[\Pi^{in} | l] + \frac{1}{1-q} E[\Pi^{out} | l]$ yields the second line in (10). $\square$

Proof of Proposition 4

The proposition is proven by showing that Δ is increasing in θ and X. $\Delta \equiv E[\Pi^{\text{in}}\,|\,l] + \frac{1}{1-q}E[\Pi^{\text{out}}\,|\,l]$ is directly related to the insider's rent and the level of cross-subsidization. An increase in the catastrophic loss X also affects the bankruptcy costs B. For the comparative statics analysis, we replace B by $B(X)$ and assume that $B(X)$ is twice differentiable. Substituting $K_h - K_l = (p_h - p_l)\theta X$ and $\hat{B}_l = \frac{(p_h-p_l)X\theta}{p_h B+(p_h-p_l)X} p_l B(X)$ in (10), yields $\Delta = (p_h - p_l)\theta X \frac{1-q}{q}[q + \frac{1}{1-q} + \ln(1-q) - \frac{p_h B(X)+(p_h-p_l)X}{p_l B(X)} + \ln \frac{p_h B(X)+(p_h-p_l)X}{p_l B(X)}]$ for $K_{pool} - K_l < \hat{B}_l$. Since $\Delta > 0$, we directly obtain $\frac{\partial\Delta}{\partial\theta} > 0$.

$$
\begin{aligned}
\frac{\partial\Delta}{\partial X} &= (p_h - p_l)\theta\frac{1-q}{q}\left[q + \frac{1}{1-q} + \ln(1-q) - \frac{p_h B(X) + (p_h - p_l)X}{p_l B(X)}\right.\\
&\quad \left. +\ \ln\frac{p_h B(X) + (p_h - p_l)X}{p_l B(X)}\right] + (p_h - p_l)\theta X\tfrac{1-q}{q}\left[(p_h - p_l)p_l[B(X) - XB'(X)]\right.\\
&\quad \left.\times\left[-\frac{1}{[p_l B(X)]^2} + \frac{1}{p_l B(X)(p_h B(X) + (p_h - p_l)X)}\right]\right].
\end{aligned}
$$

The first term is positive. Since $[-\frac{1}{[p_l B(X)]^2} + \frac{1}{p_l B(X)(p_h B(X)+(p_h-p_l)X)}] < 0$, a sufficient condition for $\frac{\partial\Delta}{\partial X} > 0$ is $B(X) - XB'(X) \leq 0$, which holds for $\partial B/\partial X > 0$ and $\partial^2 B/\partial X^2 \geq 0$. $\square$

Proof of Proposition 5

Given $K_{cat}^{\max} < K_l^{\max}$, there are three cases: (a) $K_{pool} < K_{cat}^{\max}$; (b) $K_{cat}^{\max} \leq K_{pool} < K_l^{\max}$; (c) $K_l^{\max} \leq K_{pool}$. Since p_i is constant, the likelihood of catastrophic events increases when θ increases and the quality of the cat bond's trigger increases when p_T^l increases. Thus, to prove the proposition, we have to show that (i) $\Delta - \Delta_c > 0$, (ii) $\frac{\partial(\Delta-\Delta_c)}{\partial\theta} > 0$, and (iii) $\frac{\partial(\Delta-\Delta_c)}{\partial p_T^l} > 0$ for all three cases.

For case (a), we obtain $\Delta - \Delta_c = (K_h - K_l)\frac{1-q}{q}[\frac{K_h-K_l}{B_l^{risk}} - \frac{K_h-K_l}{\hat{B}_l} + \ln\frac{B_l^{risk}}{\hat{B}_l}]$. (i) $\Delta - \Delta_c > 0$ since Δ and Δ_c differ only with respect to $\hat{B}_l$ and B_l^{risk} and both terms are increasing in $\hat{B}_l$ and B_l^{risk}; moreover, $\hat{B}_l > B_l^{risk}$ as assumed in the proposition. (ii) Substituting $\hat{B}_l = \frac{(p_h-p_l)X}{p_h B+(p_h-p_l)X}\theta p_l B$, $B_l^{risk} = (p_l - p_T^l)\theta B$, and $K_h - K_l = (p_h - p_l)\theta X$ in $\Delta - \Delta_c$ yields $\Delta - \Delta_c = (p_h - p_l)\theta X\frac{1-q}{q}[\frac{(p_h-p_l)X}{(p_l-p_T^l)B} - \frac{p_h B+(p_h-p_l)X}{p_l B} + \ln\frac{(p_l-p_T^l)(p_h B+(p_h-p_l)X)}{(p_h-p_l)Xp_l}]$. Thus, $\frac{\partial(\Delta-\Delta_c)}{\partial\theta} > 0$ since $\Delta - \Delta_c > 0$. (iii) $\frac{\partial(\Delta-\Delta_c)}{\partial p_T^l} = (p_h - p_l)\theta X\frac{1-q}{q}[\frac{(p_h-p_l)X}{(p_l-p_T^l)^2 B} - \frac{1}{p_l-p_T^l}] > 0$ since $(p_h - p_l)X > (p_l - p_T^l)B$: by assumption, $\hat{B}_l > B_l^{risk}$ and therefore $\frac{p_l B}{p_h B+(p_h-p_l)X}(p_h - p_l)X > (p_l - p_T^l)B$, which implies that $(p_h - p_l)X > (p_l - p_T^l)B$ since $\frac{p_l B}{p_h B+(p_h-p_l)X} < 1$.

For case (b), we obtain $\Delta - \Delta_c = (K_h - K_l)\frac{1-q}{q}[q + \frac{1}{1-q} - \ln\frac{1}{1-q} - \frac{K_h-K_l}{\hat{B}_l} + \ln\frac{K_h-K_l}{\hat{B}_l}] - B_l^{risk}$. (i) $\Delta - \Delta_c > 0$: $(K_h - K_l)\frac{1-q}{q}[q + \frac{1}{1-q} - \ln\frac{1}{1-q} - \frac{K_h-K_l}{\hat{B}_l} + \ln\frac{(K_h-K_l)}{\hat{B}_l}] > B_l^{risk}$ since $\frac{\partial\Delta}{\partial\hat{B}_l} = (K_h - K_l)\frac{1-q}{q}[\frac{K_h-K_l}{\hat{B}_l^2} + \frac{1}{\hat{B}_l}] > 0$ and $\hat{B}_l > K_{pool} - K_l = (1-q)(K_h - K_l)$ for case (b), so that $\Delta > (K_h - K_l)\frac{1-q}{q}[q + \frac{1}{1-q} - \ln\frac{1}{1-q} - \frac{K_h-K_l}{K_{pool}-K_l} + \ln\frac{(K_h-K_l)}{K_{pool}-K_l}] = (1-q)(K_h - K_l) = K_{pool} - K_l$; moreover, $K_{pool} - K_l > B_l^{risk}$, which implies $\Delta - \Delta_c > 0$. (ii) Substituting $\hat{B}_l = \frac{(p_h-p_l)X}{p_hB+(p_h-p_l)X}\theta p_l B$, $B_l^{risk} = (p_l - p_T^l)\theta B$, and $K_h - K_l = (p_h - p_l)\theta X$ in $\Delta - \Delta_c$ yields $\Delta - \Delta_c = (p_h - p_l)\theta X\frac{1-q}{q}[q + \frac{1}{1-q} - \ln\frac{1}{1-q} - \frac{p_hB+(p_h-p_l)X}{p_lB} + \ln\frac{p_hB+(p_h-p_l)X}{p_lB}] - (p_l - p_T^l)\theta B$. Thus, we directly obtain $\frac{\partial(\Delta-\Delta_c)}{\partial\theta} > 0$ since $\Delta - \Delta_c > 0$. (iii) $\frac{\partial(\Delta-\Delta_c)}{\partial p_T^l} = \theta B > 0$.

For case (c), $\Delta - \Delta_c = \hat{B}_l - B_l^{risk}$. (i) $\Delta - \Delta_c > 0$ since $\hat{B}_l > B_l^{risk}$. Using $\hat{B}_l = \frac{(p_h-p_l)X}{p_hB+(p_h-p_l)X}\theta p_l B$ and $B_l^{risk} = (p_l - p_T^l)\,\theta B$, we obtain $\Delta - \Delta_c = \frac{(p_h-p_l)X}{p_hB+(p_h-p_l)X}\theta p_l B - (p_l - p_T^l)\theta B > 0$ and therefore (ii) $\frac{\partial(\Delta-\Delta_c)}{\partial\theta} > 0$ and (iii) $\frac{\partial(\Delta-\Delta_c)}{\partial p_T^l} > 0$. □

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