Epidemic Financing Facilities: Pandemic Bonds and Endemic Swaps

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Sixteenth International Longevity Risk and Capital Markets Solutions Conference

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Background and Literature

- COVID-19: more than 180 million infections and 3.9 million deaths worldwide as of June 2021
- Increasing epidemic risks due globalization, climate change, and urbanization (Bloom et al., 2018; Hilsenrath, 2020)
- Challenge in epidemic risk management: undiversifiable (Cummins, 2006) and uninsurable (Hartwig et al., 2020; Richter and Wilson, 2020)
- Transferring systemic risk to capital market through financial innovations could be a solution.

Current Epidemic Risk Solutions

- Pandemic Emergency Financing Facility (PEF) (World Bank)
  - Issued in 2017 to mobilize funding to contain a pandemic
  - Problems: extremely slow in releasing the fund due to its stringent criteria and complicated mechanism
- Donor-based funds
  - e.g. Central Emergency Response Fund (UN), Country-Based Pool Funds (UN), and Contingency Fund for Emergencies (WHO)
  - Problems: unsustainable with refinancing issues
- Epidemic Insurance
  - e.g. Pathogen RX (Munich Re) launched in 2018
  - Problems: uninsurable?

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Background and Literature

Epidemic risks

Pandemic

An epidemic outbreak that spreads over multiple countries

- Low frequency & high severity
- e.g. coronavirus
- → pandemic bonds

Endemic

A recurrent disease that has a persistent presence within a specific geographic area

- High volatility
- e.g. dengue
- → endemic swaps

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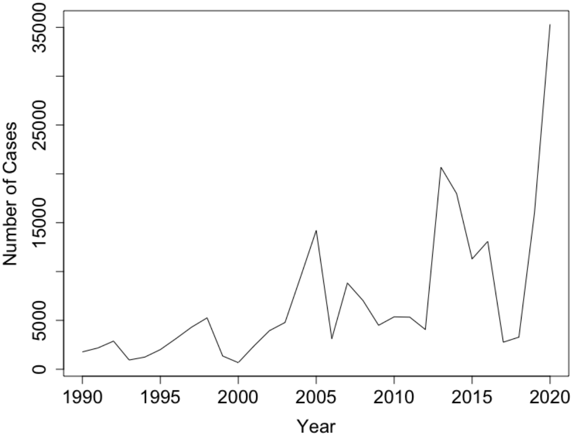

Figure 1: Annual dengue cases in Singapore

Background and Literature

Widely used epidemiological models: extensions based on susceptible-infected-removed (SIR) model (Kermack and McKendrick, 1927)

Epidemiological models capture the dynamics of infectious diseases and dependence between insurance payers and beneficiaries better than traditional actuarial models (Feng and Garrido, 2011).

- Pandemic modeling: extend the deterministic SIR model to a stochastic version (Jia and Tsui, 2005)
- Endemic modeling: extend the deterministic periodic-forced SIR-SEI model (Andraud et al., 2013) to a stochastic version

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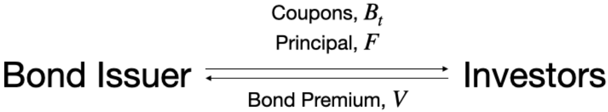
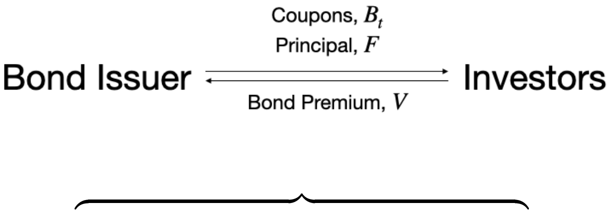
Pandemic Bond Structure

CC_t: Cumulative number of pandemic cases at time t
$RC_t^{(p)}$: Maximum rolling cases in period t with rolling period p
$RC_t^{(p)} = \max_{s \in (t-1,t]} (CC_s - CC_{s-p})$



The coupon and principal payments, B_t and F, depend on the occurrence and severity of any pandemic during term to maturity, measured by $RC_t^{(p)}$.

Pandemic Bond Structure



Design FP

- Fixed principal
- guaranteed payout of maximum amount f

Design VP

- Variable principal
- Depend on the severity of the pandemic outbreak

Pandemic Bond Structure - Fixed Principal

Design FP - Binary Coupon and Fixed Principal (BCFP)
Design FP - Linear Coupon and Fixed Principal (LCFP)

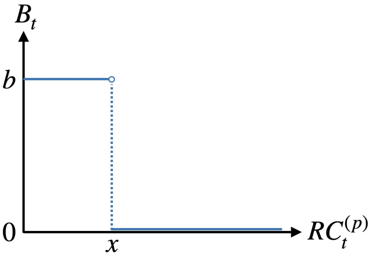


Figure 2: Binary coupon payout

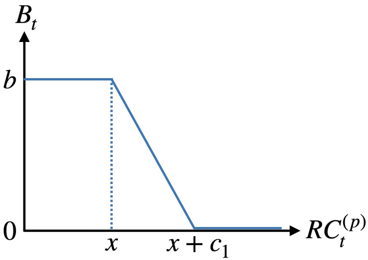


Figure 3: Linear coupon payout

Pandemic Bond Structure - Variable Principal

Design VP - Binary Coupon and Binary Principal (BCBP)
Design VP - Linear Coupon and Binary Principal (LCBP)
Design VP - Linear Coupon and Linear Principal (LCLP)

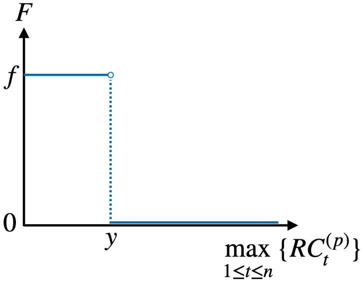


Figure 4: Binary principal payout

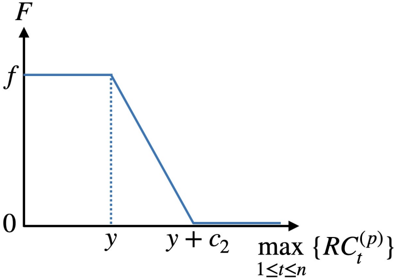


Figure 5: Linear principal payout

Endemic Swap Structure

NC_t: Number of new endemic cases in period t

$$\begin{tikzcd}
\text{Hedgers} \arrow[r, shift left, "\text{Fixed Payment, } C"] & \text{Investors} \arrow[l, shift left, "\text{Floating Payment, } D_t"]
\end{tikzcd}$$

The floating payments, D_t depend on the severity of the endemic in each period during term to maturity, measured by NC_t.

Pricing Framework

Using Wang's transform, an equivalent martingale measure $\mathbb{Q}$ with the market price of risk λ:

$$F_t^{\mathbb{Q}}(u) = \Phi\left[\Phi^{-1}(F_t(u)) - \lambda\right], \tag{1}$$

Bond premium, V:

$$V = \mathrm{E}^{\mathbb{Q}}[F]d(0,n) + \sum_{t=1}^{n} \mathrm{E}^{\mathbb{Q}}\left[B_t\right] d(0,t), \tag{2}$$

Swap fixed payment, C:

$$\sum_{t=1}^{mn} Cd\left(0, \frac{t}{m}\right) = \sum_{t=1}^{mn} \mathrm{E}^{\mathbb{Q}}\left[D_{t/m}\right] d\left(0, \frac{t}{m}\right), \tag{3}$$

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Coronavirus SIR Model

- SIR models in actuarial applications have advantages over traditional actuarial models (Feng and Garrido, 2011)
- Stochastic SIR model introduced by Jia and Tsui (2005)

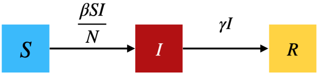
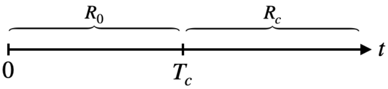


Figure 6: Pandemic SIR model

$$\begin{aligned} \frac{dS}{dt} &= -\frac{\beta SI}{N}, \\ \frac{dI}{dt} &= \frac{\beta SI}{N} - \gamma I, \\ \frac{dR}{dt} &= \gamma I. \end{aligned} \tag{4}$$



T_c: Time to active containment

R_0: Reproduction rate before T_c

R_c: Reproduction rate after T_c

$\beta = \gamma R_0$ or γR_c

$T_c \sim \text{Exp}(1/156 \text{ day}^{-1})$

Coronavirus Bond Simulation & Pricing

Severity simulation

From time $j-1$ to j:

- Number moving from S to $I \sim \text{Poisson}(\frac{\beta(j-1)I(j-1)}{N})$
- Number moving from I to $R \sim \text{Binomial}(I(j-1), \gamma)$

Frequency simulation

On average once every 15 years (IBRD, 2017):

Waiting time $\sim \text{Exp}(1/15 \text{ year}^{-1})$.

Assume no more than one event take place at the same time.

Coronavirus bond pricing

$$V = \mathrm{E}^{\mathbb{Q}}[F]d(0,n) + \sum_{t=1}^{n} \mathrm{E}^{\mathbb{Q}}\left[B_t\right] d(0,t),$$

Coronavirus Bond Pricing Results

Table 1: Bond trigger probability in %

x/N (%)	0.0001			0.01			1		
y/N (%)	0.001			0.1			10		
Year	1	2	3	1	2	3	1	2	3
$\mathrm{P}[RC_t^{(p)} \geq x]$	2.52	4.49	4.73	1.79	3.11	3.21	1.29	2.06	2.11
$\mathrm{P}[RC_t^{(p)} \geq x + c_1]$	2.39	4.26	4.47	1.70	2.93	3.02	1.23	1.93	1.98
$\mathrm{P}[RC_t^{(p)} \geq y]$	2.10	3.70	3.73	1.52	2.51	2.53	1.08	1.63	1.66
$\mathrm{P}[RC_t^{(p)} \geq y + c_2]$	1.99	3.49	3.52	1.45	2.36	2.38	1.00	1.44	1.47

Note: N is the total US population (328.2 million)

Coronavirus Bond Key Findings

- Coupon rates ↑ with
  - ↑ interest rate, ↑ market price of risk λ, and
  - ↓ trigger levels x and y.
- Large differences between Designs FP and Designs VP: Designs VP have much higher coupon rates than Designs FP.
- Small differences between binary and linear reduction design for both coupon reduction and principal reduction.

Coronavirus Bond Pricing Results

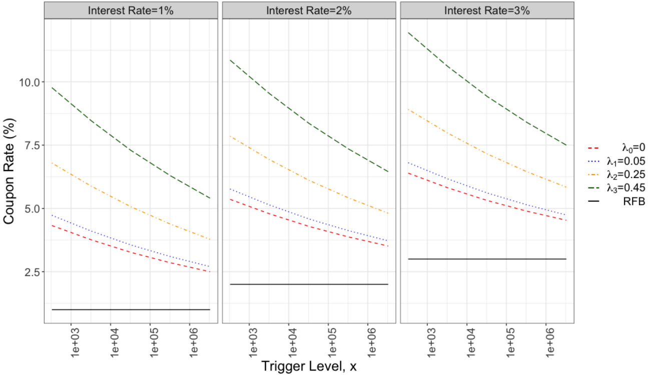


Figure 7: Coupon rates of design BCBP at different interest rates

Coronavirus Bond Pricing Results

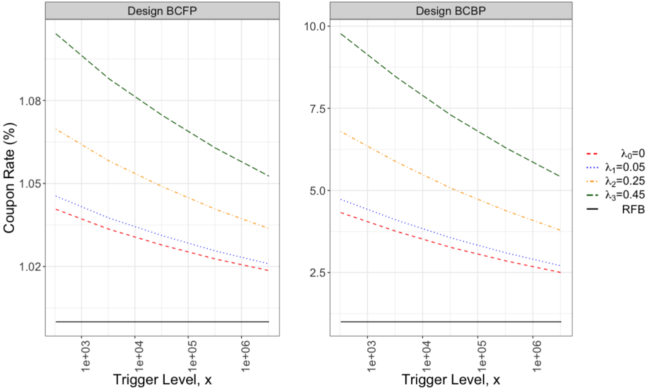


Figure 8: Coupon rates of different designs (interest rate = 1%)

Dengue Periodic SIR-SEI Model

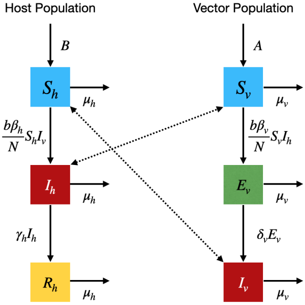


Figure 9: Dengue periodic SIR-SEI model (Andraud et al., 2013)

$$
\begin{aligned}
\frac{dS_h}{dt} &= B - \frac{\beta_h b}{N} S_h I_v - \mu_h S_h, \\
\frac{dI_h}{dt} &= \frac{\beta_h b}{N} S_h I_v - (\gamma_h + \mu_h) I_h, \\
\frac{dR_h}{dt} &= \gamma_h I_h - \mu_h R_h, \\
\frac{dS_v}{dt} &= A(t) - \frac{\beta_v b}{N} S_v I_h - \mu_v S_v, \\
\frac{dE_v}{dt} &= \frac{\beta_v b}{N} S_v I_h - (\delta_v + \mu_v) E_v, \\
\frac{dI_v}{dt} &= \delta_v E_v - \mu_v I_v, \\
A(t) &= A_0(t)(1 + \epsilon \cos(\omega t + \psi)), \\
A_0(t) &= A_0 + mt.
\end{aligned}
\tag{5}
$$

Dengue Swap Simulation & Pricing

Stochastic simulation of dengue cases

From time $t-1$ to t:

- Number moving from S_h to $I_h \sim \text{Poisson}(\frac{b\beta S_h(t-1)I_v(t-1)}{N_h(t-1)})$
- Number moving from I_h to $R_h \sim \text{Binomial}(I_h(t-1), \gamma_h)$
- Number moving from S_v to $E_v \sim \text{Poisson}(\frac{b\beta S_v(t-1)I_h(t-1)}{N_h(t-1)})$
- Number moving from E_v to $I_v \sim \text{Binomial}(E_v(t-1), \gamma_v)$

Dengue swap pricing

$$\sum_{t=1}^{mn} Cd\left(0, \frac{t}{m}\right) = \sum_{t=1}^{mn} \mathrm{E}^{\mathbb{Q}}\left[D_{t/m}\right] d\left(0, \frac{t}{m}\right).$$

Dengue Swap Pricing Results

Table 2: Summary of Dengue Swap Fixed Payments

Term to Maturity	1	2	3	4	5	6	7	8
Panel A: Interest rate = 1%								
$\lambda_0 = 0$	11,755	11,634	11,434	11,193	10,930	10,657	10,384	10,123
$\lambda_1 = 0.05$	11,849	11,756	11,574	11,343	11,087	10,819	10,549	10,291
$\lambda_2 = 0.25$	12,230	12,253	12,141	11,953	11,724	11,474	11,218	10,972
$\lambda_3 = 0.45$	12,618	12,758	12,721	12,577	12,375	12,144	11,903	11,669
Panel B: Interest rate = 2%								
$\lambda_0 = 0$	11,746	11,626	11,429	11,191	10,932	10,664	10,398	10,144
$\lambda_1 = 0.05$	11,840	11,748	11,568	11,340	11,088	10,826	10,562	10,311
$\lambda_2 = 0.25$	12,221	12,244	12,134	11,948	11,723	11,479	11,229	10,989
$\lambda_3 = 0.45$	12,608	12,748	12,711	12,570	12,371	12,146	11,910	11,683
Panel C: Interest rate = 3%								
$\lambda_0 = 0$	11,738	11,618	11,423	11,188	10,933	10,672	10,412	10,164
$\lambda_1 = 0.05$	11,832	11,740	11,562	11,337	11,089	10,832	10,575	10,331
$\lambda_2 = 0.25$	12,212	12,235	12,126	11,943	11,722	11,483	11,239	11,006
$\lambda_3 = 0.45$	12,598	12,738	12,702	12,562	12,368	12,148	11,918	11,697

Dengue Swap Pricing Results

Table 3: The Effectiveness of Dengue Swaps for Hedging Endemic Risk

Panel A: Quantiles of Annual Payments for Dengue Claims								
Year	1	2	3	4	5	6	7	8
5th Quantile	17,829	13,868	11,512	9,538	8,321	7,130	6,188	5,267
10th Quantile	19,002	15,600	13,525	11,903	10,587	9,399	8,438	7,198
25th Quantile	20,987	18,824	17,146	15,843	14,668	13,388	12,194	11,137
50th Quantile	23,340	22,754	21,691	20,584	19,337	18,054	16,860	15,898
75th Quantile	25,888	26,848	26,447	25,513	24,469	23,327	22,073	21,183
90th Quantile	28,267	30,863	31,050	30,293	29,308	28,054	27,045	26,393
95th Quantile	29,898	33,295	34,170	33,351	32,341	31,245	30,273	29,573
Panel B: Fixed Annual Payments from Dengue Swaps								
Term to Maturity	1	2	3	4	5	6	7	8
$\lambda_0 = 0$	23,509	23,268	22,869	22,386	21,859	21,314	20,769	20,247
$\lambda_1 = 0.05$	23,698	23,513	23,148	22,687	22,173	21,637	21,098	20,582
$\lambda_2 = 0.25$	24,460	24,506	24,283	23,907	23,448	22,949	22,437	21,944
$\lambda_3 = 0.45$	25,235	25,517	25,441	25,153	24,749	24,288	23,805	23,338

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Conclusion

- Increasing epidemic risks due to climate change, globalization, and urbanization
- Challenges in epidemic risk management
- Pandemic bonds and endemic swaps with simple structures
    - Pandemic bonds Designs FP and Designs VP are suitable for investors with different risk appetite.
- Provide timely additional capitals in a severe pandemic outbreak
- Stabilize hedgers' cash flows
- Create attractive returns to different investors

Thank you!

Correlation between Stock Market and COVID-19 Cases

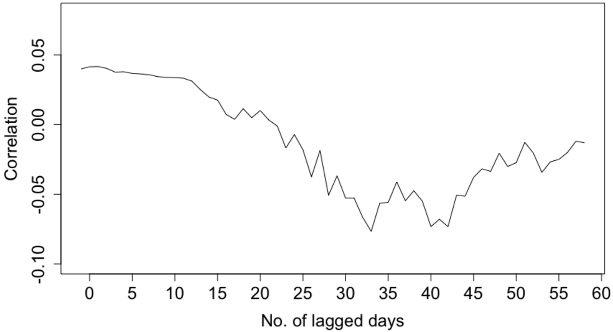

Figure 10: Overall correlations of COVID-19 rolling cases and S&P500 daily returns in 2020

Pandemic SIR Model Parameters

Table 4: SIR Model Parameters

Parameter	**Definition**	**Value**	**Reference**
β	Daily contact rate	γR_0 or γR_c	Calculated
γ (day^{-1})	Daily removal rate	1/13.96	Jia and Tsui (2005)
T_c (day^{-1})	Time until active containment	exp(1/156)	IBRD (2017)
R_0	Reproduction rate before T_c	$\Gamma(6.535, 2.335)$	IBRD (2017)
$E(R_c)$	Mean reproduction rate after T_c	0.57	IBRD (2017)
N	Total population	328.2 million	US Census Bureau (2019)
$I(0)$	Initial index case	1	Jia and Tsui (2005)
$S(0)$	Initial susceptible individuals	N-1	Jia and Tsui (2005)
$R(0)$	Initial removed individuals	0	Jia and Tsui (2005)

Dengue SIR-SEI Model Parameters

Table 5: Dengue SIR-SEI Model Parameters

Parameter	**Definition**	**Value**	**Reference**
B	Host recuritment number	$\mu_g N_h(t)$	Calculated
μ_g (years^{-1})	Host recruitment rate	1.4194%	IBRD (2020))
μ_h (years^{-1})	Host death rate	0.5%	MOH Singapore (2020)
μ_v^{-1} (days)	Vector life expectancy	14.49	Fouque et al. (2006)
γ_h^{-1} (days)	Infectious period	6	Halstead (2007)
δ_v^{-1} (days)	Extrinsic incubation period	10	Rigau-Pérez et al. (1996)
b (days^{-1})	Biting rate	0.76	Scott et al. (2000)
β_h	Probability of transmission from vector to host	0.75	Newton and Reiter (1992)
β_v	Probability of transmission from host to vector	0.75	Newton and Reiter (1992)
T_0	Initial time for simulation	Start of 2014	Start of data sample

Dengue SIR-SEI Model Parameters

Table 6: Dengue SIR-SEI Model Parameters

Parameter	**Definition**	**Value**	**Reference**
$N_h(0)$	Total Singaporean population at the end of 2013	5,399,162	IBRD (2020))
$S_h(0)$	Initial proportion of susceptible individuals at T_0(%)	56.9	Ooi et al. (2001)
$I_h(0)$	Dengue cases in the 1st week of 2014 (an approximate of the initial no. of infectious hosts	437	MOH Singapore (2019)
$E_v(0)$	Initial no. of exposed vectors	0	Audraud et al. (2013)
ϵ	Factor of periodic forcing	0.22	Audraud et al. (2013)
ψ	Phase of periodic forcing	-2.93	Audraud et al. (2013)
A_0	Initial average recruitment rate	39.445	Estimated
m	Increment rate of $A_0(t)$	0.5845	Estimated
$I_v(0)$	Initial no. of infectious vectors	391	Estimated

Sensitivity Test on Frequency Distribution

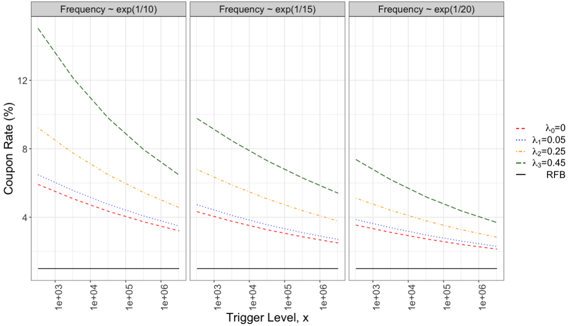

Figure 11: Coupon rates of BCBP structure with different frequency distributions (interest rate = 1%)

Sensitivity Test on R_0 Distribution

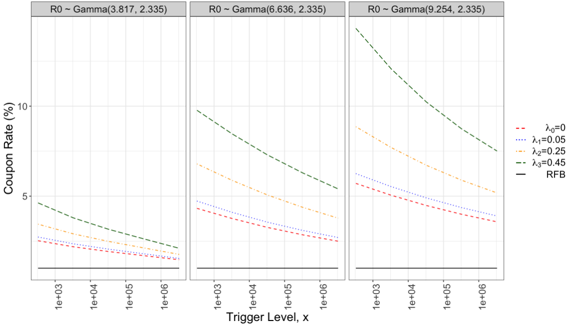

Figure 12: Coupon rates of BCBP structure with different R_0 distributions (interest rate = 1%)

Sensitivity Test on y/x ratio

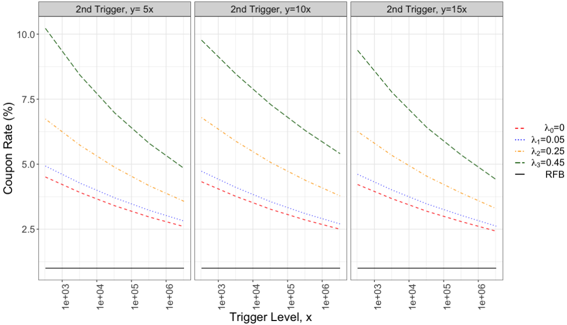

Figure 13: Coupon rates of BCBP structure with different y/x ratio (interest rate $= 1\%$)