Pandemic Risk Management: Resources
Contingency Planning and Allocation

Alfred Chong, Runhuan Feng, Linfeng Zhang
University of Illinois at Urbana-Champaign

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Based on a working paper by Xiaowei Chen (Nankai), Alfred Chong (UIUC), Runhuan Feng (UIUC), and Linfeng Zhang (UIUC).
Repeated pandemics taught us that epidemic risk is inevitable.
An example of COVID-19 coverage (JustInCase, Japan)

About COVID-19 Cover

- Procedure is completed on smartphone or web, no face-to-face contact with people is required
- A lump sum benefit payment of ¥100,000 for hospitalization for 2 days 1 night or longer
- Those who are diagnosed with new coronavirus and treat it at home are also covered
- Coverage is effective immediately after the completion of purchase process

Affordable premium (on monthly basis as shown below)

<table>
<thead>
<tr>
<th>Entry age of the insured</th>
<th>Male</th>
<th>Female</th>
</tr>
</thead>
<tbody>
<tr>
<td>15~19</td>
<td>¥ 580</td>
<td>¥ 560</td>
</tr>
<tr>
<td>20~24</td>
<td>¥ 560</td>
<td>¥ 660</td>
</tr>
<tr>
<td>25~29</td>
<td>¥ 530</td>
<td>¥ 940</td>
</tr>
<tr>
<td>30~34</td>
<td>¥ 510</td>
<td>¥ 960</td>
</tr>
<tr>
<td>35~39</td>
<td>¥ 530</td>
<td>¥ 760</td>
</tr>
<tr>
<td>40~44</td>
<td>¥ 580</td>
<td>¥ 650</td>
</tr>
<tr>
<td>45~49</td>
<td>¥ 610</td>
<td>¥ 630</td>
</tr>
<tr>
<td>50~54</td>
<td>¥ 640</td>
<td>¥ 670</td>
</tr>
<tr>
<td>55~59</td>
<td>¥ 710</td>
<td>¥ 710</td>
</tr>
<tr>
<td>60~64</td>
<td>¥ 730</td>
<td>¥ 770</td>
</tr>
</tbody>
</table>
Compartmental models

\[ S - \text{susceptible}, \ I - \text{infectious}, \ R - \text{removed} \]

\[ S'(t) = -\beta I(t)S(t)/N, \]
\[ I'(t) = \beta I(t)S(t)/N - \alpha I(t), \]
\[ R'(t) = \alpha I(t), \]

where \( S(0) = S_0, I(0) = I_0 \) and \( R(0) = 0 \).

- The total number of individuals remains constant, \( N = S(t) + I(t) + R(t) \).
- An average susceptible makes an average number \( \beta \) of adequate contacts w. others per unit time. (Law of mass action)
- Fatality/recovery rate of the specific disease, \( \alpha \).
Basic reproduction number

Average number of new infections from a single infection

\[ R_t = \frac{\beta}{\alpha} \frac{S(t)}{N}. \]

- Average time between contacts, \( T_c = 1/\beta. \)
- Average time until removal, \( T_r = 1/\alpha. \)
- Average number of contacts by an infected person with others before removal, \( T_r/T_c = \beta/\alpha. \)

(Do not confuse \( R_t \) with the size of removed class \( R(t) \).)
Importance of basic reproduction number

Average number of new infections from a single infection

\[ R_t = \frac{\beta S(t)}{\alpha N}. \]

- If \( R_t > 1 \), the epidemic will break out.
- If \( R_t < 1 \), the epidemic will die out.

Effect of public health policies (non-pharmaceutical interventions)

- Quarantine, social distancing, mandatory face mask: lower transmission rate \( \beta \);
- Vaccination: lower susceptible \( S(t) \);
Infectious disease insurance

Figure: Transmission and Insurance Dynamics
Insurance reserve

Consider an insurance policy that

- provides 1 monetary unit of compensation per time unit for each infected policyholder for the entire period of treatment; *(intended to cover medical costs)*

- collects premium at the rate of $\pi$ per time unit from each susceptible policyholder at a fixed rate per time unit until the pandemic ends or the policyholder is infected; *(monthly premium in practice)*

- **Premium incomes**

  \[ P(t) = \pi \int_0^t s(u) \, du, \quad s(u) = S(u)/N. \]

- **Benefit outgoes**

  \[ B(t) = \int_0^t i(u) \, du, \quad s(u) = I(u)/N. \]

- **Insurance reserve**

  \[ V(t) = P(t) - B(t). \]
Reserve for a typical term life contract

Figure 7.4 Policy values for each year of a 20-year term insurance, sum insured $500,000, issued to (50).

Four shapes of reserves

(We use various premium rate, not necessarily net level premium)
Importance of basic reproduction number in reserving

<table>
<thead>
<tr>
<th>Shape of $V(t)$</th>
<th>Premium $\pi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increasing and concave</td>
<td>$\left[ \frac{1}{R_\infty} - 1, \infty \right)$</td>
</tr>
<tr>
<td>Increasing and concave-then-convex</td>
<td>$\left[ \frac{1}{R_{tm}} - 1, \frac{1}{R_\infty} - 1 \right)$</td>
</tr>
<tr>
<td>Non-monotonic and concave-then-convex</td>
<td>$\left[ \frac{1}{R_0} - 1, \frac{1}{R_{tm}} - 1 \right)$</td>
</tr>
<tr>
<td>Non-monotonic and convex</td>
<td>$\left[ -\infty, \frac{1}{R_0} - 1 \right)$</td>
</tr>
</tbody>
</table>

Since $S(t)$ is a decreasing function, then $R_0 > R_{tm} > R_\infty$.

The exact expression of $R_{tm}$ is provided in Feng and Garrido (2011).
A classic example of the SIR model fitted to data from the bubonic plague in Eyam near Sheffield, England.

<table>
<thead>
<tr>
<th>Date</th>
<th>Susceptible</th>
<th>Infective</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>254</td>
<td>7</td>
</tr>
<tr>
<td>July 3-4</td>
<td>235</td>
<td>14.5</td>
</tr>
<tr>
<td>July 19</td>
<td>201</td>
<td>22</td>
</tr>
<tr>
<td>August 3-4</td>
<td>153.5</td>
<td>29</td>
</tr>
<tr>
<td>September 3-4</td>
<td>108</td>
<td>8</td>
</tr>
<tr>
<td>September 19</td>
<td>97</td>
<td>8</td>
</tr>
<tr>
<td>October 20</td>
<td>83</td>
<td>0</td>
</tr>
</tbody>
</table>

- \( s_0 = \frac{254}{261} = 0.97318, s_\infty = \frac{83}{261} = 0.31801 \) and \( i_0 = \frac{7}{261} = 0.02682 \);
- From clinical observations, an infected person stays infectious for an average of 11 days, \( \alpha = \frac{1}{0.3667} = 2.73 \);
- \( \beta/\alpha \approx \ln\left(\frac{s_0}{s_\infty}\right)/\left(1 - s_\infty\right) \), which implies \( \beta = 4.4773 \);
- Design a policy that pays 1,000 per month to all infected. The minimum monthly premium to keep positive reserves is 114.58 for each susceptible. Each survivor receives a reward of 49.44 at the end.
Contingency planning

Emerging viral pandemics “can place extraordinary and sustained demands on public health and health systems and on providers of essential community services.”
Strategic National Stockpile (SNS)

United States’ national repository of antibiotics, vaccines, chemical antidotes, antitoxins, and other critical medical supplies.

www.PHE.gov
US underprepared for COVID-19

- Failure of Congress to appropriate funding for SNS and to authorize actions to replenish stockpiles
- Supply-chain changes such as just-in-time manufacturing and globalization
- Lack of a coordinated Federal/State plan to deploy existing supplies rapidly to locations of great need.
Epidemic forecast model (Sec. 3.2.1)

Demand assessment (Sec. 3.2.2)

Resources demand prediction (Sec. 3.2)

Centralized stockpile strategy (Sec. 3.3)

Resources allocation (Sec. 5)

Centralized acquisition strategy (Sec. 4)

Contingency planning

Emergency response
Evolution of epidemic in an SEIR model

- **Susceptible (S)**
- **Exposed (E)**
- **Mild infected (I₁)**
- **Hospitalized infected (I₂)**
- **ICU infected (I₃)**
- **Recovered (R)**
- **Deceased (D)**
# Prediction of healthcare demand

An assessment of needs for personal protective equipment (PPE) set (respirator, goggle, face shield) by ECDC

<table>
<thead>
<tr>
<th>Healthcare staff</th>
<th>Suspected case $\theta^S$</th>
<th>Confirmed case Mild symptoms $\theta^{I_1}$</th>
<th>Confirmed case Severe symptoms $\theta^{I_2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nursing</td>
<td>1-2</td>
<td>6</td>
<td>6-12</td>
</tr>
<tr>
<td>Medical</td>
<td>1</td>
<td>2-3</td>
<td>3-6</td>
</tr>
<tr>
<td>Cleaning</td>
<td>1</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Assistant nursing and other services</td>
<td>0-2</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Total</td>
<td>3–6</td>
<td>14–15</td>
<td>15–24</td>
</tr>
</tbody>
</table>
Recall the SIR model ($S$ – susceptible, $I$ – infectious)

$$S'(t) = -\beta S(t)I(t)/N,$$
$$I'(t) = \beta S(t)I(t)/N - \alpha I(t).$$

The demand for PPE can be estimated by

$$X(t) = \theta^S \beta S(t)I(t)/N + \theta^I I(t).$$

(Better estimate requires a refined compartmental model such as SEIR models)
A central authority acts in the interest of a union to manage and allocate supply among different regions.

Six US northeastern states formed a coalition in April 2020 to purchase COVID-19 medical equipment to avoid price bidding competition.

US states at different phases of the pandemic:
Risk aggregation and capital allocation

- Individual loss
- Aggregate loss
- Aggregate capital
- Allocated capital
Durable resources stockpiling and allocation

Regional demand
Aggregate demand
Aggregate supply
Allocated supply
Durable resources (ventilator, ICU bed, hospital bed, etc.)

Shortage stockpiling
Durable resources (ventilator, ICU bed, hospital bed, etc.)
Oversupply stockpiling
Durable resources (ventilator, ICU bed, hospital bed, etc.)

Optimal stockpiling
Durable resources (ventilator, ICU bed, hospital bed, etc.)
Optimal allocation at the FIRST peak

Aggregate supply

First peak

Onset

Onset
Durable resources (ventilator, ICU bed, hospital bed, etc.)

Optimal allocation at the SECOND peak
Durable resources (ventilator, ICU bed, hospital bed, etc.)
Optimal allocation at the THIRD peak

Post peak

Aggregate supply

Post peak → Third Peak
Durable resources (ventilator, ICU bed, hospital bed, etc.)

Ventilator example
Single-use resources stockpil., distribution, and allocation

Regional demand

Aggregate demand

Storage and aggregate supply

Allocated supply
Single-use resources (testing kit, PPE, etc.)
Stockpiling and early distribution

Aggregate demand

Storage

Aggregate supply
Single-use resources (testing kit, PPE, etc.)

Stockpiling and late distribution

Aggregate demand

Storage

Aggregate supply
Single-use resources (testing kit, PPE, etc.)
Optimal stockpiling and distribution

Aggregate demand

Storage

Aggregate supply
Single-use resources (testing kit, PPE, etc.)
Optimal allocation
Single-use resources (testing kit, PPE, etc.)

Testing kit example


Thank you!

COVID Plan website
 covidplan.io

Contact us:
 chenx@nankai.edu.cn
 wfchong@illinois.edu
 rfeng@illinois.edu
 lzhang18@illinois.edu