Practical Applications of Operations Research to Optimize Complex Healthcare Problems

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Outline

1. Background information
2. Optimization approach
3. Healthcare applications
   a. Network optimization, capacity planning
   b. Scheduling, logistics
4. Discussion
Background Information

• What is Operations Research (OR)?
  – Professional discipline that deals with the application of scientific methods to decision making, especially to the allocation of resources
  – Uses analytical and numerical techniques to develop and manipulate mathematical and computer models of organizational systems composed of people, machines, and procedures

• Many application areas; military, manufacturing, communication, construction, banking, health care, etc.

• Several theory and techniques
  – Linear programming, integer programming, dynamic programming, network programming, nonlinear programming, heuristics
  – Simulation, Markov chains, queuing theory, inventory theory, game theory, multi-criteria decision making
What is an Optimization Model?

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
<th>Example: Inventory purchasing</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Objective function</strong></td>
<td><em>What are we trying to achieve?</em> (Maximize / minimize some thing of interest)</td>
<td>Minimize total purchasing cost of all inventory</td>
</tr>
<tr>
<td><strong>Decision variables</strong></td>
<td><em>What can we change?</em> (What the model solves for)</td>
<td>How much of each item to buy from each potential vendor</td>
</tr>
</tbody>
</table>
| **Constraints**    | *What can't we change?* (Factors that limit the model / logistical givens) | • Must buy at least \( n_j \) quantity of item \( j \)  
• Cannot buy more from vendor \( k \) than they produce |
**Mathematical Formulation**

- $j$ types of items
- Need to buy $n_j$ of each
- $k$ vendors
- Complex purchasing contracts based on total volume bought from each vendor annually
- $c_{j,k}$ = unit cost of buying item $j$ from vendor $k$
- $m_{j,k}$ = maximum item $j$ available from vendor $k$
- $x_{j,k}$ = number item $j$ bought from vendor $k$

Minimize $\sum_{j,k} c_{j,k} x_{j,k}$ \[ \text{Total cost of all items bought from all vendors} \]

Subject to:

\[ x_{1,1} + x_{1,2} + \ldots + x_{1,k} = n_1 \]
\[ x_{2,1} + x_{2,2} + \ldots + x_{2,k} = n_2 \]
\[ \vdots \]
\[ x_{j,1} + x_{j,2} + \ldots + x_{j,k} = n_j \]

$0 \leq x_{j,k} \leq m_{j,k}$ for all $j,k$
I. Network Optimization Projects

1. Sleep Apnea Testing
2. Colonoscopy Screening
3. Ultrasound Screening
4. CVT Telehealth Services
5. PTSD Treatment
6. Ob/Gyn Inpatient Admission
Examples of Networks

Questions:
- Where to locate care services?
- In what capacities?
- Which patients receive care where?
- What if demand changes?

Objectives:
- Maximize care coverage (i.e., within network care)
- Minimize cost
- Minimize travel distance
1. Sleep Apnea Testing

- Abnormal pauses in breathing during sleep
- 20% of veterans suffer
- High cost ($534 million, 2010)
- Inadequate access to testing

Are they optimal?
Can we improve the system?

Integer programming models to help decision makers explore tradeoffs between costs, coverage, service location, and capacity
General Approach

Aims to minimize total HOUSE, FEE, SET-UP, and UNDERUTILIZATION costs over an $n$-year planning horizon.

Problem definition

- Minimizes
  - Operation cost
  - Travel cost
  - Non-coverage cost
  - Set-up cost
  - Underutilization cost

- Locates $\leq P$ facilities
- Allocates patients to facilities
- Determines the capacities

“For each period”

Main assumptions

- Each patient receives his care at the facility to which he is assigned
- Demand is deterministic, equally distributed over time, and with no seasonality effects
- Facilities that currently provide this care continue to do so and capacity down-sizing is not allowed
- Care cost variations between patients, medical centers, and geographic regions are negligible
Mathematical Formulation

Minimize:

\[
\begin{align*}
\text{House cost (operation + travel)} & = \left( \sum_i \sum_j \sum_t Y_{ij}^t h_i^t \right) \left( C_1 + d_{ij} C_2 \right) \\
\text{Fee cost} & = \sum_t \left( D_t - \sum_i \sum_j Y_{ij}^t h_i^t \right) \\
\text{Set-up cost} & = \sum_j a_j \\
\text{Underutilization cost} & = \sum_t \sum_j \left( T(b_j^t + a_j^t) - \sum_i Y_{ij}^t h_i^t \right)
\end{align*}
\]

\[\rightarrow\] Minimize total cost

Subject to:

\[
\begin{align*}
\sum_{j \notin O} X_j^t & \leq P & \forall i \\
X_j^t & \geq X_j^{t-1} & \forall j, t \in \{2, 3, 4, 5, 6\} \\
b_j^t & = f_j & \forall j \\
b_j^t & = b_j^{t-1} + a_j^{t-1} & \forall j, t \in \{2, 3, 4, 5, 6\} \\
\sum_t Y_{ij}^t h_i^t & \leq T(b_j^t + a_j^t) & \forall j, t \\
\sum_t Y_{ij}^t & \leq 1 & \forall i, t \\
Y_{ij}^t - X_j^t & \leq 0 & \forall i, j, t \\
\sum_{t \mid t \leq S} Y_{ij}^t & \leq 0 & \forall i, t \\
\sum_t Y_{ij}^t h_i^t & \leq K_j & \forall j, t \\
X_j^t & = 1 & \forall j \in O, t \\
X_j^t & \in \{0, 1\} & \forall j \notin O, t \\
Y_{ij}^t & \in \{0, 1\} & \forall i, j, t \\
\alpha_j^t & \text{integer} & \forall j, t
\end{align*}
\]

At most \(P\) number of facilities provide service in each period

Closing a service over remaining planning horizon is prevented

Calculate the number of beds in each facility at the beginning of each period

Determines number of beds in each facility at each period

Assigns every demand node to at most one VA facility

Ensure that a demand node can be assigned to a facility if and only if it provides service and is within the acceptable distance

Ensures that maximum capacity of each facility is not exceeded

Ensures that all facilities currently providing service remain open

Defines the location decision variable to be binary

Defines the allocation decision variable to be binary

Defines the capacity expansion decision variable to be non-negative integer
Many scenarios
Very similar results

Cost (x1000 dollars)

Maximum acceptable travel distance (S) (miles)

Location option

Current approx 95th travel distance percentile

Current cost

Colors = improvement with new facilities, optimally located

Current performance

P=0

$2,850

$3,000

$3,150

$3,300

$3,450

$3,600

$3,750

20 30 40 50 60 70 80 90 100
Many scenarios
Very similar results

Location option
- P=0
- P=1

Cost (x1000 dollars)

Maximum acceptable travel distance (S) (miles)

Current cost

Current approx 95th travel distance percentile

Current performance

Colors = improvement with new facilities, optimally located

Approx $2,850

$3,000

$3,150

$3,300

$3,450

$3,600

$3,750
Many scenarios
Very similar results

Cost (x1000 dollars)

Maximum acceptable travel distance (S) (miles)

Location option
- P=0
- P=1
- P=2

Current cost

Current approx 95th travel distance percentile

Current performance

Colors = improvement with new facilities, optimally located
Many scenarios
Very similar results

Cost (x1000 dollars)

Maximum acceptable travel distance (S) (miles)

Location option
- P=0
- P=1
- P=2
- P=3

Current cost

Current approx 95th travel distance percentile

Current performance

Colors = improvement with new facilities, optimally located
Many scenarios
Very similar results

Cost (x1000 dollars)

Maximum acceptable travel distance (S) (miles)

Location option
- P=0
- P=1
- P=2
- P=3
- P=4

Current cost

Current approx 95th travel distance percentile

Current performance

Colors = improvement with new facilities, optimally located
Many scenarios
Very similar results

Cost ($1000 dollars) vs. Maximum acceptable travel distance (S) (miles)

Location option:
- P=0
- P=1
- P=2
- P=3
- P=4
- P=5

Current cost

Colors = improvement with new facilities, optimally located

Current approx 95th travel distance percentile

Current performance
Many scenarios
Very similar results

Current approx 95th travel distance percentile

5 - 15% reduction in total cost
15 - 45% improvement in access
50% reduction in max distance

Current cost

Colors = improvement with new facilities, optimally located
## Optimal Locations

### Optimal facility location (Number of beds)

<table>
<thead>
<tr>
<th>$S$ (miles)</th>
<th>$P$</th>
<th>Only medical centers</th>
<th>Medical centers &amp; All clinics</th>
<th>Medical centers &amp; Large clinics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>Newington (2)</td>
<td>Newington (2)</td>
<td>Newington (2)</td>
</tr>
<tr>
<td>20</td>
<td>2</td>
<td>Newington (2) Bedford (1)</td>
<td>Newington (2) Bedford (1)</td>
<td>Newington (2) Bedford (1)</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Newington (2) Bedford (1) Northampton (1)</td>
<td>Newington (2) Bedford (1) Springfield (2)</td>
<td>Newington (2) Bedford (1) Springfield (2)</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Newington (4) Providence (+1)</td>
<td>Newington (4) Providence (+1)</td>
<td>Newington (4) Providence (+1)</td>
</tr>
<tr>
<td>40</td>
<td>2</td>
<td>Newington (4) Bedford (1) Providence (+1)</td>
<td>Springfield (3) Windham (3) Providence (+1)</td>
<td>Newington (2) Springfield (3) Providence (+1)</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Newington (2+1*) Bedford (1) Northampton (2) Providence (+1)</td>
<td>Springfield (3) Fitchburg (1) Windham (3) Providence (+1)</td>
<td>Newington (2) Bedford (1) Springfield (3) Providence (+1)</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Northampton (3) Providence (+1)</td>
<td>Springfield (3) Providence (+1)</td>
<td>Springfield (3) Providence (+1)</td>
</tr>
<tr>
<td>60</td>
<td>2</td>
<td>Togus (2) Northampton (3) Providence (+1)</td>
<td>Togus (2) Springfield (3) Providence (+1)</td>
<td>Togus (2) Springfield (3) Providence (+1)</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Togus (2) Northampton (3) WRI (1) Providence (+1)</td>
<td>Togus (2) Springfield (3) Portland (2) Providence (+1)</td>
<td>Togus (2) Springfield (3) Portland (2) Providence (+1)</td>
</tr>
</tbody>
</table>

*Capacity expansion of 1 bed at period 2*
2. Colonoscopy Screening

11 medical centers
14 screening units

The aim is to find:

• Optimal locations for colonoscopy screening units
• Best location for each patient to receive care ("allocation")
• Who should receive care outside the system
• Impact of adjusting care capacities / locations and acceptable travel distance
# Mathematical Model

## Variables

- **$X_j$:** Binary variable indicating whether there is a colonoscopy screening unit at location $j$ or not
- **$Y_{ij}:** Binary variable indicating whether zip code $i$ is assigned to location $j$ or not
- **$a_j$:** Integer variable indicating the number of colonoscopy screening units at location $j$

## Mathematical Model

**Minimize**

\[
N_1(D - \sum_i \sum_j Y_{ij} h_i) + (\sum_i \sum_j Y_{ij} (d_{ij} N_2 + N_3)) + N_4 \sum_j a_j
\]

**MATH**

\[
\begin{align*}
\sum X_j & \leq P \\
\sum Y_{ij} & \leq 1 \text{ for all } i \\
Y_{ij} - X_j & \leq 0 \text{ for all } i, j \\
Y_{ij} - C_{ij} & \leq 0 \text{ for all } i, j \\
\sum C_{ij} Y_{ij} d_{ij} & \leq T(f_j + a_j) \text{ for all } j \\
\sum C_{ij} Y_{ij} d_{ij} & \leq K_j \text{ for all } j \\
X_{j \in O} & = 1 \\
X_j & \in \{0, 1\}, \ Y_{ij} \in \{0, 1\} \text{ for all } i, j \\
a_j & \in \text{integer for all } j
\end{align*}
\]

**WORDS**

1. At most $P$ number of facilities provide service
2. Each demand node can be assigned to at most one facility
3. A demand node is assigned to a facility only if it provides service
4. A demand node is assigned to a facility only if it is within acceptable distance
5. Total # of patients assigned to a facility should be less than capacity
6. Total # of patients assigned to a facility should be less than its max capacity
7. Current facilities continue to provide service
8. Binary requirement
9. Integer requirement

## Fee cost

\[ N_1(D - \sum_i \sum_j Y_{ij} h_i) \]

## House cost

\[ (\sum_i \sum_j Y_{ij} h_i (d_{ij} N_2 + N_3)) \]

## Bed cost

\[ N_4 \sum_j a_j \]
## Cost and Access Results

<table>
<thead>
<tr>
<th>$S$ (miles)</th>
<th>Total cost</th>
<th>In-system coverage</th>
<th>Saving</th>
<th>New locations</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>$13,720,710</td>
<td>21%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>30</td>
<td>$13,221,830</td>
<td>44%</td>
<td>-</td>
<td>Newington (2012, 1U)*</td>
</tr>
<tr>
<td>40</td>
<td>$12,922,540</td>
<td>53%</td>
<td>-</td>
<td>Newington (2012, 1U)</td>
</tr>
<tr>
<td>50</td>
<td>$12,356,110</td>
<td>70%</td>
<td>$436,707</td>
<td>Newington (2012, 1U)</td>
</tr>
<tr>
<td>60</td>
<td>$11,916,650</td>
<td>75%</td>
<td>$876,167</td>
<td>-</td>
</tr>
<tr>
<td>70</td>
<td>$11,640,000</td>
<td>83%</td>
<td>$1,152,817</td>
<td>-</td>
</tr>
<tr>
<td>80</td>
<td>$11,651,870</td>
<td>90%</td>
<td>$1,140,947</td>
<td>Northampton (2014, 1U)</td>
</tr>
<tr>
<td>90</td>
<td>$11,454,440</td>
<td>89%</td>
<td>$1,338,377</td>
<td>-</td>
</tr>
<tr>
<td>100</td>
<td>$11,291,980</td>
<td>95%</td>
<td>$1,500,837</td>
<td>-</td>
</tr>
</tbody>
</table>

**Poorer Compliance**

Remaining patients receive care outside the system

### Total cost

- $437K savings
- $1.150M savings
- $1.140M savings

### Coverage

- 19% increase
- 27% increase
- 34% increase

Remaining patients receive care outside the system
3. Ultrasound Screening Project

• **Current:** Limited resources, no standard policy, demand increasing by 30%

• **Questions:** Where to provide, rent, outsource

• **Results:** ~$300K/yr savings, >9.5% travel decrease
Integrated Models

Parameters
- Center location
- Zip-codes
- Demand
- Capacity

Optimization

Deterministic Solution
- Zip-code assignment
- Number of centers
- Location of centers

Stochastic Solution
- Expected # of overcapacity
- Expected # of under-utilization

Probabilistic Analysis

Cost Analysis

Final Solution
- Best strategy with minimum cost
- Minimum number of units needed
- Optimal assignment of patients to units
- Optimal locations of units
4. Clinical Video Telehealth

- VA telehealth plan: “50% by 2020”
- CVT: Remote consult by driving to a closer facility with equipment
- Dramatic unnecessary over-investment with no value

<table>
<thead>
<tr>
<th>Locations, # of units located at that location</th>
<th>Current case</th>
<th>Optimized</th>
</tr>
</thead>
<tbody>
<tr>
<td>WRJ MC, 1</td>
<td>55.6 miles</td>
<td>46.1 miles</td>
</tr>
<tr>
<td>Brattleboro CBOC, 1</td>
<td>77.3 miles</td>
<td>66.6 miles</td>
</tr>
<tr>
<td>Littleton CBOC, 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Colchester CBOC, 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Keene CBOC, 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bennington CBOC, 1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Minimizing Average Traveling Distance

- Average traveling distance saving: 17%
- Max traveling distance saving: 13.8%
5. PTSD (F2F vs. Telehealth)

- Veteran prevalence ~25% (36,469 patients in 2010)
- Access to treatment is an issue
- Patient-centered balance between in-person and video-based services

Mathematical model

\[
\begin{align*}
\text{Minimize} & \left( \sum_i \sum_y Y_{iy} \left( h_i^e (1 + r_{med}) (C_i^e + v^r d_i^e C_2) + h_i^m (C_i^m + v^m d_i^m C_2) \right) \right) \\
& + C_3 \left( O - \sum_i \sum_y (h_i^e + h_i^m) \right)
\end{align*}
\]

Subject to

\[
\begin{align*}
\sum_i Y_{iy} & \leq 1 \\
\sum_{i \in O} Y_{iy} & \leq 0 \\
\eta_i^e & = \sum_y Y_{iy} h_i^e (1 + r_{med}) k_i^e / T \\
\eta_i^m & = \sum_y Y_{iy} h_i^m k_i^m / T \\
\eta_j^e & = \sum_i Y_{iy} h_i^e (1 + r_{med}) k_i^e / (IT) \\
\eta_j^m & = \sum_i Y_{iy} h_i^m k_i^m / (IT) \\
Y_{iy} & \in \{0, 1\}
\end{align*}
\]

- Each demand node can be assigned to at most one facility
- A demand node can only be assigned to a facility within acceptable distance
- Calculate the number of psychotherapists and psychiatrists needed in general and specialized care services
- Binary requirement: 1, if demand node is covered by facility; 0, otherwise

Solution (30 miles)

- Total annual cost
  - With telehealth
  - Current cost

Coverage percentage

- With telehealth
  - Current
  - No telehealth

Demand

Solution (30 miles)
6. Ob/Gyn Inpatient Admission

- Tradeoff between MD preference and admitting cost
- “Bi-criteria” formulation, Pareto optimal solution for different $\alpha$ values

Optimization Model:

$$\min \alpha \sum \sum d_{ij} c_{ij} x_{ij} + (1 - \alpha) \sum \sum p_{ij} x_{ij}$$

subject to

$$\sum_j x_{ij} = 1 \quad \forall i \quad (1)$$

$$\sum_i d_{ij} x_{ij} \leq Cap_j + Exc_j \quad \forall j \quad (2)$$

$$\sum_i d_{ij} x_{ij} \geq t \sum_i MD_i x_{ij} \quad \forall j \quad (3)$$

$$x_{ij} \in \{0,1\} \quad \forall i, j$$
Tool Implementation

Reallocating Delivery Volumes within HVMA Care Network

<table>
<thead>
<tr>
<th>Hospitals</th>
<th>Relative Cost per Delivery</th>
<th>Delivery Number</th>
<th>Assigned Delivery Number</th>
<th>Unassigned Delivery Number</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.79</td>
<td>0</td>
<td>294</td>
<td>294</td>
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<tr>
<td></td>
<td>0.786</td>
<td>0</td>
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<td>327</td>
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<tr>
<td></td>
<td>0.684</td>
<td>0</td>
<td>223</td>
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<td></td>
<td>0.836</td>
<td>0</td>
<td>213</td>
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<td></td>
<td>0.812</td>
<td>0</td>
<td>8</td>
<td>8</td>
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<td></td>
<td></td>
<td>475</td>
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<td></td>
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<td>199</td>
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<tr>
<td></td>
<td></td>
<td>75</td>
<td>75</td>
<td>75</td>
</tr>
<tr>
<td>Total Assigned Delivery</td>
<td></td>
<td>1083</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Current Capacity</td>
<td></td>
<td>475</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Excess Capacity*</td>
<td></td>
<td>901</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Available Capacity</td>
<td></td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

Notes
1. Please only use the cells inside the blue box.
2. Do not use grey cells for assignments.
3. While doing the assignment for the white cells, you can only use a number between 0 and "Delivery Number" of that site.
4. If the unassigned delivery number cell for a site is red, this means there are unassigned deliveries for that site.
5. Once all the delivery of a site is assigned, "Unassigned Delivery" for that site will become green.
6. If a hospital is overcapacitated, "Available Capacity" will become red.
7. The assignment ends once all the deliveries are assigned to a hospital.

~3 million $ savings annually
II. Scheduling Projects

1. Pediatric Evening Coverage
2. Cancer Surgery Co-availability
3. Telehealth Specialty Consult Availability
4. Primary Care Team Continuity
1. Pediatric Evening Coverage

- Pediatric PCP network
- Inappropriate evening ED use (~$30 m/year)
- Cross-coverage for after-hours throughout network

Who
When
Where
## Model and Implementation Tool

### Model in words

**Maximize** coverage preferences  

*while*  

Satisfying all demand  

Balancing burden on MDs

### Model in math

\[
\text{Max} \sum_i \sum_j c_{ij} x_{ij}
\]

subject to

\[
\sum_j x_{ij} = D_i \quad \forall \ i
\]

\[
\sum_i x_{ij} \geq S^{\text{min}} \quad \forall \ j
\]

\[
\sum_i x_{ij} \leq S^{\text{max}} \quad \forall \ j
\]

\[
x_{ij} \in \{0, 1\} \quad \forall \ i, j
\]

### Table: Demand

<table>
<thead>
<tr>
<th>Day</th>
<th>Patient Demand</th>
<th>Number of Physicians needed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monday</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Tuesday</td>
<td>11</td>
<td>3</td>
</tr>
<tr>
<td>Wednesday</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>Thursday</td>
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<td>Friday</td>
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### Table: Preferences

<table>
<thead>
<tr>
<th>Physician</th>
<th>Monday</th>
<th>Tuesday</th>
<th>Wednesday</th>
<th>Thursday</th>
<th>Friday</th>
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<tbody>
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### Table: Schedule

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<th>Tuesday</th>
<th>Wednesday</th>
<th>Thursday</th>
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<td>3</td>
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<td>9</td>
<td>Off</td>
<td>Off</td>
<td>Off</td>
<td>Off</td>
<td>Working</td>
</tr>
</tbody>
</table>

> $3m/year savings conservatively
2. Cancer Surgery Co-availability

**General Problem**

- **Scheduled cases**
  - Advance scheduling
  - Anesthesia
  - Breast Cancer Surgery
    - Oncology surgeon team
  - Reconstruct Surgery
    - Coordinated care team
  - Lag = 0
- **Urgent cases**
  - Add-on scheduling

**Integrated Approach**

- Co-availability & Care team scheduling
  - Output
  - Optimal surgeon availabilities
    - Input
    - Downstream linked event scheduling
      - Output
      - Optimal surgery schedules
        - Input
        - Simulation evaluator & local optimizer

**Surgery only**

**Elective**
Mathematical Model

Max Z = \sum_k \sum_t \sum_r \sum_s w_{kt} \cdot p_{ktrs} \quad \text{Maximize total number of common time slots of teams}

\sum_t A_{mts} \leq 1 \quad \forall i, s \text{ and } \forall m \in G_i

\sum_s A_{mts} = R_{mt} \quad \forall i, t \text{ and } \forall m \in G_i

A_{mts} = 1 \quad \forall (m, t, s) \in O_i

\sum_{n \in D_{imt}} A_{nts} \geq A_{mts} \quad \forall i, t, s \text{ and } \forall m \in G_i, D_{imt} \neq \emptyset

A_{nts} + A_{mts} \leq 1 \quad \forall i, t, s \text{ and } \forall m \in G_i, \forall n \in U_{imt}

\sum_m A_{mts} \geq C_{it} \quad \forall i, t, s \text{ where } m \in G_i

\sum_m A_{mts} \geq \sum_k k \cdot p_{ktrs} \quad \forall t, r, s \text{ where } m \in Q_r^t

\sum_r p_{ktrs} \geq Goal_t \quad \forall t, s

A_{mts} \in \{0, 1\} \quad \forall m, t, s

p_{ktrs} \in \{0, 1\} \quad \forall k, t, r, s
Example

13 breast surgeons  18 plastic surgeons

Operating Rooms

Current Schedules (18)

<table>
<thead>
<tr>
<th>Mon</th>
<th>Tue</th>
<th>Wed</th>
<th>Thu</th>
<th>Fri</th>
</tr>
</thead>
<tbody>
<tr>
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<td>PM</td>
<td>AM</td>
<td>PM</td>
<td>AM</td>
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<tr>
<td></td>
<td></td>
<td>O4</td>
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</tbody>
</table>

Optimal Solution (35)

<table>
<thead>
<tr>
<th>Mon</th>
<th>Tue</th>
<th>Wed</th>
<th>Thu</th>
<th>Fri</th>
</tr>
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<tbody>
<tr>
<td>AM</td>
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</tr>
</tbody>
</table>

94% increase in desirable co-availability
Objective: Maximize specialty care coverage to enable PC-SC integration for immediate CVT consult

- Integer programming model allocates available provider hours to maximize anticipated CVT demand
- Considering limitations:
  - Clinician requirements
  - Technological limitations
  - Operational needs
  - Room and equipment availability

PC: Primary Care Provider
SC: Specialty Care Provider
CVT: Clinical Video Telehealth Service
Model and Results

\[ \text{Max } Z = \sum_m \sum_s d_s \cdot A_{m2s} \]

Maximum coverage of potential CVT consults

Results

- 57% of all consults able to be performed remotely
- Decreased probability of no-show and cancellation

<table>
<thead>
<tr>
<th>Specialty</th>
<th># of providers</th>
<th>Z (%)</th>
<th>CVT (h/week)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Audiology</td>
<td>8</td>
<td>56.77</td>
<td>20.3</td>
</tr>
<tr>
<td>General Surgery</td>
<td>2</td>
<td>14.84</td>
<td>1</td>
</tr>
<tr>
<td>Diabetes</td>
<td>3</td>
<td>26.46</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Z: Objective function value (total percentage of consultation performed via CVT)

\[ A_{mt(s-1)} + A_{mt(s+1)} \geq A_{mts} \quad \forall m, t \in \{1,2\}, s \in IH \]

\[ A_{mt(s-1)} \geq A_{mts} \quad \forall m, t \in \{1,2\}, s \in LH \]

\[ A_{mts} \in \{0,1\} \quad \forall m, t, s \]

\[ g_{msi} \in \{0,1\} \quad \forall m, s, i \]
4. Primary Care Team Continuity

- Primary care continuity
- Residents

- Complex schedules: PCPs, faculty, residents, PAs, RNs, ...
- Extended-PCMH concept: Provider teams (aggregated panels)
- Team coverage: familiarity with the team

- Patient centered
- Safe
- Effective

- Satisfaction
- Trust
- Loyalty
- Preventive care
- Compliance
- Less errors
- Less hospitalizations
- Less ED visit
- Less provider turn-over
- Higher utilization
- Decreased costs

Continuity of care

Family medicine
Conceptual Approach

Math model (Max weighted session coverage)

- Primary care resident teams
- Desirable for someone from every team to cover every session (care continuity), possibly weighted by session demand
- Integer programming solution & Excel GUI tool
- Spreadsheet post-optimality adaptation tool

Poor Coverage = 50%

Poor Coverage = 75%

Good Coverage = 100%
Mathematical Model

Maximize total weighted team clinic coverage:

Maximize $Z = \sum_j \sum_w \sum_s w_s \cdot X_{jws}$

Resident task assignment:

$\sum_t B_{mtws} = 1 \quad \forall m, w, s$

Team presence:

$\sum_i A_{iws} + \sum_m B_{m1ws} \geq X_{jws} \quad \forall j, w, s$ and $\forall i, m \in T_j$

Educational requirements:

$\sum_w \sum_s B_{mtws} = E_t \quad \forall m$ and $\forall (t, s) \in Education$

Service requirements:

$\sum_m B_{mtws} = S_t \quad \forall w$ and $\forall (t, s) \in Service$

Work regulations:

$C_{min}^t \leq \sum_s B_{mtws} \leq C_{max}^t \quad \forall m, w$ and $\forall t \in C$

Clinic requirements:

$D_{min} \leq \sum_m B_{m1ws} \leq D_{max} \quad \forall w, s$

Undesirable task dispersion:

$\sum_w^{w=w'+k} B_{mtws} \leq 1 \quad \forall m$ and $w' \in \{1, \ldots , (W - k)\}$

Consecutive task assignment:

$\sum_{(t,s)} B_{mtws} - 1 \leq Y_{nmw} \quad \forall n, m, w$ and $\forall (t, s) \in Consec_n$

Consecutive task limitation:

$\sum_w Y_{nmw} \leq L_n \quad \forall n, m$

Precept limitation:

$\sum_m B_{m1ws} \leq r \cdot R_{ws} \quad \forall w, s$
Results: ~20% coverage increase

Session coverage
July 2012 - May 2013

Holiday Week

Optimized
Current
Summary

• Many applications and opportunities in health care

• Significant potential savings, improved access and continuity

• Many research opportunities also, e.g:
  – Robust design, uncertainty
  – Market competition, co-existence
Discussion
Optimization in Healthcare
Current HSyE Projects

Healthcare Systems Engineering Institute
CMS Innovation Healthcare Systems Engineering Center
NSF Center for Health Organization Transformation
Northeastern University, Boston MA

www.HSyE.org
Outline

1. Network optimization: Warehouse location problem
2. Scheduling: Minimally disruptive optimization: Surgeon block scheduling
3. Capacity planning: OR Staffing optimization
1. Network Optimization
Optimal warehouse location

- The company delivers homecare medical supplies
- The medical supplies are time sensitive
- There are multiple suppliers / multiple products
- The supplies are delivered monthly

- Team: Ram, Hande, Sibel, Kyle, Anusha
Aim: optimal warehouse location

- Deliver their monthly demand to patients

- Create a robust network (that can deal with emergency cases)
  - Determine the optimal number of warehouse(s)

- Deliver the products at minimum cost
  - Determine optimum location for warehouse(s)
Problem Details

➢ Manufacturers
  • Products enter from the US-Mexico boarder

➢ Candidate warehouse locations
  • In United States (spread across the country)

➢ Customers
  • Located in United States (spread across the country)
  • Demand is accumulated using zip code of patients
  • Products are delivered to courier locations

➢ Products
  • Products are grouped in 8 groups
Current flow

Manufacturers

Warehouse(s)
(Inventories Stocked)

Couriers

Customers

*Different colors are used just to distinguish*
Map Overview

- Manufacturer
- Warehouse

- Customer/Distributor/Patient Locations
- Emergency shipments
Assumptions

- Uncapacitated flow across the network
- Deterministic demand of products
- Standard (uniform) warehouse operational cost and no setup cost as the space is rented
Mathematical Model

Index

i  Manufacturers
j  Candidate warehouse locations
k  Courier locations
l  Product

Decision Variables

\[
\begin{align*}
    x_j & = \begin{cases} 
        1 & \text{if there is an operating warehouse at warehouse location } j \\
        0 & \text{otherwise} 
    \end{cases} \\
    y_{jk} & = \begin{cases} 
        1 & \text{if courier } k \text{ is served by a warehouse operating at location } j \\
        0 & \text{otherwise} 
    \end{cases}
\end{align*}
\]

Objective Function

Minimize Total Transporation Cost \[= \sum_{i \in I} \sum_{j \in J} \bar{c}_{ij} \bar{d}_{ij} \bar{t}_{ij} + \sum_{j \in J} \sum_{k \in K} c_{jk} d_{jk} t_{jk} \]

Subject to

1. \[\sum_{j \in J} x_j = n\]
2. \[\sum_{k \in K} f_{jkl} \leq \sum_{i \in I} \tilde{f}_{ijl} \quad \forall j, \forall l\]
3. \[\sum_{k \in K} y_{jk} \leq (|K| - n + 1) x_j \quad \forall j\]
4. \[\sum_{j \in J} y_{jk} \geq 1 \quad \forall k\]
5. \[\sum_{j \in J} f_{jkl} \geq r_{kl} \quad \forall k, \forall l\]
6. \[f_{jkl} \leq r_{kl} y_{jk} \quad \forall j, \forall k, \forall l\]
7. \[\tilde{f}_{ijl} \leq x_j a_{il} \sum_{k \in K} r_{kl} \quad \forall i, \forall j, \forall l\]
8. \[\sum_{l \in L} \tilde{f}_{ijl} \leq \bar{t}_{ij} \quad 28 \quad \forall i, \forall j\]
9. \[\sum_{l \in L} f_{jkl} \leq t_{jk}^1 + 28 + t_{jk}^2 \quad \forall j, \forall k\]

Note: 28 = Capacity of the truck in terms of Pallets
Mathematical Model

Objective Function

Minimize $Total\ Transporation\ Cost = Inbound\ Cost +\ Ourbound\ Cost$

Subject to

1. Total number of open warehouses
2. Outbound quantity of flow $\leq$ Inbound quantity of flow
3. An open warehouse should at least serve 1 location
4. A location should be served by at least 1 warehouse
5. Quantity of products served to a location should satisfy the minimum requirements
6. Products can only be served if the route from warehouse to location is open
7. Products can only be received from the supplier if the supplier manufacturers that product
8. Number of FTL to the warehouse from the suppliers is based on the capacity of the truck
9. Number of FTL + LTL from the warehouse to the locations is based on the capacity of the truck
Mathematical Model

Objective Function
Minimize Total Transportation Cost = Σ_{i∈I} Σ_{j∈J} c_{ij} * d_{ij} * t_{ij} + Σ_{j∈J} Σ_{k∈K} c_{jk} * d_{jk} * t_{jk}

Subject to
1. \sum_{j∈J} x_j = n
2. \sum_{k∈K} f_{jkl} ≤ \sum_{i∈I} \bar{f}_{ijl} \quad ∀j, ∀l
3. \sum_{k∈K} y_{jk} ≤ (|K| - n + 1) * x_j \quad ∀j
4. \sum_{j∈J} y_{jk} ≥ 1 \quad ∀k
5. \sum_{j∈J} f_{jkl} ≥ r_{kl} \quad ∀k, ∀l
6. \bar{f}_{ijkl} ≤ r_{kl} * y_{jk} \quad ∀j, ∀k, ∀l
7. \bar{f}_{ijl} ≤ x_j * a_{il} * \sum_{k∈K} r_{kl} \quad ∀i, ∀j, ∀l
8. \sum_{l∈L} \bar{f}_{ijl} ≤ \bar{t}_{ij} * 28 \quad ∀i, ∀j
9. \sum_{l∈L} \bar{f}_{ijkl} ≤ t_{1jk}^1 * 28 + t_{2jk}^2 \quad ∀j, ∀k
## Results

<table>
<thead>
<tr>
<th>Number of Warehouses</th>
<th>Inbound Cost* [Manufacturer to Warehouse]</th>
<th>Outbound Cost* [Warehouse to Courier Locations]</th>
<th>Emergency shipments*</th>
<th>Transportation Cost* [Inbound+ Outbound]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$115,930.00</td>
<td>$103,340.00</td>
<td>$20,370.00</td>
<td>$239,640.00</td>
</tr>
<tr>
<td>2</td>
<td>$100,120.00</td>
<td>$92,950.00</td>
<td>$19,570.00</td>
<td>$212,640.00</td>
</tr>
<tr>
<td>3</td>
<td>$109,980.00</td>
<td>$81,400.00</td>
<td>$18,000.00</td>
<td>$209,380.00</td>
</tr>
<tr>
<td>4</td>
<td>$108,490.00</td>
<td>$81,300.00</td>
<td>$17,830.00</td>
<td>$207,620.00</td>
</tr>
</tbody>
</table>

*The Costs mentioned above are per month.

![Graph showing transportation costs](chart.png)

- **Courier Cost**
- **Outbound Cost** [Warehouse to Courier Locations]
- **Inbound Cost** [Manufacturer to Warehouse]
## Pros & Cons on # of warehouses

<table>
<thead>
<tr>
<th>Number of Warehouses</th>
<th>Factors</th>
<th>Pros</th>
<th>Cons</th>
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<tbody>
<tr>
<td>One</td>
<td>Transportation Cost</td>
<td>High</td>
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<tr>
<td></td>
<td>Warehouse/Operational Cost</td>
<td>Low</td>
<td></td>
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<tr>
<td></td>
<td>Robustness</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Aid Growth in Demand</td>
<td>Week</td>
<td></td>
</tr>
<tr>
<td>Two</td>
<td>Transportation Cost</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Warehouse/Operational Cost</td>
<td>Medium</td>
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<tr>
<td></td>
<td>Robustness</td>
<td>Medium</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Aid Growth in Demand</td>
<td>Medium</td>
<td></td>
</tr>
<tr>
<td>More than Two</td>
<td>Transportation Cost</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Warehouse/Operational Cost</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Robustness</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Aid Growth in Demand</td>
<td>Strong</td>
<td></td>
</tr>
</tbody>
</table>
2. Scheduling: Minimally disruptive optimization: Surgeon block scheduling
Problem Definition

- Poor OR utilization
- Reduction in # of ORs
- Drawbacks to re-scheduling:
  - Disruption
  - Specialist satisfaction
### Background

| **Aim:** | ➢ Improve utilization of ORs  
| ➢ Minimize disruption to current blocks  
| ➢ Alleviate costs associated with OR underutilization |

| **Approach:** | ➢ Mathematical Modeling  
| ➢ Optimization |

| **Lead Eng:** | Ally |

| **Team:** | Serpil, Jillian, Kyle, (Anusha, Logan) |
Current Schedule:

OR-1

Optimized Schedule:

Automated planning has reduced the disruption value from 4 to 3, as indicated by the highlighted changes in the schedule.
### Constraints

1. One surgeon assigned to each OR
2. A surgeon can only work one block at any given time
3. A surgeon can only work one block per day
4-5. Total max / min hour requirements
6. On-Call / fixed assignments
7. Max / min block length
8. Daily minimum utilization requirement
9-10. Total hours assigned
11-12. Weekly repeating shift requirement
Constraint Formulation

\[
\sum_i \sum_{k \leq s} \sum_{l > s} \sum_t X_{ijklt} = N \quad \forall j, s \tag{1}
\]

\[
\sum_{k \leq s} \sum_{l > s} \sum_t X_{ijklt} \leq 1 \quad \forall i, j, s \tag{2}
\]

\[
\sum_k \sum_l \sum_t X_{ijklt} \leq 1 \quad \forall i, j, s \tag{3}
\]

\[
\sum_j \sum_k \sum_l \sum_t (l - k) \cdot X_{ijklt} \leq \text{Max} H_i \quad \forall i \tag{4}
\]

\[
\sum_j \sum_k \sum_l \sum_t (l - k) \cdot X_{ijklt} \geq \text{Min} H_i \quad \forall i \tag{5}
\]

\[
X_{ijklt} = 1 \quad \forall (i, j, k, l, t) \in \text{Fixed} \tag{6}
\]

\[
X_{ijklt} = 0 \quad \forall i, j, t, (k, l) \notin \{(k, l) | \text{Max}_i \leq l - k \leq \text{Min}_i\} \tag{7}
\]

\[
\sum_i \sum_k \sum_l \sum_t (l - k) \cdot u_{it} \cdot X_{ijklt} \geq U \quad \forall j \tag{8}
\]

\[
\sum_t Y_{it} = 1 \quad \forall i \tag{9}
\]

\[
\sum_j \sum_k \sum_l (l - k) \cdot X_{ijklt} = t \cdot Y_{it} \quad \forall i, t \tag{10}
\]

\[
\sum_t (X_{ijklt} + X_{ij,k=5,l,t}) \geq W \cdot Z_{ijkl} \quad \forall i, k, l, j \in \{1, ..., 5\} \tag{11}
\]

\[
W \cdot \sum_i \sum_j \sum_k \sum_l Z_{ijkl} \geq R \cdot \sum_i \sum_j \sum_k \sum_l \sum_t X_{ijklt} \tag{12}
\]

\[
X_{ijklt}, Y_{it}, Z_{ijkl} \in \{0, 1\} \quad \forall i, j, k, l, t \tag{12}
\]
**Model Results**

- Average Surg. Utilization Before = .5158
- Average Surg. Utilization After= .6458

- **19 out of 31 surgeons improved their utilization**

- Average Daily Utilization is .55
- **13 disruptions from current schedule**
3. Capacity planning: OR Staffing optimization
Problem Definition
Shift Preferences Surveys

Staff Schedule Requests (5/3/15 - 5/30/15)
These questions will create schedules that best accommodate everyone's requests. You will receive an email confirmation after clicking "Submit" at the end of the form.
Deadline for submission: 4/3/15

* Required

Name and Email Address
If your name is missing or listed incorrectly, please email Barbara Sweeney at hsweene1@bidmc.harvard.edu.

Name *
Please select your name from the dropdown list below.

Email Address *
Please type the email address where you want your confirmation to be sent.

Days Off Requests
Please choose from the options below if you would like to request days off (in order of priority). You do not need to include PTO requests that have already been approved. Choosing the same date multiple times will increase the likelihood of having it granted.

Day Off - 1st Choice *

Day Off - 2nd Choice *

Day Off - 3rd Choice *
## Notation

### Indices

| $i \in (1..I)$ | Workers       |
| $j \in (1..J)$ | Shifts        |
| $k \in (1..K)$ | Days          |
| $w \in (1..W)$ | Weeks         |
| $t \in (1..T)$ | Time of day   |
| $l \in (1..L)$ | Worker Skills |

### Parameters

| $P_{ijkw}$ | Preference matrix indicating whether or not worker $i$ prefers to work shift $j$ on day $k$ during week $w$ |
| $RNSTRatio$ | Minimum desired ratio of RNs to STs assigned for at time |
| $f_j$ | Length of shift $j$ (in hours) |
| $H_t$ | Minimum number of workers to be assigned at time $t$ |
| $\beta_i$ | Number of weekly hours to be assigned to worker $i$ |
| $Y_{ikw}$ | The number of PTO hours worker $i$ has on day $k$ during week $w$ |
| $Spec_{ikw}$ | The number of hours of demand for workers with skill $l$ on day $k$ during week $w$ |
| $s_{il}$ | Worker $i$'s proficiency in skill $l$ (1-4 rating) |

### Decision Variables

$x_{ijkw} \in \{0,1\}$ Assignment variable is equal to 1 if worker $i$ is assigned to work shift $j$ on day $k$ during week $w$. 0, otherwise.
Constraints

(1) The objective function of the model maximizes the number of preferences satisfied by the shift assignments

(2) There is a minimum ratio of RNs to STs at all times

(3) A worker can be assigned at most one shift per day

(4) A worker must be assigned a specific number of hours every week

(5) A worker cannot be assigned a shift if they are getting vacation that day

(6) Nurse skillsets must match with surgery schedules for the day

(7) The number of 12 hour shifts per month must be less than 4 for every worker

(8) Sets the variable X as a binary
Mathematical Model

Maximize \[ \sum_{i} \sum_{j} \sum_{k} \sum_{w} P_{ijkw} \cdot x_{ijkw} \]  

Subject to

\[ \sum_{i \in RN} \sum_{j \in J_t} x_{ijkw} - \text{RNSTRatio} \cdot \sum_{i \in ST} \sum_{j \in J_t} x_{ijkw} \geq 0 \]  \( \forall t \in T, \forall k \in K, \forall w \in W \)  

\[ \sum_{j} x_{ijkw} \leq 1 \]  \( \forall i \in I, \forall k \in K, \forall w \in W \)

\[ \sum_{j} \sum_{k} (f_j \cdot x_{ijkw} + Y_{ikw}) = \beta_i \]  \( \forall i \in I, \forall w \in W \)

\[ \sum_{j} Y_{ikw} \cdot x_{ijkw} = 0 \]  \( \forall i \in I, \forall k \in K, \forall w \in W \)

\[ \sum_{i} \sum_{j} f_j \cdot s_{il} \cdot x_{ijkw} \geq \text{Spec}_{lkw} \]  \( \forall l \in L, \forall k \in K, \forall w \in W \)

\[ \sum_{j \in SC} \sum_{k} \sum_{w} x_{ijkw} \leq 4 \]  \( \forall i \in I \)

\[ x_{ijkw} \in \{0,1\} \]  \( \forall i \in I, \forall j \in J, \forall k \in K, \forall w \in W \)
Results/Measures

- Staff shift satisfaction survey
- Pre and post comparison of skillset matching
- Less overtime

Better Schedules

- Increased staff satisfaction
- Better matchup of skillsets with specialties
- Savings on overtime hours
Questions?