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Pricing Cat Bonds for Cloud Service Failures

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Abstract: The use of the cloud to store personal/company data and to run programs is gaining wide acceptance as it is more efficient and cost-effective. However, cloud services may not always be available, which could lead to losses for customers and the cloud provider (the provider is typically obligated to compensate its customers). It can protect itself from such losses through insurance, which transfers the risk to the insurer. In the case of poor cloud availability, the amount that the insurer has to pay back to the cloud provider may become so high that it endangers the insurer's financial solvency. We propose the use of cat bonds as reinsurance tools as well as the Nowak–Romaniuk pricing scheme. The outage frequency was described by the Poisson process and the loss severity was described by a Pareto random variable; we derived a closed formula for the price of a cat bond in a stochastic interest rate environment, using both one-factor and two-factor short-rate models. We demonstrated the applicability of our pricing formula in a real context.

Keywords: cyber-risks; cat bond; financial pricing; cyber-insurance

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1. Introduction

The use of cloud services to store personal or company data (cloud storage) and to run programs (cloud computing) is gaining wide acceptance, as these services are more efficient and cost-effective Naldi and Mastroeni (2016); Varghese and Buyya (2018). However, cloud infrastructures are not free of failures. Cloud services may be subject to interruptions, even prolonged ones. Given the wide reliance on such services, news of extended outages has also spread to the general press. For example, outages have been reported, lasting several hours[1] or even several days[2].

Such service disruptions can cause significant economic damages, including losses due to missing revenue, expenses for disaster recovery, customer liabilities, and reputation damage due to the loss of customers. The overall loss may easily reach hundreds of thousands of dollars for each minute of an outage, see Mastroeni and Naldi (2017); Pesola (2004).

Customers expect to receive an adequate quality of service, which typically includes some guarantees on the availability of the service, Følstad and Helvik (2016); Yuan et al. (2015b), roughly defined as the percentage of time that the cloud remains available to customers. It has been shown that the actual availability may be lacking and quite below the expectations, Nabi et al. (2016).

These guarantees are embodied in service level agreements (SLAs), e.g., Alhamad et al. (2010); Baset (2012); Hussain et al. (2017); Mubeen et al. (2018); Qiu et al. (2013); Serrano et al. (2016). Such agreements, which form contractual-like relationships between parties, state the obligations imposed on the cloud service provider through a set of service quality metrics and constraints to be met. Cloud provider compliance with these contractual-like commitments has to be monitored, see Nawaz et al. (2017). Several tools have been proposed in the literature for that purpose, such as in Alboghdady et al. (2017); Shang et al. (2020); Stephen et al. (2019); Syed et al. (2017). All of these tools have to measure a set of parameters related to the quality of service (QoS) and compare their values against SLA provisions. In this case, the obligations underwritten in SLAs may not be fulfilled. Consequently, if contractually agreed, e.g., see Yuan et al. (2015a), the cloud provider is expected to pay the penalty and/or compensate the customer's losses. If violations take place on a wide scale, penalties and compensations may endanger the economic balance of the cloud provider.

Risk analysis and risk management are essential for companies to cope with service disruption and consequent economic losses, Carfora et al. (2019); Marotta et al. (2017); Paté-Cornell et al. (2018). The cloud provider may invest in its system to increase its reliability and reduce the expected loss, but these are mitigation measures, which are not enough to prevent the risk of extreme losses, Mazzoccoli and Naldi (2020).

Cloud providers may resort to insurance, i.e., risk transfer tools, in order to fully protect themselves against the losses deriving from direct losses and the penalties to be paid to customers due to the enforcement of SLAs. Pricing insurance policies for cloud services has already been dealt with by Mastroeni et al. (2019). However, transferring the risk to the insurer puts the latter in a critical situation. Catastrophic losses may occur, which may endanger the insurer itself Khalili et al. (2019). In turn, an insurance company can resort to the same risk transfer option through a reinsurance company, although there are very few cyber re-insurers, Marotta et al. (2017), and the existing ones are reluctant to insure. Moreover, classical insurance mechanisms are inappropriate for dealing with such extreme losses. Even a single cyber catastrophe could cause problems with reserve adequacy for many insurers or the bankruptcies of insurance firms. Therefore cyber-insurance companies need new risk transfer tools.

Packaging risks in tradable assets in the form of catastrophe bonds (cat bonds) is an alternative to classical reinsurance devices to cope with the impacts of extreme cyber-catastrophes. Some works have appeared in the financial literature on cat bond pricing, but for very different application domains. In Cox and Pedersen (2000); Reshetar (2008), some approaches using discrete time stochastic processes are present, while several approaches with continuous time can be found in Burnecki and Kukla (2003); Hardle and Cabrera (2010). Moreover, in Vaugirard (2003), the author resorts to an arbitrage approach to price cat bonds. Other works, such as Baryshnikov et al. (2001); Egami and Young (2008); Unger Andre (2010), address similar issues but do not fit our problem well. An interesting approach to the cat bond pricing problem can be found in Nowak and Romaniuk (2013) and Zong-Gang and Chao-Qun Ma and Ma (2013). In the first paper, cat bonds are priced by applying models on the risk-free spot interest rate (Vasicek, Hull–White, and CIR), assuming that the occurrence of the catastrophe is independent of the behavior of the financial markets. They obtained pricing formulas through Monte Carlo simulations in the case of two payoff functions for the catastrophe bond, a stepwise function, and a piecewise linear function. The authors of the second paper used a similar approach (using the CIR model) but did not provide a closed formula for pricing.

In this paper, we deal with the problem of devising a reinsurance scheme for cloud services based on cat bonds. Our main contributions are the following:

- We introduce cat bonds in the context of cloud services (Sections 2 and 3);
- We provide closed formulas for cat bond pricing, adopting the approach of Nowak and Romaniuk using one-factor and two-factor short-rate models (Sections 4–6);
- We illustrate the application of pricing formulas in a realistic context, employing failure statistics from the real world (Section 7)

2. Cat Bonds for Cloud Services

Cat bonds have been devised as reinsurance mechanisms for natural catastrophes. In this section, we show how we can apply them to cloud services.

As briefly mentioned in the introduction, a cloud provider offers a remote service that may consist of the remote storage of the customer's files or the remote execution of programs. The files to be stored and the programs to be run reside on the cloud provider's data center and customers access them through a network connection to the cloud provider's servers (see the illustration of cloud computing in Figure 1).

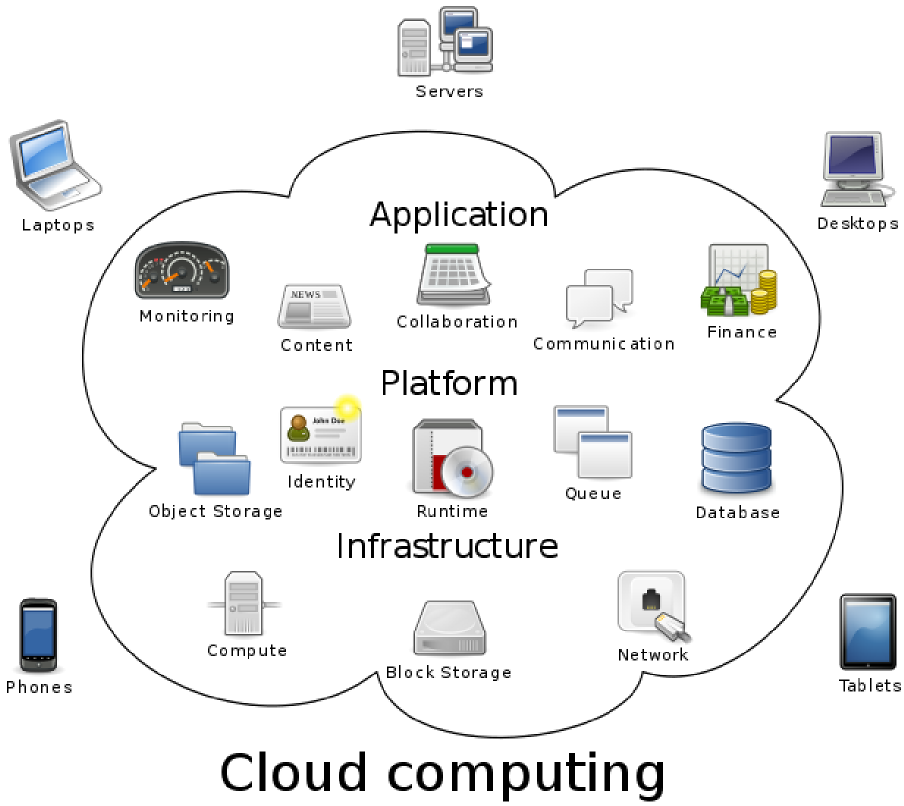

Figure 1. Cloud computing architecture.

The service is subject to outages due to either accidental or intentional causes (i.e., attacks by cybercriminals, see Elnagdy et al. 2016; Gunawi et al. 2016). In this paper, we focus on accidental failures. Major outage causes are infrastructure failures (power subsystem, cooling subsystem, IT subsystem, servers, and the network), planning mistakes, human errors, such as misconfiguration, software errors, and periodic preventive maintenance tests Bauer and Adams (2012); Endo et al. (2017); Mesbahi et al. (2018). An analysis of cloud incidents reported by customers was carried out by Fiondella et al. (2013).

Though outages may concern parts of the system and, therefore, result in service quality degradation rather than a complete breakdown (see chap. 3.3.4 of Bauer and Adams 2012), in this paper, we consider the service provided by the cloud provider as a binary variable, i.e., the service may be either ON or OFF. We can always revert to this scheme by setting a threshold on service quality so that an outage is declared if the service quality parameters fall below that threshold. Under this assumption, the cloud service status is a sequence of alternating ON and OFF periods, as shown in Figure 2. This was the same approach taken by Mastroeni and Naldi (2011).

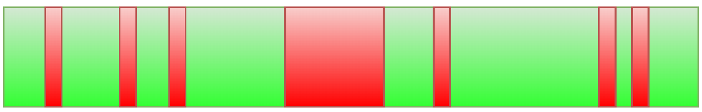

Figure 2. An example of the availability status of cloud services under the ON–OFF scheme.

Outages produce economic losses both for the cloud provider (see, e.g., the analysis carried out by the Ponemon Research Institute Ponemon 2016) and the customer. In the case of business customers, a significant source of losses is due to lost income during the outage. This loss can be estimated roughly as the proportion of the yearly revenues associated with the outage duration and can amount to hundreds of thousands of dollars per minute for large companies such as Amazon (see Table 9.1 of Machiraju and Gaurav 2015).

If the cloud provider fails to provide the service, it may have to financially compensate customers for the losses incurred, according to the service level agreement (SLA) provisions, Alhamad et al. (2010); Baset (2012); Hussain et al. (2017). A typical clause in SLA is related to the violation of availability commitments, Yuan et al. (2015b), though other commitments can be considered, such as the number of outages or the number of long outages, see Naldi and Mastroeni (2011). Consequently, a prolonged service outage may even lead to a catastrophic loss. Table 1 shows an example of the refund policies for three major cloud companies as a percentage of the service fee. We see that the cloud provider may be called to give back to the customer 50% of what it paid for the service. If a long and extensive outage occurs, the reimbursements may easily eat up the profit margin and lead to catastrophic consequences for the cloud provider.

Table 1. Refunds as a percentage of the service fee.

Provider	Monthly Uptime [%]	Service Credit [%]
Amazon[3]	99–99.99	10
	<99	30
Azure[4]	99–99.9	10
	<99	25
Google[5]	99–99.99	10
	95–99	25
	<95	50

Cloud providers may invest in their infrastructure and improve their availability as countermeasures to reduce such losses. Risk mitigation may be accompanied by risk transfer measures, such as underwriting an insurance policy. Investments may also be employed to reduce the premium, as shown for cybersecurity in Mazzoccoli and Naldi (2020, 2021, 2022); Young et al. (2016). However, refunds may have to be severely limited for the insurance mechanisms to be sustainable, Mastroeni et al. (2019). If that is not possible or acceptable to customers, the insurer may need to resort to an additional insurance layer, since it has to protect itself against the risk of huge losses, just as the cloud provider did. The insurer may transfer its risk to a reinsurer by paying a premium. Without established reinsurance schemes, the insurer may envisage resorting to cat bonds Cummins (2008).

The insurer issues cat bonds to cater for losses. In the context of cloud services, they may work as follows. If the losses due to outages remain below a given threshold (i.e., if no catastrophe occurs), the insurer pays the investors (i.e., the bond subscribers) a coupon. Instead, on catastrophic events (leading to large losses for the insurer), bond subscribers undergo reductions in revenue proportional to the losses.

In Figure 3, we show an example of the cash flow involved in insurance and cat bond emissions. On the left (in yellow), the cloud provider underwrites an insurance policy to hedge against any future risks by paying an insurer an amount of money (the premium). In the case of difficulties in underwriting a reinsurance scheme (in blue), the insurer (in red) may issue a cat bond to hedge against huge losses due to large cloud insurance claims, as shown by Cummins (2008). If a catastrophic event occurs, the insurer has to compensate the cloud provider for the losses due to customer claims, but it may do so by relying on the money collected through that cat bond emission. On the other hand, if a catastrophic event does not occur, there are no claims and, therefore, no coverage of the cloud provider's losses, but the insurer has to pay its bond subscribers (in green) the coupon and the face value of the bond at the end of the bond life.

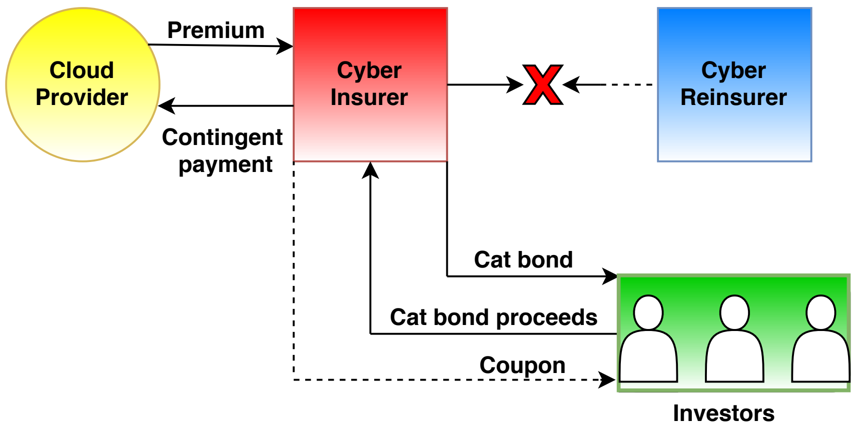

Figure 3. Process of cash flows.

3. Models for the Service Status of Cloud Service

A crucial issue to correctly price the cat bond is to have a probabilistic model for the status of the cloud service, which describes whether the cloud is available or not, considering the ON–OFF process amounts as having a probability model for the length of the ON and OFF periods. Hereafter, we safely assume that the duration of the OFF period, i.e., the time it takes for the cloud to work again, is uncorrelated with the duration of the working (ON) period, and vice versa. We also assume that the start and end times of the two periods can be precisely identified. This issue has been thoroughly investigated by Hogben and Pannetrat (2013), where different operational definitions of availability have been considered. In this section, we briefly recall the models of ON and OFF periods appearing in the literature.

The following statistical models have been proposed in the literature to describe the durations of the ON and OFF periods:

- Exponential–exponential model (or Poisson–exponential), employed in Mastroeni and Naldi (2011);
- Exponential–Pareto (or Poisson–Pareto) that was proposed by Mastroeni et al. (2019); Mastroeni and Naldi (2011) based on a dataset of customer-reported outages for five major cloud providers (Google, Amazon, Rackspace, Salesforce, Windows Azure);
- Pareto–LogNormal model, proposed by Dunne and Malone (2017) to describe the results of a measurement campaign in a small company running its own cloud.

In this paper, we adopted the Poisson–Pareto model, which allowed us to obtain closed-form expressions for the cat bond price, although the approach we propose is rather general. Our choice is related to the fact that the Poisson–Pareto model was established by looking at the tail of the OFF duration, e.g., at the extreme events that the reinsurance scheme wishes to protect against.

In the following, we indicate the duration of the ON states with A and the duration of the OFF states with D. The cumulative distribution function of the two periods are

$$
\begin{aligned}
F_A(x) &= \mathbb{P}[A < x] = 1 - \lambda_A e^{-\lambda_A x} \\
F_D(x) &= \mathbb{P}[D < x] = \begin{cases} 1 - \left(1 + \frac{\xi x}{\beta}\right)^{-\frac{1}{\xi}} & \text{if} \quad \xi \neq 0 \\ 1 - e^{-\frac{x}{\beta}} & \text{if} \quad \xi = 0 \end{cases}
\end{aligned}
\tag{1}
$$

where λ_A is the parameter of the exponential distribution, β and ξ are the scale and shape parameters of the GPD distribution.

This model was employed by Mastroeni and Naldi (2017) to assess the sustainability of refunds linked to insurance contracts for cloud services, as well as by Naldi (2017), to assess the network's contribution to the overall unavailability. The values obtained for the parameters of the two distributions are reported in Table 2.

Table 2. Parameters in the Poisson–Pareto model.

Provider	Exponential $1/\lambda$ [days]	Pareto β	ξ
Amazon	85.6	276.43	−0.12
Azure	36.67	312.32	−0.35
Google	27.53	405.29	0.39

Since we wish to set the price of a cat bond to cover extreme losses, we assess how likely huge losses are in this context. For that purpose, we compute the probability of losses larger than some multiple k of the average loss, i.e., $\mathbb{P}[D > k\mathbb{E}[D]]$. In Figure 4, we see that the probability that an outage can cause a loss (that is at least twice as high as the average loss) is 12%. Though the probability of large losses decreases fast, the probability of losses larger than five times the average loss is still a significant 2.5%.

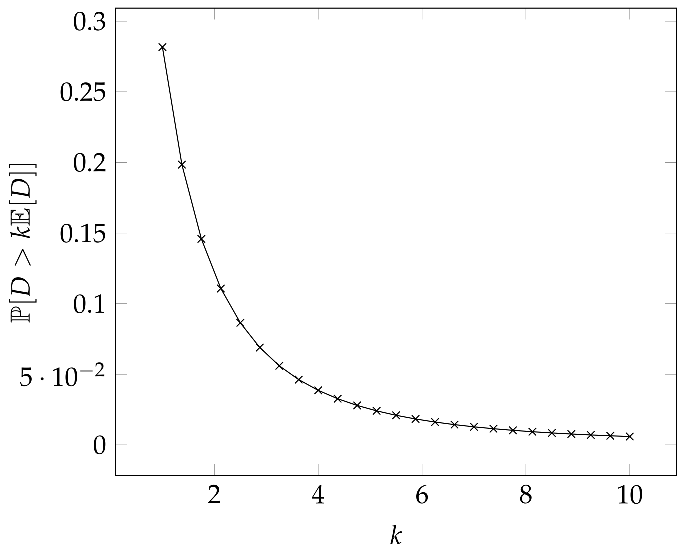

Figure 4. Probability of large losses.

4. Cat Bond General Pricing Formula

As stated in the introduction, in this paper, we obtained a closed formula to evaluate the cat bond price for cloud services, starting from the work of Nowak and Romaniuk (2013). In their work, they proposed a general formula for cat bond pricing, but, due to difficulties in managing the distribution of losses and occurrences, they did not produce a closed formula but relied on numerical results based on Monte Carlo simulations. In this section, we recall their cat bond pricing formula and adapt it to the context of cloud services. In Table 3, we report the major symbols used in our analysis.

Table 3. Description of variables and parameters used.

Variables	Description
$X(t)$	Economic loss for the number of long outages at time t
k_{lf}	Loss for each long outage
L_i	i-th loss threshold
s_i	i-th number of outages threshold
T	Duration of contract
$N(t)$	Number of outages at time t
A, D	Duration of the availability and unavailability period
ω	Threshold for long outages
λ	Parameter of the exponential distribution
ξ, β	Shape and scale parameter for GPD
w_i	i-th weight
t_i	i-th stopping time
S_i	i-th cumulative distribution function of the stopping time t_i

4.1. Cat Bond Formulation

As stated in Section 3, we adopt the Poisson–Pareto model to describe the service status of the cloud. Since we are concerned with the loss suffered by the insurer, we must relate that to the loss suffered by the cloud provider through the claim process. In Mastroeni et al. (2019), three QoS metrics were used to describe how service disruptions lead to claims (and hence, losses) for the cloud provider. Those metrics are the number of outages, the number of long outages, and the overall unavailability time. It is to be noted that, while claims lead to compensation for customers according to the selected QoS metrics, the cloud provider is indemnified in full against its losses due to compensations.

If the contract between the customer and the cloud provider is set up using the number of outages as the contingency, the cloud customer receives compensation for each outage. If the number of long outages is chosen as the contingency, the customer is compensated whenever the outage duration exceeds a given threshold. The compensation does not depend on the actual outage duration, as long as it is larger than the threshold. Finally, if the overall unavailability represents the contingency, the compensation is proportional to the sum of the outage durations.

As hinted before, in this paper, we adopted the number of long outages as the contingency that formed the basis for claims, since we were interested in extreme events (which are the most harmful for the providers and lead to catastrophic consequences).

We define by T the duration of the contract signed at time $t = 0$, so that the validity time interval is $\mathbb{T} = [0, T]$. Let us consider $t \in \mathbb{T}$. We also define by $(X_i)_i^\infty = (k_{lf}\mathbf{1}_{[D_i>\omega]})_i^\infty$ a sequence of i.i.d. random variables that describe the losses suffered by the cloud provider during the i-th catastrophic event. The variable D_i describes the period of service unavailability, k_{lf} is a positive constant and refers to the loss per long outage, while ω is a threshold imposed on outage durations to give rise to a claim, and $\mathbf{1}_{[*]}$ is the indicator function so that

$$\mathbf{1}_{[D>\omega]} = \begin{cases} 1 & \text{if } D > \omega \\ 0 & \text{otherwise} \end{cases}. \tag{2}$$

Due to our choice of the Poisson–Pareto model, we describe the number of catastrophic events until the moment t, $t \in \mathbb{T}$, through a homogeneous Poisson process $N(t)$ with intensity $\lambda_A =: \lambda$. The jumps of $N(t)$ take place when a catastrophic event occurs. So, we have

$$\begin{aligned} & N(0) = 0 \\ & \mathbb{E}[N(t)] = \lambda t \\ & \mathbb{P}(N(t) - N(s) = j) = e^{-\lambda(t-s)} \frac{[\lambda(t-s)]^j}{j!} \\ & j \in \{0, 1, 2, \dots\} \end{aligned} \tag{3}$$

Following Mastroeni and Naldi (2017) and our choice of contingency, we can set the total loss suffered by the cloud provider as proportional to the number of long outages

$$X(t) = \sum_{i=1}^{N(t)} X_i = k_{lf} \sum_{i=1}^{N(t)} \mathbf{1}_{[D_i > \omega]}. \tag{4}$$

Due to the full indemnification of the cloud provider, the quantity $X(t)$ in Equation (4) is also the loss suffered by the insurer. It is a non-decreasing stochastic process (compound Poisson process) with the right continuous trajectories of a stepwise form. The height of the jumps is the economic loss incurred in the catastrophic event, as we can see in Figure 5.

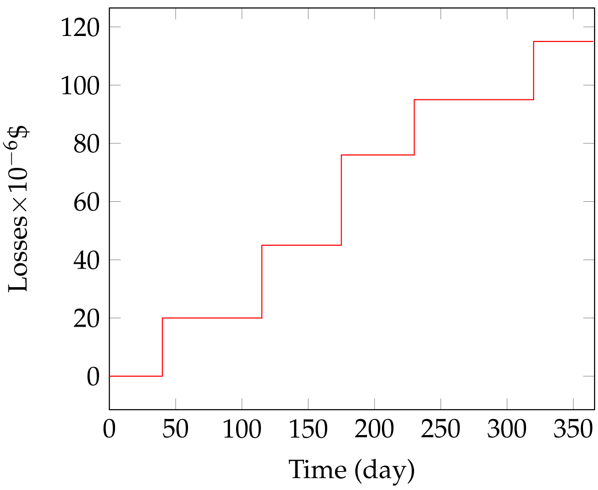

Figure 5. Example of the dynamics of $X(t)$ process.

The process described above is defined on a filtered probability space $(\Omega, \mathcal{F}, (\mathcal{F}_t)_{t\in\mathbb{T}}, \mathbb{P})$, where the filtration $(\mathcal{F}_t)_{t\in\mathbb{T}}$ is given by

$$\mathcal{F}_t = \sigma(\mathcal{F}_t^* \cup \mathcal{F}_t^{**}) \tag{5}$$

where $\mathcal{F}_t^* = \sigma(W(\tau), \tau \leq t)$ and $\mathcal{F}_t^{**} = \sigma(X(\tau), \tau \leq t)$, $t \in \mathbb{T}$, with the assumption that $\mathcal{F}_0 = \sigma(\{F \in \mathcal{F} : \mathbb{P}(F) = 0\})$ and $W(t)$ is a Brownian motion.

In order to build the cat bond, we now define a zero-coupon bond with face value $\mathcal{FV} = 1$ and maturity at time T, whose value at time t is $B(t, T)$. We also make the following assumptions:

1. The dynamics of $B(t, T)$ are described by the following equation (well established in the literature)
$$dB(t,T) = B(t,T)(\mu(t)dt + \sigma(t)dW(t)) \tag{6}$$
where $\mu(t)$ and $\sigma(t)$ are the drift and the volatility.
2. There is no possibility of arbitrage on the market (which corresponds to the completeness of the market); moreover, the pricing of the cat bond will be made under this assumption.
3. The Novikov condition is satisfied, or rather
$$\mathbb{E}^{\mathbb{Q}}\left[exp\left(\frac{1}{2}\int_0^T m^2(t)dt\right)\right] < \infty \tag{7}$$
where
$$m(t) = \frac{\mu(t) - r(t)}{\sigma(t)}$$
is the market price of risk, r is the risk-free interest rate, and $\mathbb{Q}$ is the risk-neutral measure found using the Radon–Nikodym derivative and the Girsanov theorem (see Björk (2009) for other details).
4. The occurrence of catastrophic events is independent of the behaviors of the financial markets since we are studying cloud service outages.

4.2. Cat Bond Properties

We now describe some properties of the cat bond, linking them to the service status process of the cloud.

We introduce a sequence of stopping times that describes the times at which a catastrophe occurs, i.e., the times at which the total amount of losses $X(t)$ exceeds some economic thresholds L_i
$$t_i(s) = \min\{\inf\{t \in \mathbb{T} : X(t) > L_i\}, T\}, \quad 1 \leq i \leq d, \tag{8}$$
where
$$0 < L_1 < L_2 < ... < L_d, \quad d > 1.$$

After that, we consider a cat bond, which we denote with $B(t, T, \mathcal{FV})$, which has maturity time T and cash payments in T, face value $\mathcal{FV}$, and satisfies the following properties (summarised in Table 4):

1. If the time t_1 of the first occurrence exceeds the time of contract validity T ($t_1 \notin \mathbb{T}$), the bondholder receives the face value $\mathcal{FV}$;
2. If $t_d \in \mathbb{T}$, the bondholder receives a fraction of the face value, i.e., the face value minus the sum of write-down coefficients in the percentage $\sum_{j=1}^{d} w_j$, where $w_j \in [0, 1]$, $j = 1, ..., d$, are so that
$$w_1 \leq w_2 \leq ... \leq w_d : \sum_{j=1}^{d} w_j \leq 1;$$
3. Otherwise, if $t_k \in \mathbb{T}$ and $t_{k+1} \notin \mathbb{T}$, where $k < d$, the bondholder receives a fraction of the face value, which is the face value minus the sum of write-down coefficients in the percentage $\sum_{j=1}^{k} w_j$.

Table 4. Summary of the bondholder profit.

Time of Occurrence	Profit
$t_1 \notin \mathbb{T}$	$\mathcal{FV}$
$t_d \in \mathbb{T}$	$\mathcal{FV}$ minus the sum of coefficients in the percentage $\sum_{j=1}^{d} w_j$
$t_k \in \mathbb{T} \wedge t_{k+1} \notin \mathbb{T}, k < d$	$\mathcal{FV}$ minus the sum of coefficients in the percentage $\sum_{j=1}^{k} w_j$

4.3. Cat Bond Pricing

For the sake of simplicity, we will use the notation $B_T(t)$ for the value of the bond at time t instead of $B(t, T)$. Starting from Equation (6), using well-known arguments in the financial literature (see, e.g., Björk 2009; Brigo and Mercurio 2007), we obtain the pricing formula for a zero coupon bond at time $t = 0$, depending on the face value

$$B_T(0) = \mathbb{E}^{\mathbb{Q}}\left[\exp\left(-\int_0^T r(s)ds\right)\Big|_{\mathcal{F}_t}\right]. \tag{9}$$

Now, using arguments in Carmona and León (2007); Vaugirard (2003), using assumptions 1 through 3, Nowak and Romaniuk (2013), wrote the following cat bond pricing formula

$$B_T(0, \mathcal{FV}) = \mathbb{E}^{\mathbb{Q}}\left[\exp\left(-\int_0^T r(s)ds\right)V_B(T, \mathcal{FV})\Big|_{\mathcal{F}_t}\right] \tag{10}$$

where $V_B(\cdot)$ is the payoff function.

As a consequence of assumption 4, the previous formula can be expressed as follows:

$$B_T(0, \mathcal{FV}) = \mathbb{E}^{\mathbb{Q}}\left[\exp\left(-\int_0^T r(s)ds\right)\Big|_{\mathcal{F}_t}\right]\mathbb{E}^{\mathbb{Q}}[V_B(T, \mathcal{FV})]. \tag{11}$$

We can see that the bond price in Equation (11) is the product of two mean values under the measure $\mathbb{Q}$, which we call, respectively, the mean value of the exponential of the interest rate (*MVER*) and the mean value of the payoff function (*MVPF*).

It can be seen that the *MVER* depends on the interest rate; instead, the *MVPF* depends on the payoff function.

Let us remark that Equation (11) holds under the Nowak and Romaniuk assumption that aggregate consumption depends only on financial variables. In our case, where the catastrophe is independent of the behavior of the financial markets, for any random variable Y, which depends only on catastrophic risk variables, it follows that $\mathbb{E}^{\mathbb{Q}}[Y] = \mathbb{E}^{\mathbb{P}}[Y]$ (for detailed proof, see the appendix of Ma and Ma 2013 or Cox and Pedersen 2000), where the connection between the two measures $\mathbb{P}$ (*risk-neutral measure*) and $\mathbb{Q}$ is given by the Radon–Nikodym derivative $\frac{d\mathbb{Q}}{d\mathbb{P}}\Big|_{\mathcal{F}_t}$.

So we can say that Equation (11) is equivalent to the following:

$$B_T(0,\mathcal{FV}) = \mathbb{E}^{\mathbb{Q}}\left[\exp\left(-\int_0^T r(s)ds\right)\bigg|_{\mathcal{F}_t}\right]\mathbb{E}^{\mathbb{P}}[V_B(T,\mathcal{FV})]. \tag{12}$$

5. Cat Bond Pricing for the Poisson–Pareto Model

Though we have defined the general pricing formula in Equation (10), we still need to compute the *MVPF* and *MVER* to obtain the actual price. In this section, we provide the final closed formula for the price of a cat bond for cloud service failures under the Poisson–Pareto model proposed.

Computation of the CDF of t_i

We consider first the following formula provided by Nowak et al. (2012):

$$B_T(0,\mathcal{FV}) = \mathbb{E}^{\mathbb{Q}}\left[exp\left(\int_0^T r(s)ds\right)\bigg|_{\mathcal{F}_t}\right]\mathcal{FV}(1-\mathcal{S}(T)). \tag{13}$$

Comparing Equation (11) with Equation (13) we obtain

$$\mathbb{E}^{\mathbb{Q}}[V_B(T,\mathcal{FV})] = \mathcal{FV}(1-\mathcal{S}(T)) \tag{14}$$

where the term $\mathcal{S}(T)$ is defined as the weighted sum of cdf's $\mathcal{S}_j$ of the stopping times t_j

$$\mathcal{S}(T) = \sum_{j=1}^{d} w_j\mathcal{S}_j(T) \tag{15}$$

where $\mathcal{S}_j$'s are expressed by the following identity

$$\mathcal{S}_j(T) = 1 - \sum_{n=0}^{\infty}\frac{e^{-\lambda T}(\lambda T)^n}{n!}\mathcal{S}_{\bar{X}_n}(L_j) \tag{16}$$

where $\mathcal{S}_{\bar{X}_n}$ is the CDF of $\bar{X}_n = \sum_{i=0}^{n} X_i$.

Taking into consideration the model described in Section 3 for the availability of cloud services, we can see that S_j has the form

$$\begin{aligned}\mathcal{S}_j(T) &= 1 - \sum_{n=0}^{\infty}\frac{e^{-\lambda T}(\lambda T)^n}{n!}\mathbb{P}\left[\sum_{i=0}^{n} k_{lf}\mathbf{1}_{[D_i>\omega]} \le L_j\right]\\ &= 1 - \sum_{n=0}^{\infty}\frac{e^{-\lambda T}(\lambda T)^n}{n!}\mathbb{P}\left[\sum_{i=0}^{n}\mathbf{1}_{[D_i>\omega]} \le \frac{L_j}{k_{lf}}\right]\end{aligned} \tag{17}$$

For the purpose of computing the probability term in Equation (17), we define

$$s_j := \left\lfloor \frac{L_j}{k_{lf}} \right\rfloor \in \mathbb{N},$$

where $\lfloor \frac{p}{q} \rfloor$ is the integer part of $\frac{p}{q}$, $p,q \in \mathbb{R}$, so that

$$s_1 < s_2 < \ldots < s_d.$$

Since n is a finite number and $\mathbf{1}_{[D>\omega]}$ is a discrete variable that takes only 0 or 1 values, we obtain that

$$\begin{aligned}\mathbb{P}\left[\sum_{i=0}^{n}\mathbf{1}_{[D_i>\omega]} \leq \frac{L_j}{k_{lf}}\right] &= \mathbb{P}\left[\sum_{i=0}^{n}\mathbf{1}_{[D_i>\omega]} \leq s_j\right] = \sum_{m=0}^{s_j}\mathbb{P}\left[\sum_{i=0}^{n}\mathbf{1}_{[D_i>\omega]} = m\right] \\ &= \sum_{m=0}^{s_j}\binom{n}{m}\left(1+\frac{\xi\omega}{\beta}\right)^{-\frac{m}{\xi}}\left[1-\left(1+\frac{\xi\omega}{\beta}\right)^{-\frac{1}{\xi}}\right]^{n-m}\end{aligned} \tag{18}$$

Since $\mathbb{P}\left[\sum_{i=0}^{n}\mathbf{1}_{[D_i>\omega]} = m\right]$ in Equation (18) can be zero if and only if $n \leq m$, we have an expression of the cumulative distribution functions $\mathcal{S}_j(T)$ of t_i:

$$\mathcal{S}_j(T) = 1-\sum_{m=0}^{s_j}\sum_{n=m}^{\infty}\frac{e^{-\lambda T}(\lambda T)^n}{n!}\binom{n}{m}\left(1+\frac{\xi\omega}{\beta}\right)^{-\frac{m}{\xi}}\left[1-\left(1+\frac{\xi\omega}{\beta}\right)^{-\frac{1}{\xi}}\right]^{n-m} \tag{19}$$

Replacing Equation (19) in Equation (15), we obtain the expression of $\mathcal{S}(T)$:

$$\mathcal{S}(T) = \sum_{j=1}^{d} w_j\left[1-\sum_{m=0}^{s_j}\sum_{n=m}^{\infty}\frac{e^{-\lambda T}(\lambda T)^n}{n!}\binom{n}{m}\left(1+\frac{\xi\omega}{\beta}\right)^{-\frac{m}{\xi}}\left[1-\left(1+\frac{\xi\omega}{\beta}\right)^{-\frac{1}{\xi}}\right]^{n-m}\right] \tag{20}$$

6. Interest Rate Models

In this section, we introduce the interest rate models that will be used in Section 7. First, we show two one-factor interest rate models, Vasicek and CIR models, and then a multi-factor model.

6.1. Vasicek Model

We consider a Vasicek model for the risk-free spot interest rate r. The interest rate process is mean-reverting and obeys the following equation

$$dr(t) = a(b-r(t))dt + \sigma dW(t), \tag{21}$$

where a, b, and σ are positive constants. In particular:

1. σ is the volatility and it is related to the amplitude of the randomness;
2. b is the long-term mean, which is all future trajectories of $r(t)$ will evolve around the mean level b;
3. a is the speed of reversion around the mean b;
4. $W(t)$ is a Wiener process and represents the random market risk.

Assuming a constant market price, $m(t) \equiv m$, under this interest rate model, we can write

$$\mathbb{E}^{\mathbb{Q}}\left[exp\left(-\int_0^T r(s)ds\right)\right] = e^{-T\cdot R(T,r_0)} \tag{22}$$

where

$$\begin{aligned}R(T,r_0) &= R-\frac{1}{aT}\left[(R-r_0)(1-e^{-aT})-\frac{\sigma^2}{4a^2}(1-e^{-aT})^2\right] \\ R &= b-\frac{m\sigma}{a}-\frac{\sigma^2}{2a^2}\end{aligned} \tag{23}$$

For details, see Brigo and Mercurio (2007); Björk (2009); Vaugirard (2003). The resulting bond price Formula (13) under the Vasicek model can be written as

$$B_T^{Vas}(0,\mathcal{FV}) = e^{-TR(T,r_0)}\mathcal{FV}(1-\mathcal{S}(T)) \tag{24}$$

6.2. CIR Model

The Cox–Ingersoll–Ross model is a mean reverting one-factor model where the instantaneous interest rate r obeys the following stochastic differential equation

$$dr(t) = a(b - r(t))dt + \sigma\sqrt{r(t)}dW(t) \tag{25}$$

where a, b, and σ are constants. The parameters in the CIR model have similar meanings to Vasicek model parameters:

1. σ is the volatility;
2. b is the mean of the interest rate;
3. a corresponds to the speed of adjustment to the mean;
4. $W(t)$ is the Wiener process.

Assuming that the market price is $m(t) = \frac{m}{\sigma}\sqrt{r(t)}$, under this interest rate model we have

$$\mathbb{E}^{\mathbb{Q}}\left[exp\left(-\int_0^T r(s)ds\right)\right] = K(T)e^{-J(T)r_0} \tag{26}$$

where

$$\begin{aligned} K(T) &= \left[\frac{\alpha e^{\beta T}}{\beta(e^{\alpha T}-1)+\alpha}\right]^{\gamma} \\ J(T) &= \frac{e^{\alpha T}-1}{\beta(e^{\alpha T}-1)+\alpha} \end{aligned} \tag{27}$$

$$\begin{aligned} \alpha &= \sqrt{(a+m)^2 + 2\sigma^2} \\ \beta &= \frac{a+m+\sqrt{(a+m)^2+2\sigma^2}}{2} \\ \gamma &= \frac{2ab}{\sigma^2} \end{aligned}$$

The resulting bond price Formula (13) under the CIR model can be written as

$$B_T^{CIR}(0, \mathcal{FV}) = K(T)e^{-J(T)r_0}\mathcal{FV}(1 - \mathcal{S}(T)) \tag{28}$$

6.3. Multi-Factor Model

In this subsection, we used multi-factor short-rate models, where the sum of two Gaussian factors gives the rate process. In particular, we consider an additive model of the type $r(t) = u(t) + v(t)$, where the interest rate, and in particular u and v, are described by the following stochastic differential equations

$$\begin{aligned} r(t) &= u(t) + v(t) \\ du(t) &= a_u(b_u - u(t))dt + \sigma_u\sqrt{u(t)}dW_1 \\ dv(t) &= a_v(b_v - v(t))dt + \sigma_v\sqrt{v(t)}dW_2 \end{aligned} \tag{29}$$

where u and v follow a CIR model and, respectively,

1. σ_u and σ_v are the volatilities;
2. b_u and b_v are the long-run means of u and v;
3. a_u and a_v correspond to the speed of adjustment to the mean;
4. W_1 and W_2 are two Wiener processes; thus, $dW_1dW_2 = \rho dt$, $\rho \in [-1, 1]$.

To maintain analytical tractability, we assume $dW_1dW_2 = 0dt$. In particular, we assume $\rho = 0$, since the square-root non-central chi-square processes do not work as well as linear-

Gaussian processes when non-zero instantaneous correlations are added. As stated by Brigo and Mercurio (2007), we find that

$$\mathbb{E}^{\mathbb{Q}}\left[exp\left(-\int_0^T r(s)ds\right)\right] = \mathbb{E}^{\mathbb{Q}}\left[exp\left(-\int_0^T u(s)ds\right)\right]\mathbb{E}^{\mathbb{Q}}\left[exp\left(-\int_0^T v(s)ds\right)\right] \\ = K_u(T)K_v(T)e^{-J_u(T)u_0 - J_v(T)v_0} \tag{30}$$

where $K_u(T)$, $K_v(T)$, $J_u(T)$, and $J_v(T)$ take the same forms of parameters in Equation (27), respectively. The resulting bond pricing Formula (13) under the multi-factor model is

$$B_T^{2F}(0, \mathcal{FV}) = K_u(T)K_v(T)e^{-J_u(T)u_0 - J_v(T)v_0}\mathcal{FV}(1 - \mathcal{S}(T)) \tag{31}$$

7. Numerical Results

In this section, we compute the bond price value after the cloud failure statistics for three major cloud provider companies: Amazon, Azure, and Google.

In particular, in this section, we give numerical results for cat bond pricing in the case of the two interest rate models considered, or rather Vasicek and CIR models, and then in the case of the multi-factor model described in Section 6 The parameters used in both models are described in Episcopos (2000) and are reported in Tables 5 and 6. They are based on a one-month inter-bank rate for the United States, as in Nowak and Romaniuk (2013).

This way of setting the parameters allows us to compare the results obtained for the Vasicek and CIR models and observe the impacts of the parameters a, b, and σ on the cat bond price.

We start by computing the residual face value of the cat bond, using the parameters in Table 5, and then we apply the two established interest models using the parameters in Table 6.

Table 5. Parameters used for cat bond pricing.

Parameters	Values
Number of threshold d	2
Weight w_i	0.5
First threshold s_1	10
Second threshold s_2	15
Face value $\mathcal{FV}$	1
Contract time T (year)	1

Table 6. Parameters considered in the Vasicek and CIR models for cat bond pricing.

Parameters	Vasicek	CIR
Speed of reversion a	0.0235	0.0241
Mean level b	0.055	0.054
Volatility σ	0.01	0.014
Interest rate r_0	0.0614	0.0614

7.1. Residual Face Value

In this subsection, we compute the second factor of the cat bond formula in Equation (13), i.e., the factor that depends on the model used to describe claims and losses. So, using Equation (15) and parameters in Table 5, we obtain the following residual face values for the three cloud provider companies, respectively:

1. Amazon
$$\mathcal{FV}(1 - \mathcal{S}(T)) = 0.9362$$
2. Azure
$$\mathcal{FV}(1 - \mathcal{S}(T)) = 0.9619$$
3. Google
$$\mathcal{FV}(1 - \mathcal{S}(T)) = 0.7631$$

7.2. Cat Bond Price Case of Vasicek and CIR Models

Because of the choice of the parameters in Table 6, we can see that we obtain the same value for both Equations (22) and (26)

$$e^{-TR(T,r_0)} = K(T)e^{-J(T)r_0} = 0.940533.$$

So, using the values in Table 6 and the results found in Section 7.1, we can obtain the values of the cat bond prices for the three major cloud provider companies:

1. Amazon
$$B_T(0) = 0.9405326 \times 0.9362 = 0.8805$$
2. Azure
$$B_T(0) = 0.9405326 \times 0.9619 = 0.9046$$
3. Google
$$B_T(0) = 0.9405326 \times 0.7631 = 0.7177$$

7.3. Cat Bond Price of Multi-Factor Model

Considering a multi-factor model for the interest rate, using values of the parameters in Table 7, we obtain from Equation (30)

$$K_u(T)K_v(T)e^{-J_u(T)u_0 - J_v(T)v_0} = 0.933992$$

So, combining the latter and the results obtained in Section 7.1, we obtain the cat bond prices for the three major cloud provider companies

1. Amazon
$$B_T(0) = 0.9339924 \times 0.9362 = 0.8744$$
2. Azure
$$B_T(0) = 0.9339924 \times 0.9619 = 0.8984$$
3. Google
$$B_T(0) = 0.9339924 \times 0.7631 = 0.0.7125$$

Table 7. Parameters considered in the multi-factor model for cat bond pricing.

Parameters	Multi-Factor Model
Speed of reversion a_u	0.0241
Speed of reversion a_v	0.0241
Mean level b_u	0.054
Mean level b_v	0.054
Volatility σ_u	0.099
Volatility σ_v	0.099
Interest rate u_0	0.0307
Interest rate v_0	0.0307

8. Conclusions

Cyber risks, due to their nature, may involve extreme loss values for insurers, which are best dealt with by resorting to reinsurance.

In this paper, we investigated the use of cat bonds to carry out reinsurance since cyber risks actually share many characteristics with natural catastrophes, the major field of application of cat bonds.

We have shown how cat bonds can be applied to the specific case of reinsuring against the failure of cloud services, which cover information technology activities.

Under the fairly general assumption of the Poisson–Pareto model to describe the occurrence and severity of losses, we have provided closed formulas for the cat bond price in a stochastic interest rate environment, in particular, using two well-known one-factor rate models (Vasicek and CIR) and a two-factor short-rate model. Then, we showed how they could be applied in a realistic context, considering three major cloud provider companies (Amazon, Azure, and Google).

Although the method can be extended to various modeling options, the provision of a closed pricing formula is an important step for the practical application of cat bonds.

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Notes

1 see, e.g., https://www.theguardian.com/technology/2019/mar/13/googles-gmail-and-drive-suffer-global-outages, accessed on 10 March 2019; https://www.cnet.com/news/gmail-is-down-outage-around\-the-world-for-some-users/, https://status.cloud.google.com/incident/cloud-networking/19009, accessed on 10 June 2019

2 see, e.g., https://www.cmswire.com/digital-experience/salesforces-major-outage-reinforces-pitfalls-of\-cloud-software-world/, accessed on 10 June 2020

3 https://aws.amazon.com/it/compute/sla/, accessed on 10 January 2021

4 https://azure.microsoft.com/en-us/support/legal/sla/summary/, accessed on 10 January 2021

5 https://cloud.google.com/functions/sla, accessed on 10 January 2021

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