“Modeling post-earthquake hospital system resilience”

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Motivation

- Critical issues for hospital systems
  - High demand and reduced capacity
  - Transfer of large number of patients

- Objectives:
  - Develop probabilistic formulation for:
    - Earthquake casualties
    - Reduction of functionality
    - Patient treatment and optimized patient transfer strategy
  - Provide application to Lima, Peru
Post-earthquake hospital capacity and demand

Number of people

Gap

t_{EQ}

time

Casualties
Hospital functionality

Emergency response period is key

Strategic patient mobilization speeds up patient treatment
Post-earthquake hospital system response

Casualties → Hospital functionality → Treatment and patient redistribution
Post-earthquake hospital system response

Casualties → Hospital functionality → Treatment and patient redistribution
Probabilistic formulation for multi-severity earthquake casualty occurrence

Earthquake ($M_w$, Location)  Probabilistic model:

Intensity measure (region):

$$Sa(T)|M_w, Loc. \sim \ln N(\mu_{ln Sa}, \Sigma_{ln Sa})$$

Damage state (building):

$$DS_{j,k} | Sa_{j,k} \sim \text{Multinomial}([p_{1,k}, p_{2,k}, \ldots, p_{n_{DS,k}}], 1)$$

Occupants’ injury severity (building)

$$I_{j,k} | DS_{j,k} = m \sim \text{Multinomial}([r_{1,m}, r_{2,m}, \ldots, r_{n_{HS,k}}], n_{j,k})$$

After Ceferino et al., 2018
Earthquake casualties after Mw 8.0 in Lima, Peru

- 1940 Lima earthquake scenario
  - 10 M people
  - Nighttime

- Assessment of fatalities and 3 injury severities
  - Exposure and ground motions in a 1 km x 1km grid
  - 36 structural typologies (Villar et al., 2017)
Casualties needing operating rooms (ORs)

- **Severity 1 (minor)**
- **Severity 2:**
  - Need hospital hospitalization, but not life threatening
    - Burns, fractures.
  - A few might need ORs
  - 60% confidence interval: <4k - 50k>
- **Severity 3:**
  - Need immediate treatment or life threatening
    - Punctured organ, crush syndrome
  - Most will need ORs
  - 60% confidence interval: <0.5k - 6k>
Post-earthquake hospital system response

- Casualties
- Hospital functionality
- Treatment patient redistribution
Probabilistic formulation for hospital post-earthquake functionality

Earthquake (Mw, Location)  Probabilistic model:

Intensity measure (region):

... \( S_a(T_{k,j,k}) \) ... \( S_a(T) \mid \text{Mw,Loc.} \sim \ln N(\mu_{lnSa}, \Sigma_{lnSa}) \)

Damage state (building):

... \( D_{S,j,k} \) ... \( D_{S,j,k} \mid S_{a,j,k} \sim \text{Multinomial}(\{p_{1,j,k}, p_{2,j,k}, \ldots, p_{n_{DS},k}\}, \ 1) \)

Functional operating rooms/beds (building)

... \( F_{j,k} \) ... \( F_{j,k} \mid D_{S,j,k} = m \sim \text{Binomial}(q_m) \)
Post-earthquake functional operating rooms (ORs)

- **Hospital database:**
  - 41 public hospital campuses
  - More than 500 buildings

- **Hospital functionality:**
  - Based on structural damage
  - ORs were assumed to work in:
    - 100% of the non-damaged buildings
    - 50% of the slightly damaged building
  - 60% confidence interval: <7% - 51%>
Post-earthquake hospital system response

Casualties

Hospital functionality

Treatment and patient redistribution
Modeling for post-earthquake patient treatment and redistribution

- Static framework

- However, patient treatment is a dynamic process
  - Treatment procedures
  - Patient transfer among hospitals
Network model

**Nodes:**
- Triage
- Discharge

**Edges:**
- Treatment
- Transportation

**Patient flow variables:**
- $x_{i,j}(t)$: Flux of patients at time $t$
- $b_i(t)$: Patients entering triage $i$ or leaving discharge at time $t$
Minimum cost time-varying network flow

Minimize \( \alpha \sum_{t=0}^{T} \sum_{i=1}^{n_h} -x_{i,i+n_h}(t) \times t + \beta \sum_{t=0}^{T} \sum_{i=1}^{n_h} \sum_{j=1}^{n_h} x_{i,j}(t) \)

Patient Waiting Time  Number of trips

s.t. : Constraints:

(1) Flow conservation: \( \sum_{j=1}^{n_h} x_{i,j}(t) - \sum_{j=1}^{n_h} x_{j,i}(t - \tau_{i,j}(t)) + y_i(t + dt) - y_i(t) = b(i), \quad \forall i \in \text{Triage}, t \in \{0, dt, \ldots, T\} \)

(2) Operating room and ambulance constraints + Positive flow
\( 0 \leq x_{i,j}(t) \leq u_{i,j}(t), \quad \forall (i,j) \in E, t \in \{0, dt, \ldots, T\} \)

(3) Positive number of patients waiting in triage
\( 0 \leq y_i(t), \quad \forall (i) \in \text{Triage}, t \in \{0, dt, \ldots, T\} \)

Linear Programming (LP) Problem
Optimized patient treatment protocol

- **1000 realizations of:**
  - Casualties needing ORs
  - Functional ORs
  - Optimized patient transportation protocols

- **Observations**
  - Most casualties occur in the periphery of the city.
  - Most available ORs are at the city center.
  - Routes from the periphery to the center are key for optimized patient redistribution.
Conclusions

- Critical issues for post-earthquake hospital resilience:
  - High demand and reduced capacity
  - Mobilization of large number of patients

- Development of probabilistic formulation for:
  - Multi-severity casualties
  - Hospital bed and operating room availability
  - Optimization for patient redistribution

- Application to Lima subjected to a Mw 8.0 earthquake shows:
  - $<0.5k - 6k>$ might need ORs.
  - Only $<7\% - 51\%>$ ORs might be functional.
  - Patient transportation routes from the periphery to the center is key for timely treatment.
THANK YOU

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