Optimizing Inter-facility Patient Transfer Decisions During a Pandemic: A Queueing Network Approach

Vahid Sarhangian [1]

Joint work with: Timothy C. Y. Chan[1], Frances Pogacar [3], Erik Hellsten [3], Fahad Razak [1,2], Amol Verma [1,2]

1. University of Toronto; 2. St. Michael's Hospital; 3. Ontario Health

Motivation

- Geographical mismatch between demand for hospitalization and hospital capacity during the pandemic
  - Some hospitals experienced high occupancy levels, while other hospitals had plenty of capacity
  - High occupancy levels associated with worsened health outcomes (Eriksson 2017, Bravata 2021)
  - Inequity in access to care

One Hospital Was Besieged by the Virus. Nearby Was 'Plenty of Space.'

Even as Elmhurst faced "apocalyptic" conditions, 3,500 beds were free in other New York hospitals, some no more than 20 minutes away.

Why Surviving the Virus Might Come Down to Which Hospital Admits You

In New York City's poor neighborhoods, some patients have languished in understaffed hospitals, with substandard equipment. It was a different story in Manhattan's private medical centers.

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- Transfer decisions in Ontario:
  - The Incident Management System (IMS) oversaw the transfer of non-ICU patients
  - This work was initiated in collaboration with Ontario Health that provided quantitative support to the Greater Toronto Area (GTA) IMS
  - The GTA IMS accounted for 64% of the transfer activity in the province
  - The GTA IMS group met weekly/daily to review current and projected occupancy levels of hospitals in the GTA and propose patient transfers

Objectives and Approach

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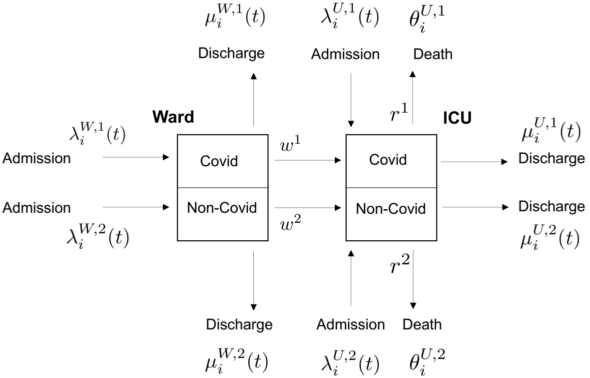
- **Approach**:
  - Queueing model of patient flow within and between hospitals of a health system
  - Formulate the problem of optimizing inter-facility decisions as a stochastic queueing control problem
  - Propose a solution method
  - Validate the model and test the performance of the approach in a case study using data from 21 hospitals in the GTA

Queueing Model - Single Hospital

- Two-stage tandem queue with blocking



  - Two patient classes: (1) Covid and (2) non-Covid
  - Infinite capacity ward, finite capacity ICU
  - When ICU is at capacity, patients occupy and *block* ward beds

Stochastic Control Problem

- Network of hospitals $\mathcal{H}$
- Discrete-time control over a finite horizon of length T
- **Decision epochs:** End of each day, after all new admissions have been realized
- **State**: W/ICU Occupancy and number of new arrivals for each patient type k and hospital $i \in \mathcal{H}$:
  $Q_i(t) := (Q_i^{W,1}(t), Q_i^{W,2}(t), Q_i^{U,1}(t), Q_i^{U,2}(t))$,
  $A_i(\tau) := (A_i^{W,1}(\tau), A_i^{W,2}(\tau), A_i^{U,1}(\tau), A_i^{U,2}(\tau))$
- **Admissible policy**: Mapping from the current state to the number of new patients of each type to be transferred from hospital i to hospital j, $\forall i, j \in \mathcal{H}$
- **Objective**: Minimize the *expected total cost* over the horizon

Stochastic Control Problem - Costs

Total cost is a weighted sum of:

- **Over-occupancy** costs: Number of patient-days above ward and ICU occupancy thresholds $\mathcal{T}_i^W, \mathcal{T}_i^U$

$$C_T^{(1)} = \sum_{i \in \mathcal{H}} \int_0^T c^W (Q_i^W(t) - \mathcal{T}_i^W)^+ + c^U (Q_i^U(t) - \mathcal{T}_i^U)^+ dt$$

- **Transfer** costs (fixed cost d_{ij} and distance-dependent variable cost b_{ijk}) for each hospital pair:

$$C_T^{(2)} = \sum_{k \in \mathcal{K}} \sum_{i \in \mathcal{H}} \sum_{j \in \mathcal{H}} N_{ij}^k(T)(b_{ijk} + d_{ij})$$

Stochastic Control Problem - Costs

- **COVID load inequity**: Number of patient-days above a hospital's "fair COVID share":

$$C_T^{(3)} = \sum_{i \in \mathcal{H}} c^f \int_0^T \Bigg(Q_i^{U,1}(t) + Q_i^{W,1}(t) - \frac{n_i^{U_1} + n_i^{W_1}}{\sum_{i \in \mathcal{H}} n_i^{U_1} + n_i^{W_1}} \sum_{i \in \mathcal{H}} (Q_i^{U,1}(t) + Q_i^{W,1}(t)) \Bigg)^+ dt.$$

"fair COVID share" = proportional to bed capacity

Solution Approach

- Fluid model of single hospital model
  - Deterministic approximation of the transient dynamics without transfers
  - Justified by a FSLLN (Mandelbaum et al. 1998 and Zychlinski et al. 2020)
  - Accurately approximates the transient dynamics when the system is "large"
- Associated fluid control problem for the entire network
- Translate the solution for the stochastic system using a model predictive (rolling horizon) approach

Solution Approach - Fluid Control

- $q(t)$: number of COVID and non-COVID patients in the ward and ICU at time $t \geq 0$.
- $p_{ij}^{W,k}(t)$ and $p_{ij}^{U,k}(t)$ denote the fraction of class k ward and ICU fluid arriving at hospital i that is transferred to hospital j.

$$\begin{aligned}
\text{min } & c_T^{(1)} + c_T^{(2)} + c_T^{(3)} \\
\text{s.t. } & \sum_{j \in \mathcal{H}} p_{ij}^{W,k}(t) = 1, \quad \forall k \in \mathcal{K}, i \in \mathcal{H}, t \in [0, T], \\
& \sum_{j \in \mathcal{H}} p_{ij}^{U,k}(t) = 1, \quad \forall k \in \mathcal{K}, i \in \mathcal{H}, t \in [0, T], \\
& q_i(0) = q_i, \quad \forall i \in \mathcal{H}, \\
& \text{DEs governing the dynamics of } q(t).
\end{aligned}$$

- Non-convex, but can be solved through a MIP reformulation after discretization

Case Study - Setting

- 21 hospitals within the GTA:
  - Average daily acute bed capacity of 8,534 beds
  - Average daily Medical/Surgical level 3 ICU bed capacity of 576

- Performance metrics:
  1. Patient-days/hospital over 95% occupancy in wards and ICUs.
  2. Patient-days/hospital over fair share of COVID patients.

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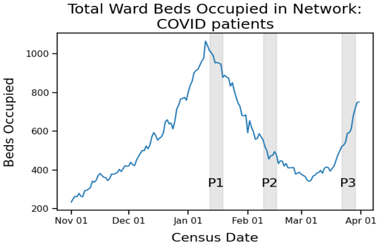
- 3 different time periods:
  1. Jan 15 - Jan 22, 2021
  2. Feb 9 - Feb 16, 2021
  3. Mar 22 - Mar 29, 2021

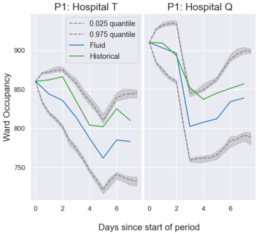


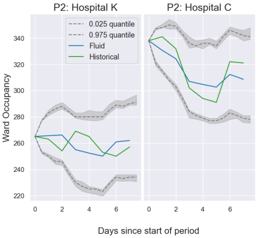
Data Sources & Parameter Estimation

1. General Medicine Inpatient Initiative (GEMINI)
   - Patient-level administrative and clinical data (7 hospitals)
2. Ministry of Health (MOH)
   - Daily counts of ward capacity, occupancy, admissions, and discharges.
3. Critical Care Info (CCIS)
   - Daily counts of ICU capacity and occupancy.
4. GTA IMS transfer logs
   - IMS directives for transfers, actual transfers that occurred.

- For some parameters, we pool data from the GEMINI hospitals to get a pooled estimate, and apply it to all hospitals
- For others, we utilize hospital-specific occupancy data to directly estimate hospital-specific parameters

Validation


P1: Hospital T
P1: Hospital Q
0.025 quantile
0.975 quantile
Fluid
Historical
Ward Occupancy
900
850
800
750
0
2
4
6
0
2
4
6
Days since start of period


P2: Hospital K
P2: Hospital C
0.025 quantile
0.975 quantile
Fluid
Historical
Ward Occupancy
340
320
300
280
260
240
220
0
2
4
6
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2
4
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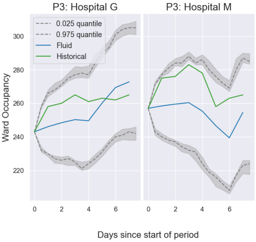
Days since start of period


P3: Hospital G
P3: Hospital M
0.025 quantile
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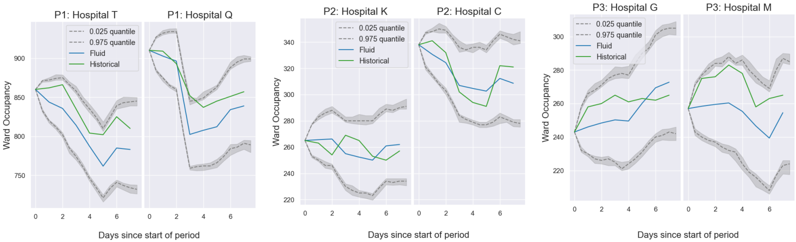

- Estimated 95% confidence bands for the ward and ICU occupancy of each hospital in each time period under the no-transfer policy
- For 83% of the wards and 93% of ICUs (across all three periods) the historical occupancies are within the confidence bands

Case Study Results - Value of Patient Transfers

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- Compared with no transfers (with daily transfer limit of 5): 13.4-21.0% reduction for the ward and 11.3-23.4% for the ICU over-occupancy; 0.4%-9.2% for COVID load inequity

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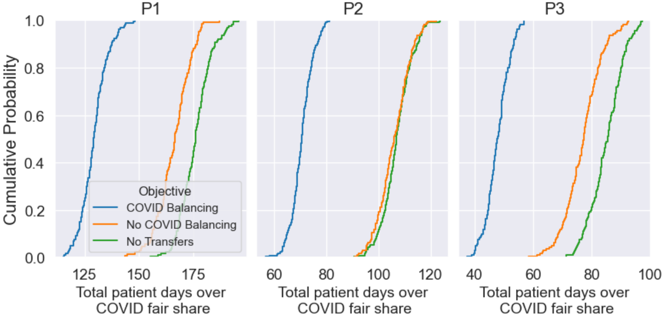

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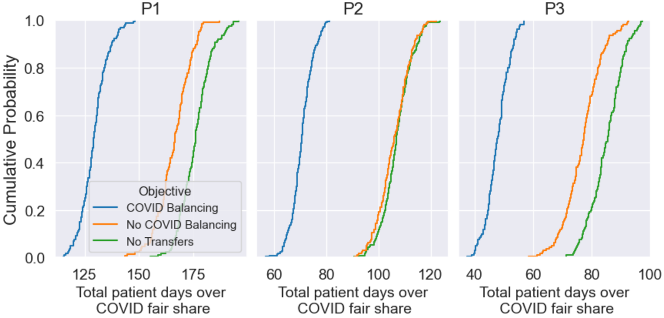

- COVID balancing has little impact on the over-occupancy reductions

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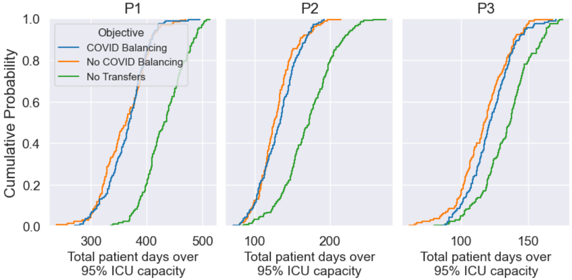
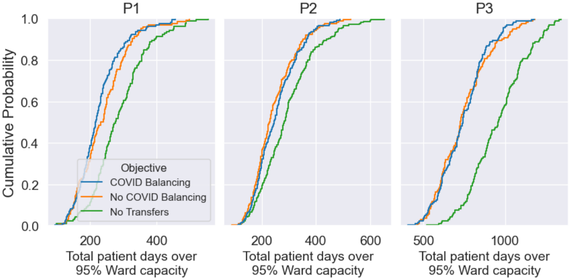
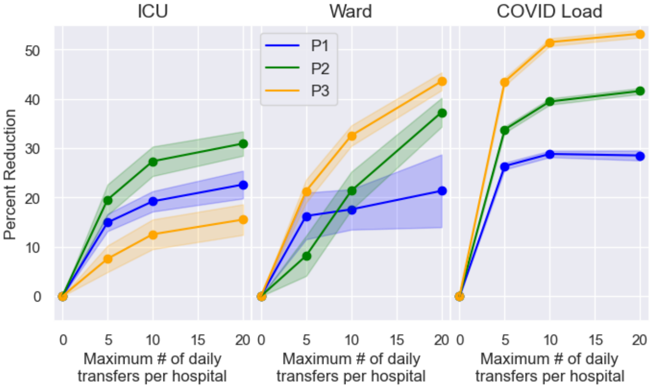


ICU



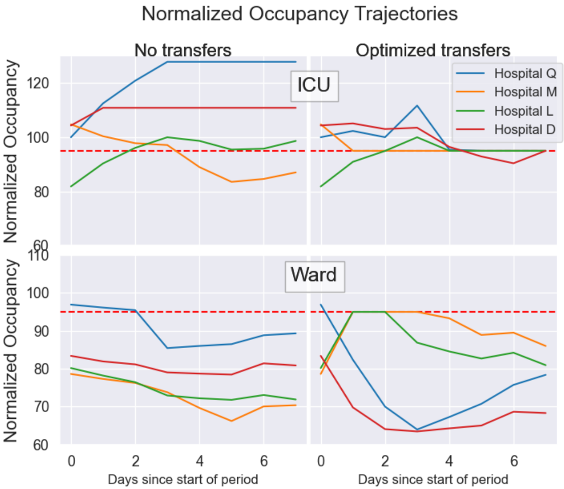
Ward

Case Study Results - Marginal Benefit of Increasing Daily Transfer Limits



- In most cases majority of the benefits are achieved with max 5 transfers per day

Optimal Trajectories



- Proactive ward transfers provide downstream benefits for ICU

Summary and Future Work

- A queueing network approach to guide patient transfer decisions
- Evaluated the performance of the proposed framework in a case study using real-data:
  - Significant reduction in ICU and ward over-occupancy levels
  - Much of the benefits can be realized with at most 5 daily transfers per hospital
  - Including COVID fair share in the objective can lead to significant benefits for COVID balancing, while having little effect on the over-occupancy reductions

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  - Including COVID fair share in the objective can lead to significant benefits for COVID balancing, while having little effect on the over-occupancy reductions
- Extensions and future work:
  - Model and data extensions
  - Structure of optimal transfer policy
  - Can the majority of the benefits be realized through sparsely connected networks?
  - Empirical evaluation of the impact of transfers

Chan, Timothy and Pogacar, Frances and Sarhangian, Vahid and Hellsten, Erik and Razak, Fahad and Verma, Amol, Optimizing Inter-Hospital Patient Transfer Decisions During a Pandemic: A Queueing Network Approach (2021). Available at SSRN: http://dx.doi.org/10.2139/ssrn.3975839