Pricing in the Primary Market for CAT Bonds: Beyond the Expected Loss

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Abstract

Global losses from extreme events are on the rise. Insurance companies highly rely on the ILS market and especially on CAT bonds to transfer the risk they are exposed to onto investors. However, because CAT bonds are not standardized, it is a challenging question how to price them accurately. With this work I intend to offer a model that is grounded in theory yet also tractable. In order to identify the main determinants of the cat bond spread at issuance I run a series of OLS regressions using a dataset that comprises 1087 CAT bond tranches issued between June 1997 and March 2020. I find evidence that besides expected loss, CAT bond spreads fluctuate in line with the general level of reinsurance premiums and the BB-Spread. Covered territory, sponsoring firm and rating have also a great impact. The pricing model proposed exhibits a robust fit across different calibration subsamples and achieves a higher in-sample and out-of-sample accuracy than several previous specifications.

Key words: CAT bond spread, pricing model, out-of-sample analysis

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1) INTRODUCTION

Over the years, unfortunately, a large number of natural disasters have occurred, including earthquakes, hurricanes, cyclones, tropical storms, etc., which in addition to disastrous social and economic consequences, they also had a dramatic impact on the insurance industry. Indeed, due to the catastrophes of greater scale, the insurance sector, as a whole, has proven to be unable to bear the economic burden resulting from such events. Hurricane Andrew and Hurricane Katrina are just two examples of catastrophes that caused respectively more than $26 and $30 billion of damages. Clearly, a single insurance company could never be capable of supporting the coverage of such amounts of losses on its own; subsequently to Andrew, as even the use of reinsurance did not turn out to be entirely sufficient, nine companies - small and medium sized - have gone bankrupt because they were unable to cope with the large flows of claims that followed events with a high rate of destruction. Therefore, in such a scenario, it was necessary the implementation of an innovative solution to implement better risk management. On the basis of this reasoning a new type of securities deriving from securitization has made its way onto the market of the risks arising from the insurance of catastrophic events: Insurance Linked Securities.

ILS provide access to capital for the insurance industry, which thus finds a viable alternative to the traditional reinsurance, with almost unlimited capital because the possibilities of entry and diversification of investments for investors are countless. The most common category of ILS is that of CAT bonds, which in structure are very similar to common bonds: they offer intermediate coupons and the return of the nominal value at maturity; the innovation is that the actual payout of the promised yield depends on random events: natural catastrophes. It means that, if certain contractually specified conditions occur (such as strong hurricanes or earthquakes), investors may lose a part, or the total amount invested because the capital is employed to cover claims endured by the insurance companies sponsoring the bonds. According to this structure, the pure insurance risk is isolated from other risks such as systemic risk, counterparty risk, credit risk, etc. On the one hand, by retaining the recurring risks and transferring the “HILPs” (high impact low probabilities), insurance companies are able to reduce the problems associated with cyclicality and losses that cannot be systematically modeled. On the other hand, investors are attracted to this type of securities because, in addition to offering diversification for their portfolios, they also provide higher spreads than corporate bonds with similar rating levels. Indeed, CAT bonds are famous for the high yields paid to investors.

The value of the CAT bond spread is assumed to be a percentage of the nominal value of the bond and is influenced by several factors depending on the pricing model taken into account; a constant presence in the models proposed in the literature is that of expected loss[1], which indicates the expected loss on the risk exposure underlying the CAT bond and is therefore an entity not knowable a priori; therefore, the attribution of a value to the spread is necessarily based on estimates. The different pricing models mentioned in this work consider the spread as different functions of the expected loss: the simplest model theorize a linear relation between the expected loss of a catastrophic layer of insurance exposure and the related spread; other types of models, slightly more complex, refer to the conditional expected loss or exhibit non-linear relationship between the spread and the expected loss.

Clearly, the expected loss has already been proven to be the main driver of the CAT bond spread, however it is essential to consider not a stand-alone risk measure, but the overall risk of the portfolio coming from the inclusion of a CAT bond. In fact, in the context of catastrophic risks, it is obvious that the various harmful events occur independently of each other, consequently the CAT Bond yields, that are expressive of different risks, are different and independent of each other. The type of catastrophic risk insured, and the geographical area covered are key elements for the determination of the spread, however there are few studies focused on this direction. One of the main limitations is the scarcity of data as CAT bond transactions are often private and this can also explain why several empirical findings stay in conflict with each other.

The aim of this work is to determine further drivers of the CAT bond spread besides the expected loss using a dataset that comprises 1087 CAT bond tranches issued between June 1997 (the beginning of this market) and March 2020. Once the information was hand-collected and assembled, I ran several OLS regressions and analyzed the performance of different possible model specifications. Initially I included the main characteristics of CAT bonds such as trigger, territory,

[1] The expected loss can be seen as the result of the product between a measure of the severity of the catastrophic event and its estimated probability of occurrence evaluated in terms of frequency.

peril, size, term, expected loss, rating, sponsor, reinsurance cycle, and corporate bonds spread. However, not all of them were significant determinants of the CAT bond spread.

Overall, expected loss is confirmed to be the main driver of cat bond spread at the time of issuance. Nevertheless, other factors are proven to influence the spread at issuance as well. Not surprisingly, CAT bond spread fluctuates in line with the Synthetic Rate on Line Index meaning that it is highly influenced by the general level of the reinsurance premium (or rate-on-line) being paid for ILS. CAT bond spread is also affected by the trend in corporate bonds market with low rating levels; indeed, three out of four CAT bonds issued are speculative-grade. Furthermore, the bond rating judges the quality and creditworthiness of a bond and it is shown to be another driver of the spread. Also, territories covered and sponsoring firms are not to be ignored when pricing CAT bonds. Following Braun (2014), I propose a Multifactor Model which takes into account these factors rather than considering the expected loss as the only driver of CAT bond spreads. Once the main determinants are identified, I assess the robustness of the Multifactor model in several ways.

First of all, I split my dataset into two subsamples referring to different time periods. Results are consistent confirming the validity of the model. In particular, even if the magnitude of the effects of different variables changed in time, the R-squared is always the same: 94%, which, to the best of my knowledge, is the highest value compared to the ones achieved by previous models used in the literature. The other pricing models considered are the following: the first and basic linear model in expected loss; the polynomial model in the natural logarithm of the expected loss; Major and Kreps (2002) model which assumes the spread to be a power function of expected loss; Lane (2000) model that considers the spread to be a sum between the expected loss and the risk load arising from the unexpected loss; and finally the Fermat Capital Management (2005) model that controls for the peril rank. In the in-sample analysis none of these models exhibits a R-squared value even closer to the one achieved by the Multifactor model.

I also include an out-of-sample-analysis, both with an expanding window and rolling window (to account for possible cyclicality) to see how this model would have performed in the past 10 years. Results confirm that Multifactor model performs better than the historical average CAT bond spread. Moreover, an out-of-sample analysis is also conducted in comparison to the aforementioned pricing models using different calibration and test periods. Once again, Multifactor model shows the lowest errors and the highest R-squared values among the others.

The rest of the paper proceeds as follows: Section II describes the primary market and the typical structure of CAT bonds. Section III introduces data, descriptive statistics and the econometric model proposed. In this section I also make a comparison between the performance of different models previously proposed. Once an out-of-sample analysis is carried out to check for robustness, in Section IV I derive the final conclusions.

2) CAT BOND IN THE PRIMARY MARKET

CAT bonds, also known as Catastrophe bonds, are a type of risk-linked security used to transfer a specified set of risks from a sponsor to investors. The sponsor is typically an insurance or reinsurance company seeking to reinsure against catastrophic events like hurricanes or earthquakes that usually occur with low frequency but very high severity in terms of economic consequences. Indeed, the catastrophe bonds market emerged in the '90s from a need by insurance companies to alleviate some of the risks they would face in case a major catastrophe occurred and they would not be able to cover the damages by the invested premiums.

On the other side, investors - which are hedge funds, pension funds or wealthy individuals - are appealed by this type of security for several reasons. First of all, CAT bonds can help to differentiate the risk in the portfolio, as natural disasters do not correlate to stock market moves. Not to case, they are classified alongside CAT options and other derivatives that are used to hedge operational risk. Moreover, they offer high-yield interest payments over the life of the bond and this is even more attractive for investors.

As mentioned, this high-yield debt instrument is designed to raise money for companies in the insurance industry in the event of a natural disaster. A CAT bond allows the issuer to receive funding from the bond only if specific conditions, such as an earthquake or tornado, occur. In other words, if any of the catastrophes covered by the bond happens during the life of the bond, then the bond is said to be triggered and investors may lose part, or the total amount invested. On the other hand, if no catastrophe occurs, they receive high coupons for all the life of the bond and reacquire the principal amount at maturity. One advantage is that, on average, CAT bonds have short maturities of one-to-five years, which reduces – but not excludes - the likelihood of a payout to the insurance company, including loss of principal.

Put in a nutshell, CAT bonds can help to hedge a portfolio against certain types of risk, they offer high-yields and have short maturities. These are the reasons why they appeal to a large and growing pool of investors seeking uncorrelated assets and diversification.

2.1) DEVELOPMENT OF THE CAT BOND PRIMARY MARKET

Catastrophe bonds were first issued in the mid 1990's. The very first catastrophe that spurred the creation of the CAT bond market was Hurricane Andrew in 1992, it was the strongest landfalling hurricane in decades and the costliest one, until it was surpassed by Katrina in 2005.
As illustrated in Figure 1, from 1997 through 2005, CAT bond issuance was steady but low, averaging $1.2 billion annually. The event that made CAT bonds become popular as a means of diversifying risk was Hurricane Katrina that depleted reinsurance capital by $62 billion an cause reinsurance prices to jump.

The fast increase in reinsurance prices attracted significant amounts of capital to the CAT bond market. This influx of capital allowed CAT bond issuers to post consecutive years of record issuance (almost $10 billion in 2007) and it is assumed that the CAT bond market will continue to grow in the future (Cummins and Weiss, 2009). Global losses from extreme events are on the rise. Now more than ever, organizations need to better quantify and manage their catastrophe risk.

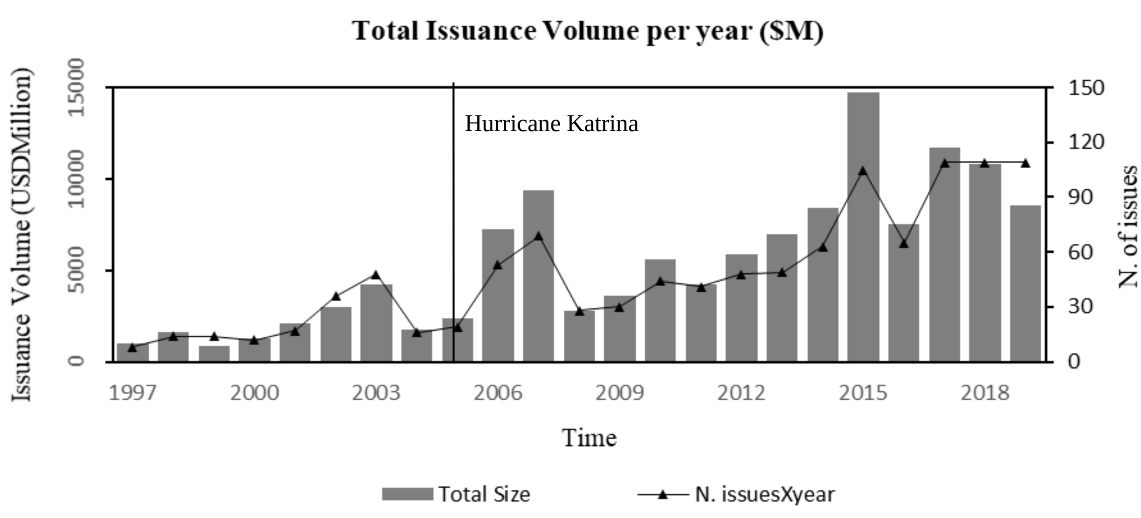

Figure 1: Historical Cat Bond Issuance Volume
The bar chart shows the yearly number of transactions and their aggregated issuance volumes in millions of US

dollars from June 1997 until December 2019. The straight line indicates the most important catastrophe: Hurricane Katrina, that boosted the expansion of the CAT bonds market.

An important condition for successful trading of securities is the determination of accurate prices. However, because CAT bonds are not standardized, it is a challenging question how to price CAT bonds accurately. There can be various factors that influence the risk premium that is required by investors. For instance, it is usually assumed that the chosen trigger mechanism or the peril affect the CAT bond premium. However, in the literature there are only few empirical studies that analyze on relatively small data sets which factors determine the CAT bond premium. This work is focused in this direction and relies on Braun (2014) findings.

The clear majority of pricing models for CAT bonds is based only on the expected loss. Figure 2 shows the average values over time of the CAT bond Spread, expected loss and Multiple[2]. The average BB Spread is included for comparison purpose.

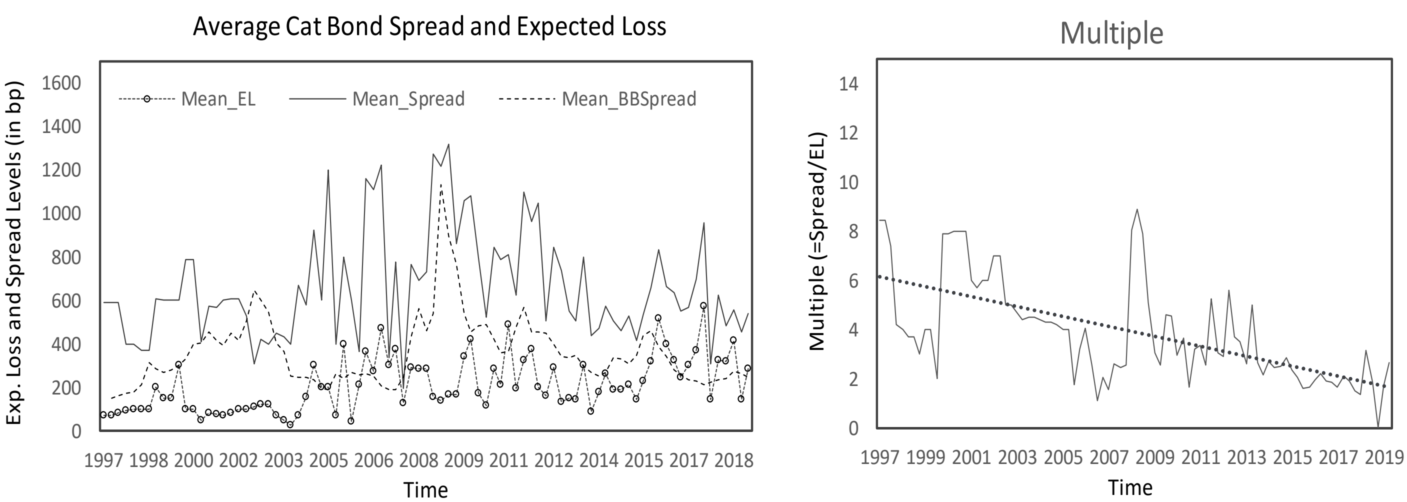

Figure 2: Average Cat Bond Spread, Expected Loss and Multiple over Time
The graph on the left shows the average Cat Bond Spread, expected loss and BB Spread over time, from 1997 until 2019. The graph on the right illustrates the Multiple over the same time period. For this graph, a trendline is included.

In the graph on the left, the most evident peak is reached around 2008/2009, the period following the default of Lehman Brothers that saw a massive surge in corporate bond spreads, while expected

[2] Multiple is the ratio of Spread to Expected Loss and it measures the compensation per unit of expected loss.

losses remained largely stable. This resulted in an increase in Multiple as well. However, it seems that the spreads in the cat bond market remains higher than those in the corporate bond market. In spite of this, Multiple has decreased over time, from an average value of 6 to an average value of 2, meaning that investors receive lowers compensation per unit of expected loss.

2.2) CAT BOND STRUCTURE

One limitation is that CAT bonds are usually issued by a Special Purpose Vehicle (SPV) which needs complex structuring requirements to be set up. However, it is considered to be a guarantee because the SPV is a subsidiary created by a parent company to isolate financial risk. It is also known as bankruptcy-remote entity since its legal status as a separate company makes its obligations secure even if the parent company goes bankrupt. The SPV issues the securities and assumes personally all the obligations arising from the issue, the transferring party is called “sponsoring firm” or just “sponsor” and usually subscribes the entire capital of the SPV. In order to understand the mechanism behind, Figure 1 provides an illustration.

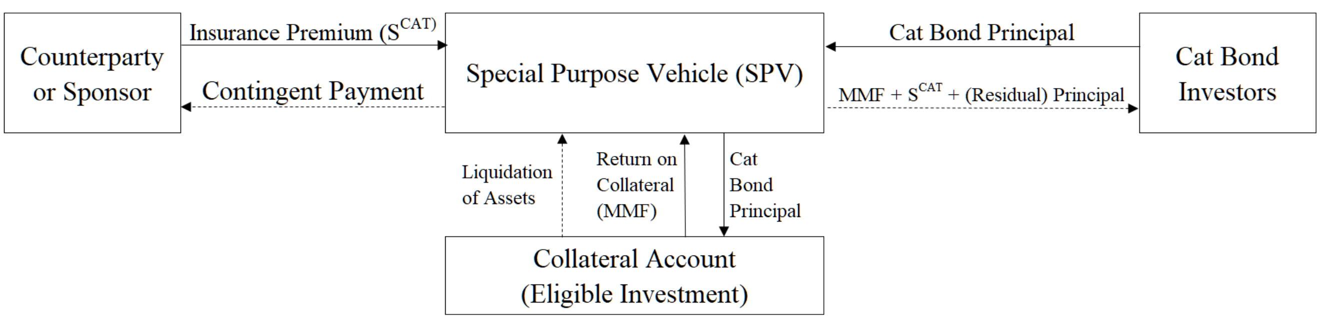

Figure 2: Typical Structure of a Cat Bond transaction
The MMF is the money market fund.

In a typical transaction the sponsor enters into a risk transfer contract with a special purpose vehicle and pays a premium to the SPV as an exchange for coverage. The SPV simultaneously hedges the contract by issuing notes to investors in the capital markets and the proceeds from the notes are then invested in assets to maintain stable value and generate a floating return. Today’s collateral accounts are almost exclusively composed of money market funds that invest in short-term sovereign debt (discount notes), such as US T-Bills, which are extremely secure and highly liquid, with easily observable prices (Braun, 2014). Investors receive a stream of coupon payments that include the insurance premium (the spread of the CAT bond) and the return on collateral; eventually, at maturity, they get the principal back. However, if a pre-defined catastrophic event does occur, they suffer a loss of interest, principal or both. In this case, the principals are released to help the insurer pay claims arising from the event.

The occurrence of a catastrophe is measured by a trigger mechanism that defines the default of the bond. Trigger mechanisms can be separated into indemnity triggers and non-indemnity triggers. The main difference between the two groups is that indemnity triggers are tied to the sponsor's specific losses, while non-indemnity triggers are typically tied to an index or parameter that is outside of the primary insurer's direct control, thus reducing moral hazard. Empirical results, indeed, confirm that in the case of indemnity triggers lax claim handling in the end can exacerbate moral hazard on the side of the insured, who might be more likely to file fraudulent or exaggerated claims (Götze and Gürtler, 2019).

Non-indemnity triggers, instead, seem to mitigate this effect. This type of triggers can further be divided into parametric (index) triggers, industry index triggers, modeled loss triggers and multiple triggers. For example, an "industry index trigger" CAT security links the payout to an index of aggregate losses of the whole insurance sector. "Parametric triggers" securities, instead, link a payout to a physical description of disaster (e.g., intensity of the earthquake). Both trigger mechanisms are, in effect, "instrument variables" for the insurer's losses since they are intended to be highly correlated with the insurer's losses but are outside the insurer's control (Doherty and Smetters, 2002). In this case the sponsor is exposed to the basis risk, which is the risk that the amount of losses borne by him is greater than the compensation from the SPV indicated by the trigger. Thus, there is a trade-off between basis risk and transparency: the triggers, which ensure greater transparency by minimizing moral hazard, involve a greater basis risk for the originator.

Moreover, the natural hazard risk securitized by cat bonds is specified by a combination of covered territory and reference peril. The covered territory refers to the geographic area in which a catastrophe must happen to trigger the bond, while the reference peril indicates the underlying type of disaster the bond is offering coverage for. Today, the most widespread combinations of covered territory and reference peril are U.S. Wind, U.S. Earthquake, Europe Wind, and Japan Earthquake (AON Benfield, 2011).

In order to better quantify and manage the catastrophe risk, firms such as Risk Management

Solutions, AIR Worldwide and EQECAT deliver the risk insights needed, combining science, technology and risk modeling. They use the best-available analytics to structure even the most complex transactions. For each transaction, the probability of a first dollar loss, the probability of a full exhaustion of the principal, and the expected loss are provided. The rating of each cat bond tranche is based on the value of the expected loss, the higher expected loss the lower the rating the agency gives the bond.

The common essence of the risk transfers by CAT securities is to diversify by pooling risks and to reduce the pool's probabilities by layering (Fackler, 2012). Layering means that the aggregate risk of the pool is split by what is called non-proportional risk transfer. For instance, assume the US are to be insured against hurricanes, losses can be as high as 300 (say Million USD). The insurance company is strong enough to cope with losses up to 120, so a capacity of 180 in excess of that is needed. One investor (or reinsurer) may be willing to write the risk but only being able to bear a maximum amount of 20, i.e. the insurance company must find further reinsurance on top of 140. Another investor preferring layers with a quite low probability of loss steps in, agreeing on a 50 in excess of 140 layer but not more. To insure the whole risk a further cover of 110 in excess of 190 is needed, which could be placed with a specialized investor offering large capacities but only accepting layers having an extremely low probability of loss.

Put simply, in this way the risk is split into four parts: the first risk, usually retained (by the sponsor); a low "bottom" layer, which receives a premium every year being a higher percentage of the cover due to the higher probability of loss (there might still be loss free years, however, losses are not exceptional events); an intermediate layer; and finally an extremely unbalanced "top" layer which receive a premium every year and in most years investors will not have to pay anything because the probability of the bond being triggered is low, but for this reason the premium is only a small percentage of the cover, thus investors get a steady return, being however small compared to the cover (= capital at risk). In the very rare case of a loss, in particular if it is a total loss, they will have to pay a high multiple of the annual yield.

According to the data, almost half of the CAT bond notes are issued in multiple tranches.

Table 1 provides an example of a two-tranches CAT bond issuance. The issuer is represented by the Bermuda-based special purpose reinsurer Kilimanjaro Re Ltd. (Series 2014-1) which is sponsored by the Everest Reinsurance Company looking to secure a four-year source of fully-collateralized retrocessional reinsurance protection. Protection is afforded on an industry loss basis, using a PCS index[3] weighted by territory for each peril. Two-hundred and fifty Million USD notes are split into two tranches of equal amount, both providing Everest Re with U.S. named storm and U.S. earthquake protection. They have same maturity, April 2018, and same rating, BB-, provided by S&P.

The Class A tranche of notes has an attachment probability (which is the probability of first dollar loss) of 2.24%, an exhaustion probability of 1.14% and an expected loss of 1.6% and will pay investors a coupon of 4.75% annually. The attachment point for the Class A notes is at an industry index level of $1.4 billion while the exhaustion is at an industry index level of $2.15 billion meaning that investors start to lose their money once the whole insurance sector has already suffered $1.4 billion of losses.

Kilimanjaro Re Ltd. (Series 2014-1) – At a glance:		
Issuer	Kilimanjaro Re Ltd. (Series 2014-1)	
Sponsor	Everest Reinsurance Company	
Risk modeling	AIR Worldwide	
Risk/Perils covered	U.S. named storms, U.S. earthquakes	
Size	$ 250 M	
Trigger Type	Industry loss index	
Class	A	B
Issue Date	Apr-14	Apr-14
Maturity	Apr-18	Apr-18
Size	$125m	$125m
Rating	BB-	BB-
Expected Loss	1.60%	1.46%
Probability of first loss	2.24%	2.18%
Exhaustion Prob.	1.14%	0.94%
Spread	4.75%	4.50%

Table 1: Kilimanjaro Re Ltd. (Series 2014-1), an example of a CAT bond transaction.

The Class B tranche of notes, instead, has lower probability of first loss and of exhaustion because the attachment point is set at an industry index level of $2.15 billion and it exhausts at an index

[3] The PCS is a recognized worldwide authority on property catastrophe losses committed to serving the global insurance and reinsurance industry. It has more than 60 years of experience identifying catastrophes and compiling proprietary catastrophe loss estimates. The PCS Catastrophe Loss Index offers the reliability, consistency, and transparency that issuers of insurance-linked securities need to make smarter decisions with their capital.

level of $2.9 billion. As a result, the expected loss is lower as well (1.46%). Since this tranche of notes results to be less risky than the Class A, it also exhibits a lower premium. This is true because both tranches exhibit the same rating, however it is very common that in multiple-tranches transactions, tranches have different seniority. Senior tranches usually have higher ratings and lower coupons from the rating agencies since the holders of senior tranches have higher priority of being paid. On the other hand, junior tranches have speculative grades, but the higher risk is compensated by larger coupon payments (Egmai and Young, 2007).

3) EMPIRICAL ANALYSIS

3.1) DATA

Cat bond data are difficult to collect due to one of their characteristics: they are often private.
In order to overcome this problem, I combined information from the Artemis Deal Directory and Trade Notes by Lane Financial LLC with market researches and quarterly reports.
I was able to assemble a dataset that comprises 1087 cat bond tranches and, to the best of my knowledge, this is the largest sample to date. The timespan goes from June 1997 to March 2019 and for each transaction I gathered information about the spread, expected loss, probability of first loss and conditional expected loss. Moreover, in order to investigate what really drives the spread, I also hand-collected data about the issue date, size (in USD), term, trigger type, covered territory, reference peril, sponsor and rating. However, observations before 2003 are characterized by a high percentage of missing values.

The Artemis Deal Directory also lists catastrophe bond losses, transactions that have been triggered, paid out or defaulted and those considered at risk of doing so. Of the 1087 issued tranches, only 63 belong to the triggered list and for those ones I compiled the original dataset with information about the cause of loss, the amount of the loss and the date in which the trigger started.

Finally, I completed my dataset adding two more variables which are considered potential environmental cyclical drivers of the cat bond spread: the Synthetic Rate on Line Index (RoL) and the U.S. High Yield BB Option-Adjusted Spread. The former is constructed using data from the insurance-linked security (ILS) and insurance-linked warranty (ILW) market and it is published by Lane Financial LLC on a quarterly basis. It draws on secondary market quotes for all outstanding ILS as well as ILW premiums to measure shifts in catastrophe risk prices; for this reason, it is one of the bellwether benchmarks for the sector, meaning that it provides an approximation of the general level of the reinsurance premium (or rate-on-line) being paid for ILS and cat bond transactions.

The U.S. High Yield BB Option-Adjusted Spread, instead, tracks the performance of US corporate debt which has been rated below investment grade and it has been publicly issued in the US domestic market. This subset includes all securities with a given investment grade rating BB. Since most cat bonds exhibit a BB rating, the U.S. High Yield BB Spread is useful to capture the influence of the corporate bond markets which can be a further driver of the cat bond spread. These data are provided by the Bank of America and are collected on a monthly basis.

Figure 2 provides a graphical historical evolution of these two potential drivers of the cat bond spread.

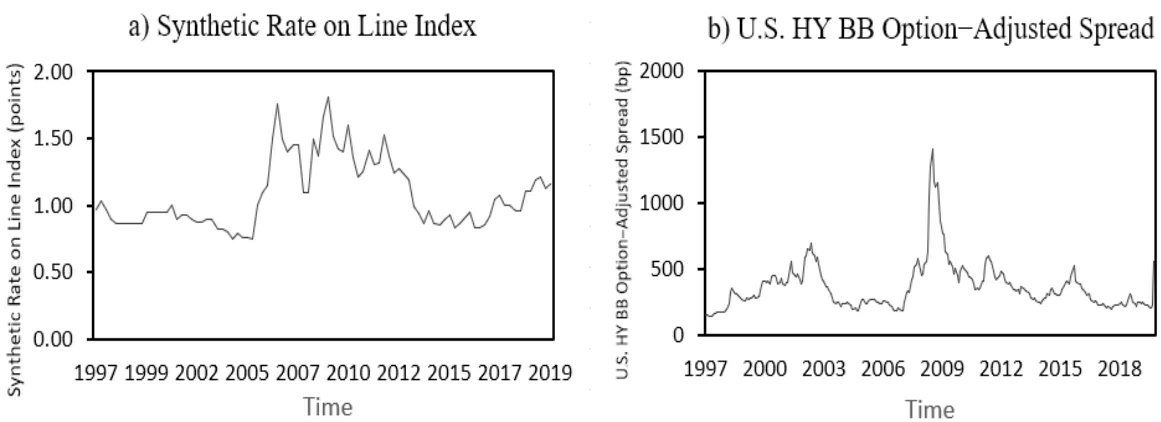

Figure 1: Potential Cyclical Drivers of the Cat Bond Spread

Graph a) represents the historical evolution of the Synthetic RoL Index (measured in points) which captures the general level of the reinsurance premium.

Graph b) represents the historical evolution of the BB Spread (measured in basis points) which captures the influence of the corporate bond markets.

If the Synthetic RoL Index shows values above 1, it should be highly likely to observe higher prices since such values indicate an “hard market”. Indeed, “hard market” periods are characterized by an increase in premiums increase and a decrease in the capacity for most types of insurance.

Historically, hard markets have followed years with significant loss activity resulting in depletion of reinsurance capital. Sometimes this increase is localized to a specific area impacted by loss, while at other times it can raise the cost of reinsurance across the entire market.

3.2) DESCRIPTIVE STATISTICS

Before moving to the descriptive statistics, it is worth to understand that the catastrophe bond spread is a function of the expected loss and the risk premium, as illustrated in Figure 4. The expected loss is the average value of losses over a full range of scenarios, while the risk premium is the required margin by investors. In turn, the risk premium is a function of the peril zone and the expected loss, but it also depends on the trends across year, so called soft and hard markets.

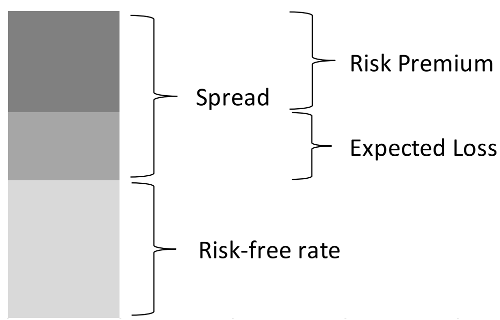

Figure 2: The Cat Bond Spread Composition

It shows that the catastrophe bond spread is a function of the risk premium and the expected loss.

As mentioned before, the dataset comprises 1087 cat bond tranches and Table 2 provides descriptive statistics such as mean, median, standard deviation, maximum and minimum for the key variables. In particular, the average value of the Spread, over the whole sample, is slightly above 700 basis points and it's important to notice that it is quite high compared to the average expected loss, which is almost 250 basis points. This implies that in the cat bond market, on average, investors receive a premium for the risk equal to 4.57% that is almost 1 percentage point higher than the average BB-rated corporate bonds risk premium of 3.67% (measured over the same period).

Looking at the other statistics, such as standard deviation, maximum and minimum of the first three variables it is possible to observe that they change a lot over time: for instance, the minimum value of the Expected Loss is 0.5 basis points, but the maximum reaches a value of 1575bp. Similarly, the risk premium can be as low as 64 bp or as high as 4039 bp. As a consequence, the spread varies a lot as well. According to Table 2, the Spread is, on average, more than 11 times higher than the expected loss. This information is accounted for in the variable Multiple which is nothing more than the quotient of the Spread to Expected Loss.

Furthermore, the size of CAT bonds can go from billions of USD to a few hundred, but on average the amount issued is 113.13 Million USD.

Concerning the maturity, my sample comprises transactions with terms from a minimum of 6 months up to a maximum of 20 years and the maturity can even change if the cat bond is, or might be, triggered; however, on average CAT bonds mature after 42 months, that is three years and a half.

Variable	Mean	Median	Std. Dev.	Max	Min
Spread (bp)	706.52	600.00	498.53	4920.00	65.00
Expected Loss (bp)	249.88	167.00	248.71	1575.00	0.50
Risk Premium (bp)	456.65	420.00	358.71	4039.00	64.00
Multiple	11.62	3.50	42.74	450.00	1.18
Size ($M)	113.13	86.00	112.96	1500.00	0.30
Term (months)	42.03	36.00	31.50	240.00	6.00

Table 2: Descriptive Statistics for the 1087 Cat Bonds in the Sample

It shows the mean, median, standard deviation, maximum and minimum values for the following variables: Spread (basis points), Expected Loss (basis points), Risk Premium (basis points), Multiple, Size (Millions of Dollars) and Term (months). The sample accounts for 1087 cat bond tranches and the timespan goes from June 1997 to March 2020.

These variables are further analyzed in Table 3 where CAT bonds are sorted by territory, peril, trigger, sponsor and rating. I will analyze in detail each category.

Concerning the geographical area, more than half of the total number of CAT bonds covers the US (62.38%), almost one fourth (22.52%) covers multiple territories. These two subcategories are characterized by the highest spreads and risk premiums. This is not a case, indeed the vast majority of risk capital in the cat bond market relates to events on U.S. soil, thus characterizing the country as a peak territory (Braun,2014). Multiterritory (and multiperil) bonds have this characteristic as well: they are appealing because they cover multiple territories (and/or multiple perils) in one transaction, reducing considerably transaction costs. On the contrary, bonds covering territories such as Europe or Japan, which represent respectively the 5.07% and 5.66% of the total number of issues, have the lowest spreads and risk premiums because they are considered to be covering nonpeak territories. This may be due to their scarcity and valuable diversification properties (Braun,2014). The size, instead, seems not to follow any pattern among different territories. Finally, maturity terms are much longer for bonds covering Japan and multiple territories.

Moving to the Peril category, half of the CAT bonds covers against multiple perils, while the other half covers against two perils: 28.91% against wind (including windstorms, hurricanes, tornados, etc.) and 16.67% against earthquake. Wind and Multiperil Bonds exhibit, on average, higher spreads (744.42bp and 848.98bp respectively) and risk premiums (508.94 and 556.35) compared to Earthquake bonds, meaning that investors are willing to take on more risk to obtain higher premiums. Indeed, Earthquake bonds exert lower expected loss as well, maybe due to a lower probability of first loss[4] (PFL). So far, Multiperil and Multiterritory bonds seem to have been the most attractive exhibiting the highest multiples (higher spreads associated with lower expected losses).

Turning to the trigger mechanism, more than half of cat bond issues display an indemnity trigger. According to Dieckmann (2011) CAT bonds using an indemnity trigger should be imposed by investors with a higher risk premium than non-indemnity triggered because of the moral hazard they are subjected to, however table 3 shows they have the lowest spread compared to non-indemnity triggers. It is surprising since they also have the largest size ($128.95M) and longest maturity (52.37 months, almost four and a half years). However, the prevailing risk-return trade-off seems to be particularly attractive for these transactions, since they offer by far the largest average multiple of spread to expected loss (18.08).

Among non-indemnity triggers, Industry Loss and Parametric Index are the most frequent, representing respectively 24.20% and 12.95% of the total number of bonds. Instead, Modeled Loss and Multiple triggers, together, account for less than 10%. Moreover, the latter subcategory is characterized by a very high average spread (almost 1106 bp) and risk premium (702.26 bp).

[4] The probability of first loss (PFL) is the probability of a first dollar loss suffered by the investor, that is the probability of reaching the attachment point that triggers the bond.

Intuitively, Multiple trigger bonds have a higher probability to be triggered compared to single trigger bonds.

	No.	Percent	Spread (in bp)	EL (in bp)	RP (in bp)	Multiple (in bp)	Size ($M)	Term (in months)
Territory								
US	529	62.38	789.99	251.35	553.11	6.45	118.63	29.95
Europe	43	5.07	507.27	201.00	288.93	3.06	112.40	37.58
Japan	48	5.66	282.50	81.93	197.46	7.67	162.05	46.94
Other	37	4.36	596.07	319.96	284.67	2.15	111.24	34.20
Multiterritory	191	22.52	832.11	315.60	524.93	8.71	107.87	42.58
	848	100.00						
Peril								
Wind	222	28.91	744.42	245.35	508.94	4.08	126.00	31.49
Earthquake	128	16.67	435.55	152.39	282.69	5.91	159.58	35.68
Multiperil	418	54.34	848.98	295.77	556.35	8.48	117.92	38.76
	768	100.00						
Trigger								
Indemnity	504	53.50	582.38	208.05	424.26	18.08	128.95	52.37
Industry Loss	228	24.20	855.55	289.26	569.80	4.10	126.20	32.90
Parametric Index	122	12.95	626.41	265.59	367.85	4.04	128.84	37.75
Modeled Loss	37	3.93	742.71	162.45	621.21	6.70	103.48	36.87
Multiple Trigger	51	5.41	1105.98	403.72	702.26	9.97	72.99	32.67
	942	100.00						
Sponsor								
Swiss Re	128	13.96	931.63	317.40	637.35	14.38	73.61	37.94
Other	789	86.04	661.06	240.58	464.20	11.49	136.50	48.83
	917	100.00						
Rating								
High Yield	430	78.00	700.59	177.10	556.01	5.47	120.19	47.70
Investment Grade	121	21.00	332.28	112.18	284.89	91.13	144.08	65.07
	551	100.00						

Table 3: Descriptive Statistics for Different Categories of Cat Bonds in the Sample
Classification of the 1087 cat bonds in the sample, in the period June 1997 – March 2020, according to covered territory, reference peril, trigger type, sponsor, and rating class. For each category the number and percentage of tranches as well as their average spread, expected loss, risk premium, multiple, size, and term are provided. Due to missing values the total number of tranches for each category may differ from 1087.

Concerning the sponsoring firm, out of 1087 tranches, the 13.96% is sponsored by Swiss Re. On average, this subcategory exhibits higher spread, risk premium and multiple compared to bonds sponsored by other companies. The size instead is much lower ($73.61M against $136.50M), possibly due to the firm's increasing usage of shelf offering programs. Since these allow new transactions to be executed quickly whenever required, the volumes of the individual securities tend to be much smaller than those of regular cat bond issues (Braun, 2014).

Furthermore, according to the ratings, the 78% of the total number of issues are low-rated, these tranches are considered to be of speculative-grade, for this reason they have the highest spreads and risk premiums. However, their multiple is very low compared to the Investment Grade subcategory. The latter, indeed, shows a huge multiple (91.13), meaning that the lower spread is more than enough to compensate for the lower expected loss. Consequently, investors of highly rated cat bonds receive a tremendous compensation per unit of expected loss. The less riskiness of this subcategory bonds allows them to be issued with a larger size and longer maturity.

Finally, Table 4 contains statistics about the triggered cat bonds. The total number of triggered tranches from 1997 until March 2020 is 63 which represents mere 5.79% of the total number of issues (1087). Although the sample comprises 63 observations, the list is reduced to 53 due to missing values. According to the table, the amount of losses has been as low as 500 USD and as high as 300 Million USD. This deviation from the mean is due to (i) different original sizes of the bonds and (ii) different percentage of loss, meaning that some bonds are not completely triggered, and the residual principal is devolved to investors. The average percentage of loss is 60.69% of the capital invested. Some investors lost few hundreds of USD, other 300 Million, however the average loss for triggered CAT bonds is 60.60 Million USD.

Table 4 further analyze losses according to the catastrophe. Earthquakes have activated only 4 triggers so far. However, the average amount of loss for this category is more than double ($131.48M) the average loss caused by wind catastrophes ($59.14M); the minimum and maximum values are higher as well. Thus, Earthquake bonds are more severe in terms of loss, but they have a lower probability of being triggered which justifies their lower spreads. Wind bonds, instead, produce lower losses but they are more likely to be triggered and investors require higher premiums to bear this risk.

However, CAT bond market is changing continuously because it is linked to natural events and there is an upward trend of the losses caused by natural catastrophes[5] attributable to weather-related events like storms and flood (Hoeppe, 2016). In particular, catastrophes in 2017 and 2018 have

[5] In the Appendix, Table 10 is provided. It contains information about the number of triggered CAT bond tranches by year and by the natural catastrophe that activated the trigger.

activated almost 40 triggers in total and the vast majority was caused by hurricanes or tornados, while until 2016 only few losses have been suffered. Monitoring these changes can help to predict investors' preferences and to price accordingly.

Variable	Obs	Mean	Std. Dev.	Min	Max
Loss in $M	53	60.06	57.60	0.50	300.00
Loss in % (of the original Size)	53	60.69%	0.38	0.72%	100.00%
Loss($M) caused by:					
Wind	37	59.14	44.57	1.04	200.00
Earthquake	4	131.48	125.45	15.90	300.00

Table 4: Triggered Cat Bonds Descriptive Statistics

The table shows the number of observations, the mean, standard deviation, minimum and maximum for the size of the loss (in USD and in percentage of the original size). The bottom part of the table analyzes the loss (in USD) according to its cause: wind and earthquake. These data are drawn from a sample of 53 triggered bonds from June 1997 to March 2020.

3.3) METHODOLOGY: THE PRICING MODEL FOR CAT BONDS

Although there are different modeling approaches for CAT bond premiums in the literature, several empirical findings remain in conflict with each other. I would say the main reason is that most of the empirical analyses is based on rather small samples. The contribution of my work points exactly in this direction: the dataset I used is the largest sample to date and can provide more reliable results. Moreover, besides expected loss, which has already been proven to be the main driver of the CAT bond spread, my focus is to identify further cat bond spread determinants at issuance. Indeed, according to the descriptive statistics presented in the Section 3.2, there might be other factors influencing CAT bond spreads.

In particular, the following hypotheses are derived:

a) The size of the bond may influence the magnitude of the spread. At a first glance, investors purchasing CAT bonds with bigger size may incur in higher losses in case the bond is triggered and may feel necessity for a higher premium. Moreover, according to previous studies, a larger size of deal may require a bigger number of investors and therefore a higher reward as more investors need to be satisfied by the price (Papachristou, 2011). However, I assume this effect is mitigated by the fact that each tranche is priced independently and thus, I agree with the hypothesis that investors might require *lower* yields to maturity for *larger* issue volumes since transaction costs decrease significantly with trade size (Edwards et al., 2007). According to these considerations, I propose the following first hypothesis:

H1: *The spread of a cat bond issue decreases with its size.*

b) Moreover, in line with the liquidity preference theory, an investor should demand a higher premium on securities with long-term maturities that carry greater risk because, all other factors being equal, investors prefer cash or other highly liquid holdings. This consideration leads me to the following second hypothesis:

H2: *Cat bond spreads increase with the term of the security.*

c) As I already stated, typically, the default of a CAT bond is measured by a trigger mechanism. In the case of indemnity triggers, investors face more information asymmetries in terms of moral hazard compared to non-indemnity triggers and may ask for higher premium. Additionally, the rating process takes longer compared to other trigger mechanisms and a more detailed risk analysis is necessary resulting in a longer preparation phase. Empirical evidence has indeed shown that indemnity triggered CAT bonds are imposed with an additional premium (Dieckmann, 2011). However, this result was based on a small sample and it is interesting to assess whether it still holds.

H3: *Spreads are higher for indemnity trigger CAT bonds.*

d) Turning to the covered territory and the reference peril, descriptive statistics display higher spreads for peak territories (i.e., US, Multiterritory) and peak perils (i.e., wind and earthquake) and even higher spreads for bonds combining the two. In comparison to them, risk loads for non-peak zones and non-peak perils have been significantly lower, reflecting their diversifying nature in a cat bond portfolio (Papachristou, 2001). Moreover, bonds covering for hurricanes in the US or typhoons in Japan are perceived to be riskier because these catastrophic events are quite common. As a result, the likelihood that the bond may be triggered is higher and investors may require higher premium for bearing this risk. Thus, I formulate the following hypothesis:

H4: *Spreads are higher for CAT bonds covering peak territories and/or peak perils.*

e) Another feature worth analyzing is the company that sponsors the cat bonds. In fact, investors may ask for a higher premium if they have concerns about a possible credit risk in the structure of the cat bond. Since Swiss Re Company has sponsored almost 15% of all cat bond issues, one might think that the company's credibility is well-established and therefore investors may demand a lower spread for bonds sponsored by Swiss Re.

H5: *CAT bonds sponsored by Swiss Re exhibit lower spreads.*

f) Besides the credibility of the sponsoring firm, investors can claim a higher premium if the bond has a low rating. Ratings, indeed, offer information about the quality of the bond (Ciumaş and Coca, 2015) and this suggests the following hypothesis:

H6: *The higher the rating class of a cat bond, the lower its spread.*

g) Finally, as aforementioned, spreads can be highly influenced by factors not directly related to the bond issuance but linked to market trends. According to this, all other factors being equal, CAT bond spreads can be higher in periods of "hard market" and lower in periods of "soft market" (Cummins and Weiss, 2009). Thus, if the RoL Index provides an approximation of the general level of the reinsurance premium, I expect to find a positive relationship between the Synthetic Rate on Line Index and the CAT bond spreads. Consistently, since most cat bonds exhibit a BB rating and the U.S. High Yield BB Spread captures the influence of the market of corporate bond rated below investment grade, I further expect to find higher spreads associated with a higher level of premiums in the corporate bond market. The following two hypotheses are then derived:

H7: *CAT bond spreads fluctuate in line with the reinsurance underwriting cycle.*

H8: *Corporate bond spreads exert a positive influence on cat bond spreads.*

My analysis is based on the OLS regression methodology because, according to previous researches, linear models are the most accurate ones to explain primary market cat bond spreads (Galeotti et al., 2012).

To test the above-mentioned hypotheses, I propose the following model:

$$S_i^{CAT} = \alpha + \beta_1 EL_i + \beta_2 SIZE_i + \beta_3 TERM_i + \beta_4 INDEM_i + \beta_5 WIND_i + \beta_6 EQ_i$$
$$+ \beta_7 MT_i + \beta_8 US_i + \beta_9 EU_i + \beta_{10} JP_i + \beta_{11} US_i \text{ x } WIND_i + \beta_{12} US_i \text{ x } EQ_i$$
$$+ \beta_{13} EU_i \text{ x } WIND_i + \beta_{14} JP_i \text{ x } EQ_i + \beta_{15} SR_i + \beta_{16} ROL_i + \beta_{17} IG_i + \beta_{18} BBSPR_i + \varepsilon_i$$

where S_i^{CAT} is the observed spread for each CAT bond tranche measured in basis points (bp); EL is the expected loss measured in percentage points (pp); SIZE refers to the volume issued and it is measured in Millions of USD; TERM refers to the maturity of the bond and is measured in months;

INDEM is a dummy variable that takes value equal to 1 if the transaction refers to an indemnity-trigger CAT bond, 0 otherwise; WIND, EQ, MT, US, EU, JP are dummy variables as well, referring to the perils and the territories covered by the bond. In particular WIND and EQ equal 1 respectively if the CAT bond covers against wind perils (such as hurricanes, tornados, typhoons, windstorm) and earthquake perils; if both are equal to 0, then the transaction refers to a multiperil bond. The variables MT, US, EU and JP, instead, take value of 1 respectively if the CAT bond covers multiple territories, the US, Europe and Japan. If none of these variables equals one, then the bond relates to another geographic area (e.g., Mexico). In the same way, SR is another dummy variable included to test hypothesis 5 (H5); it equals 1 if the cat bond is sponsored by Swiss Re, 0 otherwise. The last dummy variable included in the model is IG; it takes value of 1 for investment-grade and zero for high-yield rating bonds. Investment-grade bonds are those rated from AAA to BBB- and high-yield bonds from BB+ to D. The last mentioned are in fact speculative-grade transactions and should exhibit higher spreads. Finally, ROL and BBSPR are the two possible environmental cyclical drivers, respectively the Synthetic Rate on Line Index (measured in points) and the U.S. High Yield BB Spread (measured in percentage points).

I ran several linear regressions and Table 5 provides the results for three models. In the first model I included all the variables, but few of them were significant. This can be due to a problem of overfitting, that’s why I finally decided to keep only the most relevant ones. Specifically, from Model 1 to 3 I proceeded removing the insignificant variables in order to derive a reliable pricing model.

In particular, the first three hypotheses (H1, H2, H3) need to be rejected since the size, the term and the indemnity trigger seem not to be significant drivers of the CAT bond spread, even if I reduce regressors in the estimation. In addition, their coefficients are not large so that their effect is economically insignificant, too. Regarding the trigger, in neither model specification there is a significant influence of the dummy variable INDEM, this result goes against previous findings (Dieckmann, 2011; Cummins and Weiss, 2009). According to them, bonds with indemnity triggers have higher premiums and are less traded compared to CAT bonds with non-indemnity trigger mechanisms. However, my dataset includes much more observations confirming that more than half of the CAT bond issues exhibit an indemnity trigger and those bonds are the ones having lower premiums, on average, compared to non-indemnity trigger bonds. This result raises the question as to why moral hazard is not consistently priced by investors on the CAT bond market. Three possible reasons can be identified. First, it is difficult to identify moral hazard in a particular CAT bond transaction, mainly because it depends on company characteristics (e.g., size). Second, most CAT bonds are used to insure tail risks, meaning that a large share of risk in the insurance portfolio is retained by the sponsor, thus the consequences for investors may be limited in many cases. Third, this outcome can be attributed to the ongoing development of the CAT bond market, which is continuously evolving. Investors, today, may not require a higher premium for indemnity trigger mechanisms since the moral hazard may be mitigated by the perceived credibility investors have of the sponsoring firms and a risk sharing pricing structure.

Moving to hypothesis 4 (H4), it is possible to notice from the table that perils do not impact on the CAT bond spread but territories do. Even though earthquake catastrophes have caused higher losses, the coefficient is negative because these events are less frequent. Anyway, none of the two variables referring to the perils covered is significant, suggesting that investors do not care about what peril the CAT bond is covering for, rather they care about the regions covered. The variables US and MT not to case, have a strong positive significant impact on the price of the bonds. Investors, in fact, require higher premiums because of the higher risk exposure: the US are the country most affected by catastrophes (also due to its extension) and the probability of such events is much higher if the bond covers multiple territories. It seems that risks which occur in larger numbers are perceived to be less valuable for the diversification (Braun, 2014), thus require higher premiums. Contrarily, I do not find any significant predictive power of the interaction terms.

Furthermore, considering Model 3, the SR coefficient is significant at 1% (sign. level) and this confirms the hypothesis 5 (H5) that sponsoring firms with a good reputation can benefit from a reduction in premiums they have to pay. In particular, if the CAT bond is sponsored by Swiss Re Company, the spread decreases by almost 39 basis point, all other factors being equal.

	Model 1			Model 2			Model 3		
	Coef.	P-val.	Sig.	Coef.	P.val	Sig.	Coef.	P.val	Sig.
Intercept	-396.72	0.037	**	-638.95	0.000	***	-623.60	0.000	***
Expected Loss	158.85	0.000	***	178.20	0.000	***	177.41	0.000	***
Size	-0.03	0.867		0.08	0.357				
Term	-1.73	0.247							
Indemnity	23.73	0.522		-0.42	0.986				
Wind	37.72	0.813							
Earthquake	-120.51	0.314		-80.48	0.126				
Multiterritory	221.30	0.147		147.19	0.000	***	175.75	0.000	***
US	242.10	0.037	**	239.69	0.000	***	264.77	0.000	***
Europe	-103.68	0.400							
Japan	-21.71	0.928							
USxWind	-93.59	0.574							
USxEarthquake	40.70	0.758							
EuropexWind	120.00	0.600							
JapanxEarthquake	210.54	0.363							
Swiss Re	3.26	0.950		-14.88	0.061	*	-38.78	0.007	***
RoL Index	471.26	0.000	***	543.82	0.000	***	522.74	0.000	***
Investment Grade	-107.16	0.006	***	-142.29	0.001	***	-134.87	0.001	***
BB Spread	16.76	0.011	**	38.12	0.000	***	37.61	0.000	***
df	123			259			270		
SEE	245.46			220.81			200.76		
Adj - R^2	0.71			0.7615			0.76		
White's Test	83.71	0.458		108.37	0.000	***	23.86	0.778	

Table 5: CAT Bond Spread Determinants – Proposed Models N° 1,2,3
The table represent the coefficients (Coef.), p-values (P-val.) and significance (Sig.) of possible CAT bond spread drivers for different models. The sample considered includes all the available data of the 1087 CAT bond tranches issued from June 1997 until March 2020. (*=10%, **=5%, ***=1% level of significance).

Turning to hypothesis 6 (H6), it is confirmed as well: bonds with high ratings are perceived to be less risky and thus exhibit lower spreads. The coefficient of the variable IG (which stands for "Investment Grade") is significant in all three model specifications at 1% level and its economic effect is significant as well: if CAT bonds are investment grade, their spreads is lowered by almost 135 basis points. However, the largest effect on the spread is captured by the RoL Index, meaning that CAT bond prices are highly influenced by market trends, the so-called "hard" and "soft" market. Indeed, an increase in the RoL Index by 1 point causes an increase in the CAT bond spread by more than 5 percentage points. Thus, hypothesis 7 (H7) is accepted. However, the magnitude of this effect is further analyzed in Table 6.

Finally, the CAT spread is not only affected by the general level of the reinsurance premium, rather it is influenced by the corporate bond markets as well, confirming hypothesis 8 (H8).

Lastly, the Expected Loss and the Intercept are significant in all model specifications. If, on the one hand the expected loss is confirmed to be a significant driver of the spread, on the other hand the intercept does not have any economic significance. According to these considerations, I also analyzed different model specifications presented in Table 6. I kept the significant variables, grouping together the US or multiple geographic areas as peak territories, and I deleted the intercept term.

	Model 4			**Model 5**			**Model 6**		
	Coef.	P-val.	Sig.	Coef.	P-val.	Sig.	Coef.	P-val.	Sig.
Expected Loss	157.85	0.000	***				156.29	0.000	***
Peak Territory	135.13	0.000	***	223.06	0.000	***	144.80	0.000	***
Swiss Re	-61.69	0.065	*	-8.61	0.855				
RoL Index	172.92	0.000	***	279.66	0.000	***	163.98	0.000	***
Investment Grade	-221.52	0.000	***	-204.86	0.000	***	-233.30	0.000	***
BB Spread	34.09	0.000	***	45.94	0.000	***	33.58	0.000	***
df	274			286			284		
Adj - R^2	0.94			0.86			0.94		
White's Test	32.54	0.114		18.69	0.346		32.76	0.018	**

Table 6: CAT Bond Spread Determinants – Proposed Models N° 4,5,6

The table represent the coefficients (Coef.), p-values (P-val.) and significance level (Sig.) for different model specifications. Model 4 includes all the significant variables, Model 5 does not account for the expected loss, Model 6 does not include the dummy Swiss Re. Degrees of freedom, adjusted R-squared and White’s Test performance are provided. (* = 10%, ** = 5%, ***=1%)

According to the table, Model 4 seems to be the best among the others, with an R-squared of 94%. In Model 5 I tried to delete the variable Expected Loss, but it resulted in notable sacrifice of explanatory power of the model (ΔR^2= -8%), confirming the expected loss to be undoubtedly one of the most important drivers of CAT bond spreads. In Model 6, instead, I didn’t consider the variable Swiss Re, the explanatory power of the model didn’t change, however coefficients of the other variables were modified resulting in a misleading estimation. Similar considerations are derived if, one by one, the other regressors are omitted (Table 11 with relative results is provided in the Appendix).

In conclusion, I ultimately suggest the following econometric pricing model[6] for cat bonds in the primary market (which refers to Model 4):

$$S_i^{CAT} = \beta_1\, EL_i + \beta_2\, PEAK + \beta_3\, SR_i + \beta_4\, ROL_i + \beta_5\, IG_i + \beta_6\, BBSPR_i + \varepsilon_i$$

It has an adjusted-R^2 equal to 94% and it is homoscedastic. The expected loss, the RoL Index and the rating class are the main drivers of CAT bond spreads. In particular, an increase by 1 percentage points in the expected loss causes an increase by almost 1.58 percentage points in the spread, while the premium is lowered by 2.22 percentage points if the bond exerts a high rating. The spread is lowered even in the case the bond is sponsored by Swiss Re company, but in a different extent (it decreases by 0.62 percentage points). Furthermore, according to the model, bonds covering peak territories should exhibit spreads increased by 1.35 percentage points, all other factors being equal. Finally, ROL and BBSPR coefficient confirm the environmental cyclical trends to be important drivers. The Synthetic Rate on Line Index, in particular, presents the highest coefficient, meaning that CAT bond spreads are highly affected by soft and hard market trends.

These results are in line with previous findings (Braun, 2014). Braun was the pioneer of this model, however, as time has passed by, the magnitudes of the effects of the different variables have changed. This justifies my choice to include robustness checks with regard to subsamples for different time periods. In particular the full sample was split into two, the first subsample goes from June 1997 until December 2009. The second one, instead, starts in January 2010 and goes until March 2020.

The effects of all variables, considered in absolute errors, have decreased over time. Whereas, the magnitude of the RoL Index coefficient has increased significantly. It demonstrates how soft and hard market trends result to be the main driver of the CAT bond spread today.

[6] This pricing model was already proposed by Braun (2014) and my work includes additional data that still confirm its validity.

	Full Time Period			6/1997 - 12/2009			1/2010 - 03/2020		
	Coef.	P-val.	Sig.	Coef.	P-val.	Sig.	Coef.	P-val.	Sig.
Expected Loss	157.8502	0.000	***	173.18	0.000	***	157.45	0.000	***
Peak Territory	135.1295	0.000	***	189.39	0.029	***	133.05	0.003	***
Swiss Re	-61.6903	0.065	*	-169.52	0.005	***	-43.91	0.022	**
RoL Index	172.9199	0.000	***	170.97	0.052	*	234.26	0.009	***
Investment Grade	-221.519	0.000	***	-274.27	0.010	***	-182.47	0.001	***
BB Spread	34.08794	0.000	***	34.07	0.000	***	18.86	0.041	**
df	274			116			158		
Adj - R^2	0.94			0.94			0.94		
White's Test	32.54	0.114		30.25	0.142		10.41	0.988	

Table 7: Robustness with Regard to Subsamples for Different Time Periods

The table provides coefficients, P-values and significance levels (*=10%, **=5% and ***=1%) for the same model (Model 4), estimated firstly for the whole sample and then for two subsamples.

3.4) COMPARISON WITH PREVIOUS MODELS

There exist several modeling approaches for CAT bond premiums in the literature, however none of them seem to perform better than the model just proposed. Both an in sample and out-of-sample performance are conducted to compare the different alternative specifications with the proposed model and the latter (which will be referred to as “Multifactor (2014)”) achieves better R-squared in both performances.

The alternative previous models are the following:

a) The first and basic one is a linear model in expected loss:

$$S_i^{CAT} = \alpha + \beta \, EL_i$$

b) Subsequently a polynomial model in the natural logarithm of the expected loss was proposed:

$$S_i^{CAT} = \alpha + \beta \ln(EL_i) + \gamma \ln(EL_i)^2$$

c) Then, Lane (2000) presented the framework of pricing CAT bonds with the financial approach: the 3-parameter model:

$$S_i^{CAT} = EL_i + \alpha \, PFL_i^{\beta} \, CEL_i^{\gamma}$$

Where the spread is the sum of the expected losses (EL), which represent the investor’s compensation for his expected losses, and the risk load which is also the unexpected loss. The author further decomposes the unexpected loss component of the spread as the expected excess return (EER). The EER is a Cobb-Douglas function type of the conditional expected losses (CEL), which capture the asymmetrical nature of the losses, and the probability of first loss (PFL).

d) Similarly, Major and Kreps (2002) model assumes the spread to be a power function of expected loss:

$$S_i^{CAT} = \alpha \, EL_i^{\beta}$$

e) Finally, Fermat Capital Management (2005) proposed the following model specification:

$$S_i^{CAT} = EL_i + \lambda \sqrt{\frac{EL_i(1 - EL_i)}{\xi_i}}$$

where λ is the Sharpe Ratio, according to Fermat Capital Management and ξ_i is the "peril rank" (or catastrophe risk weight). The introduction of ξ_i allows to capture the diversification phenomenon on the market through the model (Gatumel and Guegan, 2008). For example, the Florida hurricanes are certainly the more important risk in terms of insurance exposure: so, ξ_i equals 1 for the issues covering this risk. If the European windstorm is the sixth exposure, ξ_i equals 6. Hence, the higher is ξ_i, the higher will be the market price of risk.

3.4.1) In Sample Analysis

Table 8 provides the estimated coefficients and relative P-values for the five alternative model specifications and the latest proposed model (Multifactor). Results are based on the in sample analysis including all the available data from June 1997 until March 2020 about CAT bond transactions.

Figure 5 provides a graphic representation of the aforementioned approaches.
Out of all the models considered, Multifactor presents the best in sample fit with the lowest Standard Error of the Estimates (200.76) and the highest R-squared (94%) compared to the other specifications that consider the expected loss to be the only driver of the spread. Furthermore, White's test has been employed as heteroskedasticity diagnostics: Lane (2000) and Multifactor are the only two models in which it is possible *not* to reject the null hypothesis of homoskedasticity in variances in the errors, confirming the validity of the latest model.

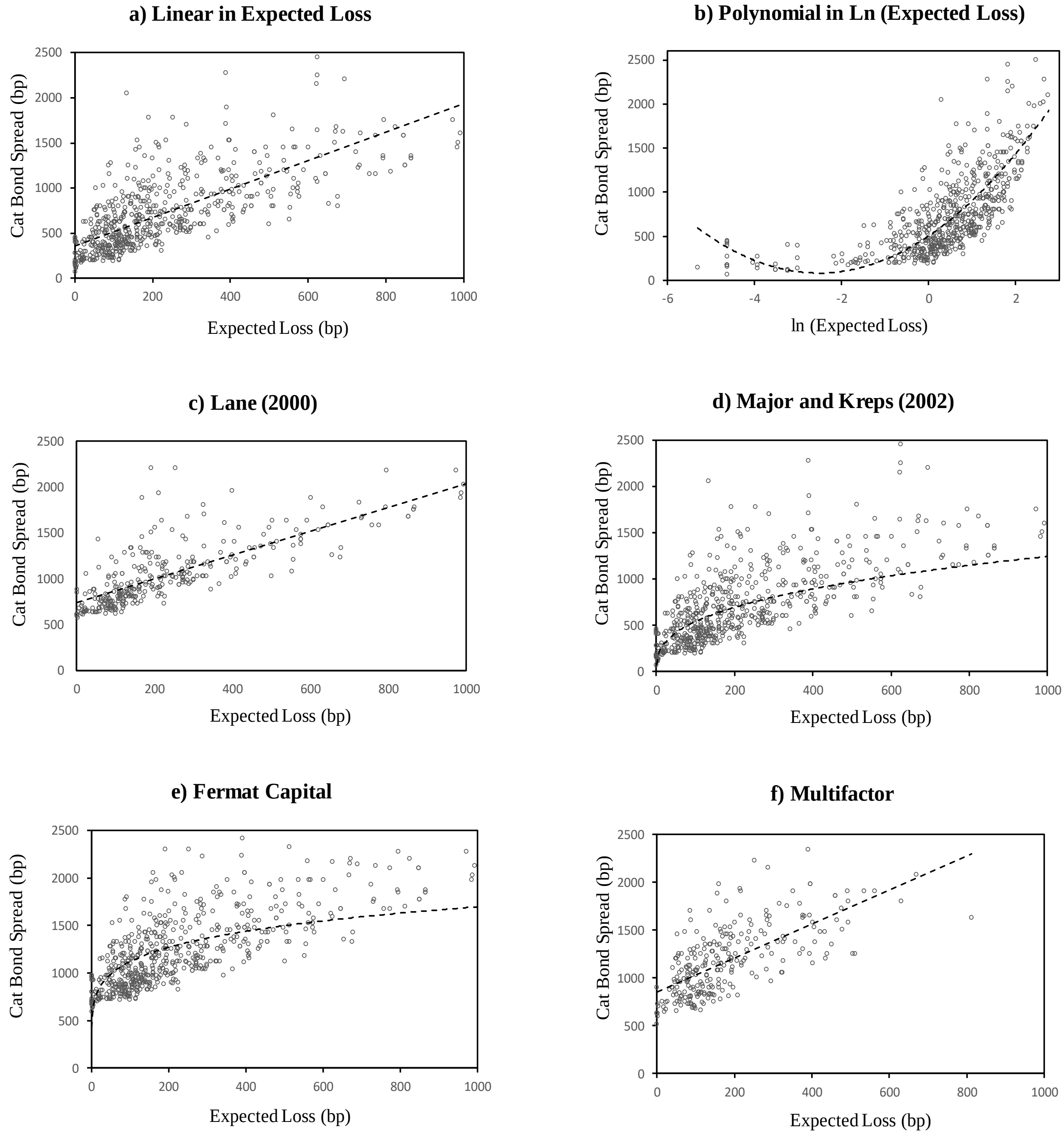

Figure 3: In Sample Fit Graphic Illustration of all Fitted Models

The graphs represent the in sample fit of all models proposed. They have been estimated by means of OLS on the sample of 1087 CAT bond tranches issued from June 1997 to March 2020. The dashed lines represent the predicted values of the spread for different magnitudes of the expected loss (in basis points). To provide a graphical representation in a two-dimension graph, all variables besides the Spread and the Expected Loss are set to their sample mean.

	Linear in EL			Polynomial in Ln(EL)			Lane (2000)			Major/Kreps (2002)			Fermat Capital			Multifactor			
	Coeff.	P-val.	Sig.	Coeff.	P-val.	Sig.	Coeff.	P-val.	Sig.	Coeff.	P-val.	Sig.	Coeff.	P-val.	Sig.		Coeff.	P-val	Sig.
α	358.62	0.000	***	504.48	0.000	***	125.8	0.000	***	539.848	0.000	***				β_1	157.9	0.000	***
β	157.52	0.000	***	334.05	0.000	***	0.184	0.000	***	0.36255	0.000	***				β_2	135.1	0.000	***
γ				66.26	0.000	***	0.081	0.18								β_3	-61.69	0.065	*
λ													53.05	0.000	***	β_4	172.9	0.000	***
																β_5	-221.5	0.000	***
																β_6	34.09	0.000	***
df	616			615			327			615			616				274		
SEE	330.05			342.76			461.63			373.83			466.97				200.76		
Adjusted R^2	0.58			0.54			0.16			0.56			0.70				0.94		
White's Test	23.78	0.000	***	35.21	0.000	***	2.19	0.823		60.31	0.000	***	27.17	0.000	***		32.54	0.114	

Table 8: In Sample Fit of different model specifications.

This table includes the standardized coefficients, P-values and significance levels (* = 10%, ** = 5%, ***=1%) of six alternative pricing models for CAT bonds. Last model refers to the one proposed with this work. Degrees of freedom, Standard Error of the Estimates and Adjusted R^2 are provided as well. White's test has been employed as heteroskedasticity diagnostics.

However, an out-of-sample analysis is required to exclude the overfitting problem, meaning that the Multifactor function may be too closely fit to a limited set of data points. Overfitting the model, indeed, generally takes the form of making an overly complex model to explain idiosyncrasies in the data under study.

3.4.2) Out-of-Sample Analysis

A good way to test the assumptions of a model and to realistically compare its forecasting performance against other models is to perform out-of-sample validation, which means to withhold some of the sample data from the model identification and estimation process, then use the model to make predictions for the hold-out data in order to see how accurate they are and to determine whether the statistics of their errors are similar to those that the model made within the sample of data that was fitted.

The out-of-sample analysis for the Multifactor model is conducted in comparison with the previously considered alternatives.

Table 9 shows the results of the following common out-of-sample performance measures for three different calibration and test periods:

- Mean Error (ME):

(1) $$\text{ME} = \frac{1}{N'} \sum_{i=1}^{N'} \left(S_i^{CAT} - \hat{S}_i^{CAT} \right)$$

- Mean Absolute Error (MAE):

(2) $$\text{MAE} = \frac{1}{N'} \sum_{i=1}^{N'} \left| S_i^{CAT} - \hat{S}_i^{CAT} \right|$$

- Root mean square error (RMSE):

(3) $$\text{RMSE} = \sqrt{\frac{1}{N'} \sum_{i=1}^{N'} \left(S_i^{CAT} - \hat{S}_i^{CAT} \right)^2}$$

- Out-of-sample R-squared (R_{OS}^2):

(4) $$R_{OS}^2 = 1 - \frac{\sum_{i=1}^{N'} \left(S_i^{CAT} - \hat{S}_i^{CAT} \right)^2}{\sum_{i=1}^{N'} \left(S_i^{CAT} - \bar{S}_i^{CAT} \right)^2}$$

Where $\bar{S}_i^{CAT} = \bar{S}^{CAT}$ equals the historical average spread in the calibration sample[7], while N' refers to the number of observations in the test sample[8]. Finally, S_i^{CAT} is the observed spread of transaction i and $\hat{S}_i^{CAT}$ represents the spread generated by the pricing model.

Table 9 contains results of the ME, MAE, RMSE and R_{OS}^2 according to equations (1) through (4). Results are divided into three panels referring to the different calibration and test periods. Specifically, Panel A estimates the parameters of the model on a subsample that goes from June 1997 until December 2009, forecasts are then run from the beginning of 2010 until March 2020. In panel B, instead, the test sample starts in January 2014 and finally, panel C uses all the available data until December 2015 to test if the model would have worked well in the last 4 years. Once again, Multifactor model shows the best performance: it exhibits the lowest ME, MAE and RMSE and the highest R_{OS}^2 among all model specifications and throughout different calibration and test samples.

[7] The calibration sample refers to the part of data used to estimate the parameters of the model.
[8] The test sample is made of the remaining transactions priced with the parameters deriving from the calibration sample.

	Multifactor	Linear in EL	Polynomial in Ln(EL)	Lane (2000)	Major/Kreps (2002)	Fermat Capital
Panel A: Calibration Sample: 06/1997–12/2009 (N = 163); Test Sample: 01/2010 – 03/2020 (N′ = 453)						
ME	-105.45	-278.32	-328.00	180.80	-209.66	-37.80
MAE	183.61	333.08	378.86	250.86	278.22	197.51
RMSE	216.79	418.52	447.26	385.12	325.16	243.17
R^2 *OS*	0.58	0.14	0.01	0.09	0.48	0.71
Panel B: Calibration Sample: 06/1997 – 12/2013 (N = 331); Test Sample: 01/2014 – 03/2020 (N′ = 285)						
ME	-163.16	-345.58	-344.24	67.03	-232.00	-56.85
MAE	202.89	361.85	368.14	193.85	222.35	147.68
RMSE	221.96	417.89	411.71	308.98	259.11	190.81
R^2 *OS*	0.65	0.14	0.17	0.45	0.55	0.82
Panel C: Calibration Sample: 06/1997 – 12/2015 (N = 406); Test Sample: 01/2016 – 03/2020 (N′ = 210)						
ME	7.84	-309.28	-293.61	-436.65	-139.03	9.76
MAE	148.01	336.60	330.80	436.98	222.35	148.15
RMSE	186.96	407.68	376.32	452.86	259.11	208.31
R^2 *OS*	0.76	0.09	0.22	-0.13	0.63	0.76

Table 9: Out-of-sample Performance Measures for Different Calibration and Test Periods

The table shows the mean errors (ME), mean absolute errors (MAE), root mean square errors (RMSE) and the out-of-sample R-squared ($\boldsymbol{R^2_{OS}}$) for all the model specifications. All models have been estimated on the subsample of N bonds issued during the indicated calibration period and then applied to price the remaining N′ transactions in the test period.

For instance, in panel B, Multifactor model $\boldsymbol{R^2_{OS}}$ reaches a value of 65% against a poor 14% of the Linear one. The only exception is made for Fermat Capital model, indeed, in panel B it shows the best performance for all the measures considered: lower errors and higher R-squared. Better results are also achieved in panel A but only for two measures (ME, $\boldsymbol{R^2_{OS}}$). However, taking into consideration only $\boldsymbol{R^2_{OS}}$ values throughout the three panels, it's clear that in Fermat Capital the R-squared is not increasing as more information are added in the calibration sample, meaning that Fermat Capital performs better in subsamples (only specific periods). Finally, I would argue that Multifactor model is the best choice among the alternatives because its performance improves as data included in the calibration sample increases, confirming the explanatory power of the regressors chosen.

However, an out-of-sample analysis with calibration and test periods does not account for possible changes in the structure of the data over the time because there is only one estimation of the model. The most accurate way to compare models is using expanding and rolling windows.

Table 10 shows the R-squared[9] achieved in the Multifactor model's out-of-sample analysis using both expanding and rolling windows. Each column in the table refers to a different year in which the forecasts started to be computed. For instance, column 1 is labeled "2010" because forecasts begin in 2010 (and run until March 2020), the last column instead considers forecasts only starting from 2016. First, I used an expanding window meaning that for each forecast all the information available up to that point in time was included to estimate the parameters. However, I also repeated the calculation using a rolling window. This accounts for possible cyclical trends in the CAT bond market.

Results in table 10 suggest positive and quite high R-squared in both cases; however, the rolling window out-of-sample analysis seem to be better until column "2015" suggesting a possible trend repetition in the market. On the other hand, in the last column the R-squared of the expanding window out-of-sample analysis reaches a value of 0.978, confirming once again that Multifactor model performs better than the historical average of the Cat bond Spread.

		2010	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**
Expanding Window:	R^2	0.635	0.614	0.595	0.684	0.666	0.639	0.978
Rolling Window:	R^2	0.635	0.661	0.666	0.713	0.682	0.652	0.747

Table 10: Out of Sample R-squared: Expanding and Rolling Windows

The table represents the R-squared of the out of sample forecasts starting in different years. The first row refers to recursive forecasts (expanding window). The second, instead, to rolling window forecasts; in this case the window estimation is not constant throughout different columns: in 2010 it is of 12 years and in each subsequent column it includes one year more (i.e., in 2011 the estimation window is of 13 years and so on).

Thus, taking into account all the considerations, when pricing CAT bonds, it is reasonable to examine other variables besides expected loss.

4) CONCLUSION

In this paper I have analyzed which factors determine the CAT bond premium. Using the largest sample to date which accounts for 1087 CAT bond tranches issued between June 1997 and March

[9] R-squared presented in table 9 are computed following equation (4).

2020, I find evidence that the expected loss, the covered territory, the sponsor, the reinsurance cycle, and the BB corporate bond spread are major drivers of the cat bond spread.
These findings are in line with previous ones, in particular, I find a strong positive dependency of the reinsurance cycle and CAT bond premiums. Thus, I can conclude that CAT bond premiums do have a cyclical behavior that is similar to the reinsurance cycle. In addition to this, since the majority of CAT bond tranches have low ratings, CAT spreads do fluctuate in line with the BB corporate bond spread. In spite of this, it is important to note that, on average, CAT bonds offer higher yields compared to similar corporate bonds (the difference is more than 1 percentage point). Furthermore, there is evidence of additional premium components if the rating of the bond declines and if the bond offers coverage for peak territories such as the US.

Although Dieckmann (2011) identified the applied trigger mechanism as a premium determining factor, according to my results indemnity triggers seem not to be priced at all. One explanation is that it is rather difficult to identify moral hazard in a particular CAT bond transaction; moreover, most CAT bonds are used to insure tail risks, meaning that a large share of risk in the insurance portfolio is retained by the sponsor, therefore, the consequences for investors may be limited in many cases.

This work can help insurance and reinsurance companies to consider further determinants rather than the solely expected loss when pricing CAT bonds. Robustness checks and the high R-squared confirm the reliability of the proposed model, however, the CAT bond market is recent and therefore still developing. Moreover, it has been proven that financial crises have a significant impact on CAT bond premiums (Gürtler et al., 2012). The COVID-19 pandemic has caused an unprecedented human and health crisis affecting all sectors. It has also activated the trigger of two CAT bond tranches: in total, the payout looks like to be just below $196 million. Hence, in future research, one could aim to develop a similarly accurate approach to assess whether this catastrophe has changed investors' perceptions and expectations and thus has shifted the pricing model away from the one proposed in this work.

APPENDIX

	Wind	Earthquake	Other	Total
2000			1	1
2001			1	1
2002				0
2003				0
2004				0
2005				0
2006				0
2007				0
2008			4	4
2009	2			2
2010			1	1
2011	2		4	6
2012				0
2013	1			1
2014			2	2
2015				0
2016	2			2
2017	15	1	3	19
2018	15		3	18
2019	3	1		4
2020			2	2

Table 11: Number of Triggered CAT Bond Tranches by Year and by Cause

The table shows the total number of the triggered tranches by year and by the natural catastrophe that activated the trigger. Before 2000 no CAT bond has been triggered. The catastrophes are mainly concentrated in the last 5 years.

Model 7 Coef.	Model 7 P-val.	Model 7 Sig.	Model 8 Coef.	Model 8 P-val.	Model 8 Sig.	Model 9 Coef.	Model 9 P-val.	Model 9 Sig.	Model 10 Coef.	Model 10 P-val.	Model 10 Sig.	Model 11 Coef.	Model 11 P-value	Model 11 Sig.
165.05	0.000	***	164.59	0.000	***	163.59	0.000	***	145.95	0.000	***	162.05	0.000	***
240.59	0.000	***	250.46	0.000	***				29.13	0.399		145.64	0.000	***
-33.08	0.335					-62.76	0.057	*	71.78	0.065	*	-85.57	0.012	**
						248.951	0.000	***	202.30	0.000	***	269.54	0.000	***
-212.25	0.000	***	-222.89	0.000	***	-180.69	0.000	***				-239.72	0.000	***
59.38	0.000	***	57.11	0.000	***	34.24	0.000	***	36.58	0.000	***			
275			285			295			532			274		
0.93			0.93			0.93			0.91			0.93		
18.28	0.3713		20.08	0.3713		32.87	0.017	**	139.33	0.000	***	44.68	0.000	***

Table 12: Alternatives of the Multifactor Model

This table shows possible alternatives of the Multifactor Model. In each model I deleted one or more regressors. None of these models performs better than the complete one (Model 4).

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