Pandemic Risk Management: Resources Contingency Planning and Allocation

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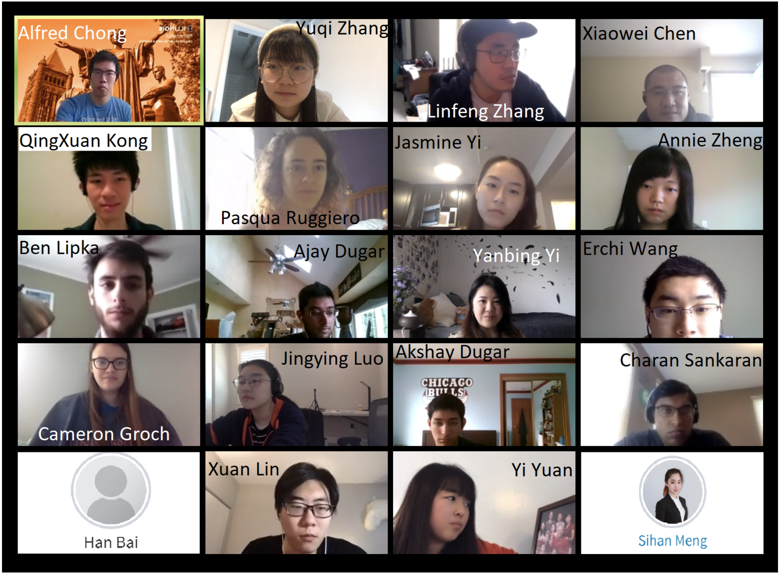
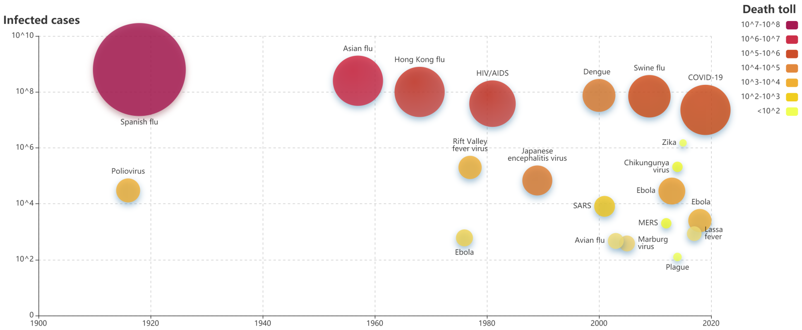
Based on a working paper by Xiaowei Chen (Nankai), Alfred Chong (UIUC), Runhuan Feng (UIUC), and Linfeng Zhang (UIUC).

Illinois Risk Lab



Long history of pandemics

Repeated pandemics taught us that epidemic risk is inevitable.



Contingency planning

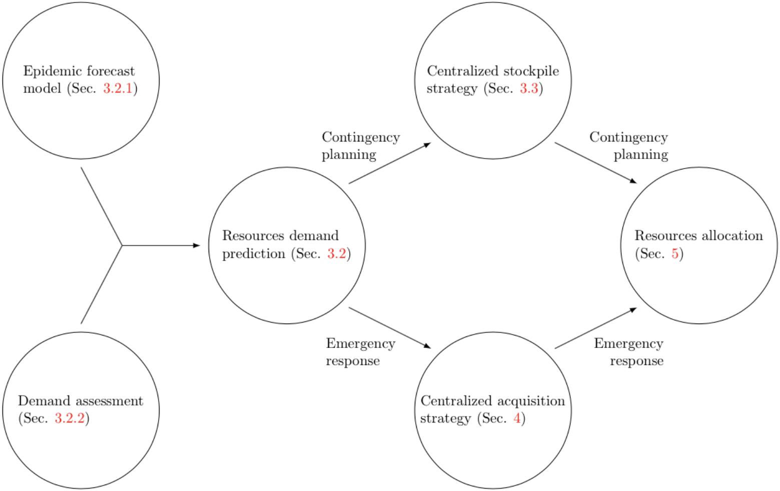
Emerging viral pandemics "can place extraordinary and sustained demands on public health and health systems and on providers of essential community services."

Strategic National Stockpile (SNS)

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

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)
Contingency planning
Emergency response
Centralized stockpile strategy (Sec. 3.3)
Centralized acquisition strategy (Sec. 4)
Contingency planning
Emergency response
Resources allocation (Sec. 5)

Compartmental models

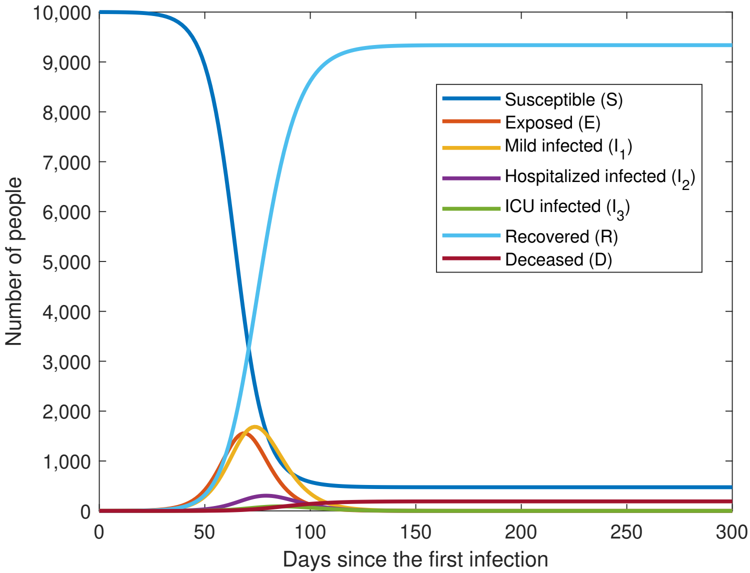
S – susceptible, I – infectious, R – removed

$$\begin{aligned} S'(t) &= -\,\beta I(t)S(t)/N, \\ I'(t) &= \beta I(t)S(t)/N - \alpha I(t), \\ R'(t) &= \alpha I(t), \end{aligned}$$

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 β of **adequate** contacts w. others per unit time. (Law of mass action)
- Fatality/recovery rate of the specific disease, α.

Evolution of epidemic in an SEIR model



Prediction of healthcare demand

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

	Suspected case	Confirmed case Mild symptoms	Confirmed case Severe symptoms
Healthcare staff	Number of sets per case θ^{S}	Number of sets per day per patient θ^{I_1}	θ^{I_2}
Nursing	1-2	6	6-12
Medical	1	2-3	3-6
Cleaning	1	3	3
Assistant nursing and other services	0-2	3	3
Total	3–6	14–15	15–24

Recall the SIR model (S – susceptible, I – infectious)

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

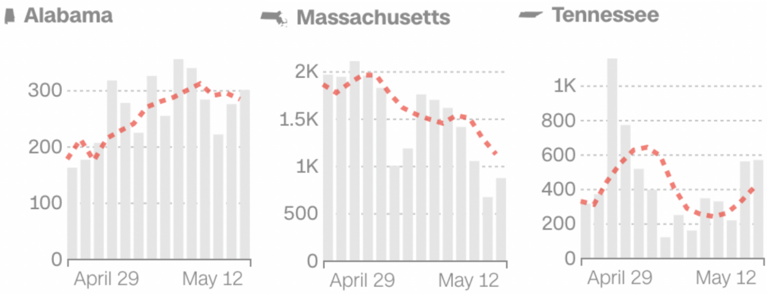
The demand for PPE can be estimated by

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

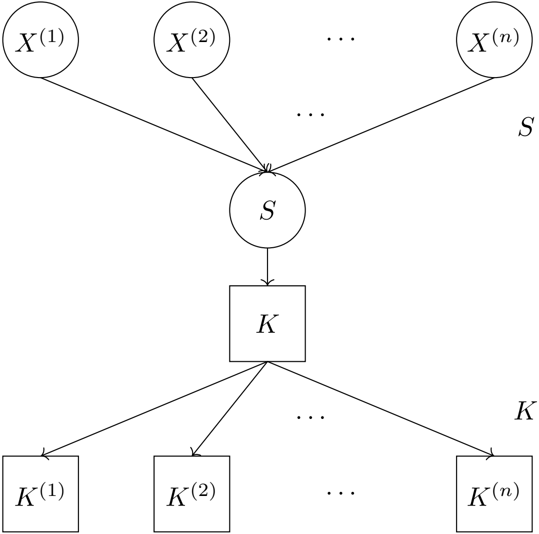
(Better estimate requires a refined compartmental model such as SEIR models)

Resources allegiance

- 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

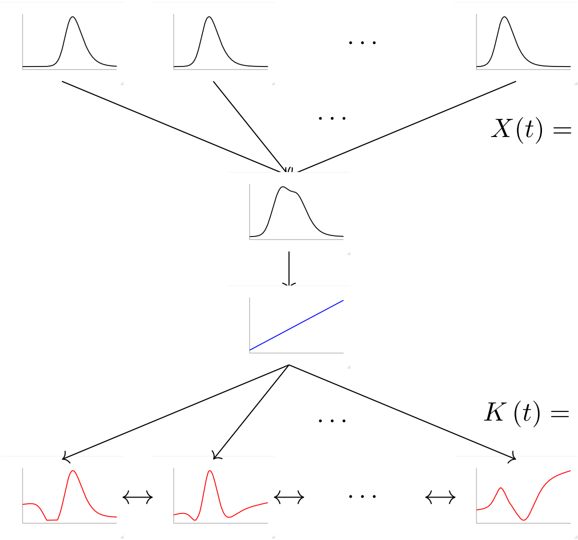


$$S = X^{(1)} + \cdots + X^{(n)}$$

$$K = \rho\,(S)$$

$$K = K^{(1)} + \cdots + K^{(n)}$$

Durable resources stockpiling and allocation



$$X(t) = X^{(1)}(t) + \cdots + X^{(n)}(t)$$

$$K(t) = K_0 + at$$

$$K\left(t\right) = K^{(1)}\left(t\right) + \cdots + K^{(n)}\left(t\right)$$

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

Optimal stockpiling

$$\boxed{\min_{K_0 \geq 0} \sum_{j=1}^{m} \omega_j \left(\frac{\theta_j}{2} \left(X_j - (K_0 + aj) \right)^2 + c_j \left(K_0 + aj \right) \right) + c_0 K_0.}$$

If $\sum_{j=1}^{m} \omega_j \theta_j \left((X_j - aj) - \frac{c_j}{\theta_j} \right) \geq c_0$,

$$K_0 = \frac{\sum_{j=1}^{m} \omega_j \theta_j \left((X_j - aj) - \frac{c_j}{\theta_j} \right) - c_0}{\sum_{j=1}^{m} \omega_j \theta_j}.$$

If $\sum_{j=1}^{m} \omega_j \theta_j \left((X_j - aj) - \frac{c_j}{\theta_j} \right) < c_0$,

$$K_0 = 0.$$

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

Optimal allocation

$$\min_{K_j^{(i)}} \sum_{j=1}^{m} \sum_{i=1}^{n} \omega_j^{(i)} \left(\frac{\theta_j^{(i)}}{2} \left(X_j^{(i)} - K_j^{(i)} \right)^2 + \nu_j^{(i)} \left(K_j^{(i)} - K_{j-1}^{(i)} \right) \right)$$

$$\text{s.t.} \sum_{i=1}^{n} K_j^{(i)} = K_j, \quad \text{for } j = 1, 2, \ldots, m.$$

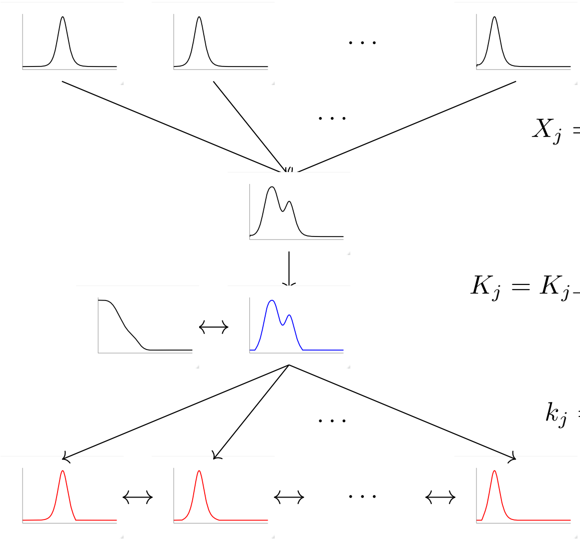
For any $j = 1, 2, \ldots, m$, and $i = 1, 2, \ldots, n$,

$$K_j^{(i)} = \left(1 - \frac{\frac{1}{\omega_j^{(i)} \theta_j^{(i)}}}{\sum_{r=1}^{n} \frac{1}{\omega_j^{(r)} \theta_j^{(r)}}} \right) \left(X_j^{(i)} - \frac{\nu_j^{(i)} - \nu_{j+1}^{(i)}}{\theta_j^{(i)}} \right) + \frac{\frac{1}{\omega_j^{(i)} \theta_j^{(i)}}}{\sum_{r=1}^{n} \frac{1}{\omega_j^{(r)} \theta_j^{(r)}}} \left(K_j - \sum_{r=1; r \neq i}^{n} \left(X_j^{(r)} - \frac{\nu_j^{(r)} - \nu_{j+1}^{(r)}}{\theta_j^{(r)}} \right) \right).$$

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

Ventilator example

Single-use resources stockpil., distribution, and allocation



$$X_j = X_j^{(1)} + \cdots + X_j^{(n)}$$

$$K_0, k_1, \ldots, k_m$$

$$K_j = K_{j-1} + a - k_j + (k_j - X_j)_+$$

$$k_j = k_j^{(1)} + \cdots + k_j^{(n)}$$

$$\min_{K_0,k_1,\ldots,k_m} \sum_{j=1}^{m} \omega_j \left(\frac{\theta_j}{2} (X_j - k_j)^2 + c_j K_j \right) + c_0 K_0$$

$$\text{s.t. } K_0 \geq 0, k_j \geq 0, K_j = K_{j-1} + a - k_j + (k_j - X_j)_+ \geq 0.$$

For any $j = 2, \ldots, m$,

$$V(j-1, K_{j-1}) = \min_{k_j,\ldots,k_m} \sum_{l=j}^{m} w_l \left(\frac{\theta_l}{2} (X_l - k_l)^2 + c_l K_l \right)$$

$$= \min_{k_j \geq 0} \left(w_j \left(\frac{\theta_j}{2} (X_j - k_j)^2 + c_j K_j \right) + V(j, K_j) \right);$$

$$V(0, K_0) = \min_{k_1,\ldots,k_m} \sum_{l=1}^{m} w_l \left(\frac{\theta_l}{2} (X_l - k_l)^2 + c_l K_l \right) + c_0 K_0$$

$$= \min_{k_1 \geq 0} \left(w_j \left(\frac{\theta_j}{2} (X_j - k_j)^2 + c_j K_j \right) + c_0 K_0 + V(j, K_j) \right).$$

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

Optimal allocation

$$\min_{k_j^{(i)}} \sum_{j=1}^{m} \sum_{i=1}^{n} \omega_j^{(i)} \left(\frac{\theta_j^{(i)}}{2} \left(X_j^{(i)} - k_j^{(i)} \right)^2 + \nu_j^{(i)} k_j^{(i)} \right)$$

$$\text{s.t.} \sum_{i=1}^{n} k_j^{(i)} = k_j, \quad \text{for } j = 1, 2, \ldots, m.$$

For any $j = 1, 2, \ldots, m$, and $i = 1, 2, \ldots, n$,

$$k_j^{(i)} = \left(1 - \frac{\frac{1}{\omega_j^{(i)} \theta_j^{(i)}}}{\sum_{r=1}^{n} \frac{1}{\omega_j^{(r)} \theta_j^{(r)}}} \right) \left(X_j^{(i)} - \frac{\nu_j^{(i)}}{\theta_j^{(i)}} \right) + \frac{\frac{1}{\omega_j^{(i)} \theta_j^{(i)}}}{\sum_{r=1}^{n} \frac{1}{\omega_j^{(r)} \theta_j^{(r)}}} \left(k_j - \sum_{r=1; r \neq i}^{n} \left(X_j^{(r)} - \frac{\nu_j^{(r)}}{\theta_j^{(r)}} \right) \right).$$

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

Testing kit example

COVID Plan website

`covidplan.io`

References

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Thank you!

COVID Plan website

covidplan.io

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