Using Stochastic Programming to Improve Service Quality in an Outpatient Infusion Center

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Cancer and Cancer Treatment

- **Cancer Statistics**
  - 1,638,910 new cases of cancer in the United States (2012)
  - Second leading cause of death in the United States

- **Outpatient Oncology**
  - 29.2 million visits in the US with a primary diagnosis of cancer
  - 23 million adult patient visits for chemotherapy
  - 84% of visits for chemotherapy occur in the outpatient setting

- **Chemotherapy Infusion Center**
  - Facility where cancer treatment is given on an outpatient basis
University of Michigan Comprehensive Cancer Center

• 1 of 41 United States centers to earn the National Cancer Institute “Comprehensive” designation
• 93,319 Outpatient Visits
• 51,884 Infusion Treatments
Infusion Center Challenges

- Long patient waiting times
- Heavy nurse workload
  - Overtime
  - Equity
  - Safety concerns
- High demand for outpatient oncology services
- Cost
  - Nurse utilization
  - Pharmaceutical waste
Meet Mrs. J

- 52 y.o. woman diagnosed with Small Cell Carcinoma of the Cervix
- Chemotherapy regimen: Day 1: Cisplatin + Etoposide; Day 2 & 3: Hydration
- Scheduled infusion time: Day 1: 300 minutes; Day 2 & 3: 150 minutes
- Protocol: 4-6 Cycles, Every third week
- Travel: 60 miles each way
Appointment 1: Lab Draw

7:30 am – Lab Draw
Appointment 2: Clinic

7:30 am – Lab Draw
8:30 am – Clinic
Appointment 3: Infusion

- 7:30 am – Lab Draw
- 8:30 am – Clinic
- 9:30 am – Infusion
Mrs. J Leaves

- 7:30 am – Lab Draw
- 8:30 am – Clinic
- 9:30 am – Infusion
- 2:30 pm – Discharge
During her visit to the Cancer Center...

• Mrs. J will spend 90 minutes waiting on average
• She will see 2 different nurses during her infusion
• She will not arrive home until 5:00 pm
• She will return to the Cancer Center at 07:30 am the next two days for two hours of hydration each day.
Project Goals

• Improve quality of cancer care delivery in the infusion center
  – Reduce patient waiting times
  – Reduce total length of day of operations
  – Improve patient and nurse safety
Observations & Data → Patient Flow Mapping → Simulation Model → Outputs → Analysis → Future Steps

Scheduling Model
Patient Flow

Patient Arrives

Lab Collection • Labs sent for processing

Clinic Appointment • New Orders • Imaging Process • Need for Modifications

Infusion • Vitals Signs, Height & Weight verified • Safety Checks • IV Access obtained

Pharmacy Preparation

Patient discharged
Computer Simulation Model
Computer Simulation Model
Inputs - Outputs

**Inputs**
- Patient types
- Nurse preparation time
- Nurse discharge time
- Pharmacy preparation time
- Patient appointment schedules
  - Baseline
  - LPT heuristic
  - SPT heuristic
  - Stochastic model

**Computer Simulation**

**Outputs**
- Average patient waiting times
- Hours of operation
- Chair utilization
- Average time in system
LPT and SPT Sequencing Rules

- Patient arrivals are sequenced based on the mean of their infusion time distribution
  - LPT: Longest treatment time first
  - SPT: Shortest treatment time first
Stochastic Scheduling Model

• Generates appointment schedule that reduces patient waiting times and total length of operations for a workday

• Nature
  – Large scale MIP model

• Stochasticity
  – Scenarios represent variability
  – Scenarios sample infusion, preparation and discharge times from distributions

• Results
  – Appointment times
  – Patient sequence
  – Patient-Chair assignment
Stochastic Scheduling Model
Formulation

Decision Variables

\( a_p \) : appointment time of patient \( p \)

\( w_p^\omega \) : waiting time of patient \( p \) in scenario \( \omega \)

\( d_p^\omega \) : exit time of patient \( p \) in scenario \( \omega \)

\( x_{pc}^\omega \) : binary, 1 if patient \( p \) is assigned to chair \( c \) in scenario \( \omega \); 0 otherwise

\( z_{p'p} \) : binary, 1 if patient \( p' \) is scheduled before patient \( p \); 0 otherwise

\( L^\omega \) : end of day in scenario \( \omega \)

Parameters

\( s_p^\omega \) : preparation time of patient \( p \) in scenario \( \omega \)

\( t_p^\omega \) : infusion time plus discharge time of patient \( p \) in scenario \( \omega \)

\( m \) : number of scenarios

\( \lambda \) : weight in the objective function

\( M \) : large number
Objective Function: Trade-off between the total expected waiting time and the expected end of day

\[
\min_{a, z, x, d, w, E} \quad \lambda \sum_{p \in P} \sum_{\omega \in \Omega} \frac{1}{m} w_p^\omega + (1 - \lambda) \sum_{\omega \in \Omega} \frac{1}{m} L^\omega
\]
Stochastic Scheduling Model Formulation

\[ \min_{a,z,t,w,E} \lambda \sum_{p \in P} \sum_{\omega \in \Omega} \frac{1}{m} w^\omega_p + (1 - \lambda) \sum_{\omega \in \Omega} \frac{1}{m} L^\omega \]

subject to \[ \sum_{c \in C} x^\omega_{pc} = 1 \]
\[ \forall p \in P, \forall \omega \in \Omega \]

Each patient should be assigned to exactly one infusion chair.
Stochastic Scheduling Model
Formulation

\[
\min_{a,z,x^\omega,d^\omega,w^\omega,E^\omega} \lambda \sum_{p \in P} \sum_{\omega \in \Omega} \frac{1}{m} w^\omega_p + (1 - \lambda) \sum_{\omega \in \Omega} \frac{1}{m} L^\omega
\]

subject to
\[
\sum_{c \in C} x^\omega_{pc} = 1 \quad \forall p \in P, \forall \omega \in \Omega
\]
\[
a^\omega_p + w^\omega_p + s^\omega_p + t^\omega_p = d^\omega_p \quad \forall p \in P, \forall \omega \in \Omega
\]

Value of exit time of patient $p$ in each scenario
Stochastic Scheduling Model Formulation

Free chair constraint: A patient can sit in a chair only if all previously sequenced patients assigned to the same chair have been discharged.
Stochastic Scheduling Model Formulation

\[
\min_{a,z,x,\omega,d,\omega,w,\omega,E,\omega} \quad \lambda \sum_{p \in P} \sum_{\omega \in \Omega} \frac{1}{m} w_p^\omega + (1 - \lambda) \sum_{\omega \in \Omega} \frac{1}{m} L^\omega
\]

subject to

\[
\sum_{c \in C} x^\omega_{pc} = 1 \quad \forall p \in P, \ \forall \omega \in \Omega
\]

\[
a_p + w_p^\omega + s_p^\omega + t_p^\omega = d_p^\omega \quad \forall p \in P, \ \forall \omega \in \Omega
\]

\[
a_p + w_p^\omega + M(3 - x^\omega_{pc} - x^\omega_{pc'} - z_{pp'}) \geq d_p^\omega \quad \forall c \in C, \ \forall p, p' \in P, \ \forall \omega \in \Omega
\]

\[
a_p + w_p^\omega + M z_{pp'} \geq a_{p'} + w_{p'}^\omega + s_{p'}^\omega \quad \forall p, p' \in P, \ \forall \omega \in \Omega
\]

Available nurse constraint: A patient can sit in a chair if the nurse has finished preparing all previously sequenced patients
Stochastic Scheduling Model
Formulation

\[
\begin{align*}
\min_{a,z,t,x,d,v,w,E} & \quad \lambda \sum_{p \in P} \sum_{\omega \in \Omega} \frac{1}{m} w^\omega_p + (1 - \lambda) \sum_{\omega \in \Omega} \frac{1}{m} L^\omega \\
\text{subject to} & \quad \sum_{c \in C} x^\omega_{pc} = 1 \\
& \quad a_p + w^\omega_p + s^\omega_p + t^\omega_p = d^\omega_p \\
& \quad a_p + w^\omega_p + M(3 - x^\omega_{pc} + x^\omega_{p'c} - z_{p'p}) \geq d^\omega_p \\
& \quad a_p + w^\omega_p + Mz_{pp'} \geq a_{p'} + w^\omega_{p'} + s^\omega_{p'} \\
& \quad L^\omega \geq d^\omega_p \\
& \forall p \in P, \forall \omega \in \Omega \\
& \forall p \in P, \forall \omega \in \Omega \\
& \forall c \in C, \forall p, p' \in P, \forall \omega \in \Omega \\
& \forall p, p' \in P, \forall \omega \in \Omega \\
& \forall p \in P, \forall \omega \in \Omega
\end{align*}
\]

All patients should be discharged to end the day
Stochastic Scheduling Model Formulation

\[
\begin{align*}
\min_{a,z,x,\omega^p,d^p,w^p,E^\omega} & \quad \lambda \sum_{p \in P} \sum_{\omega \in \Omega} \frac{1}{m} w^p_{\omega} + (1 - \lambda) \sum_{\omega \in \Omega} \frac{1}{m} L^\omega \\
\text{subject to} & \quad \sum_{c \in C} x^\omega_{pc} = 1 \\
& \quad a_p + w^p_{\omega} + s^\omega_p + t^\omega_p = d^\omega_p \\
& \quad a_p + w^p_{\omega} + M(3 - x^\omega_{pc} - x^\omega_{p'c} - z_{p'p}) \geq d^\omega_{p'} \\
& \quad a_p + w^p_{\omega} + M z_{p'p} \geq a_{p'} + w^\omega_{p'} + s^\omega_{p'} \\
& \quad L^\omega \geq d^\omega_{p'} \\
& \quad (a_{p'} - a_p) + M(z_{p'p}) \geq 0 \\
& \quad z_{p'p} = 1 - z_{p'p} \\
& \quad \forall p \in P, \forall \omega \in \Omega \\
& \quad \forall p \in P, \forall \omega \in \Omega \\
& \quad \forall c \in C, \forall p, p' \in P, \forall \omega \in \Omega \\
& \quad \forall p, p' \in P, \forall \omega \in \Omega \\
& \quad \forall p \in P, \forall \omega \in \Omega \\
& \quad \forall p, p' \in P \\
& \quad \forall p, p' \in P
\end{align*}
\]

Definition of variable \( z_{p'p} \)
Stochastic Scheduling Model Formulation

\[ \min_{a,z,x,d,w,E} \sum_{p \in P} \sum_{\omega \in \Omega} \frac{1}{m} w^\omega_p + (1 - \lambda) \sum_{\omega \in \Omega} \frac{1}{m} L^\omega \]

subject to

\begin{align*}
\sum_{c \in C} x^\omega_{pc} &= 1 \\
a_p + w^\omega_p + s^\omega_p + t^\omega_p &= d^\omega_p \\
a_p + w^\omega_p + M(3 - x^\omega_{pc} - x^\omega_{pc'} - z^\omega_{p'p}) &\geq d^\omega_{p'} \\
a_p + w^\omega_p + Mz^\omega_{pp'} &\geq a_{p'} + w^\omega_{p'} + s^\omega_{p'} \\
L^\omega &\geq d^\omega_p \\
(a_{p'} - a_p) + M(z^\omega_{p'p}) &\geq 0 \\
z^\omega_{pp'} &= 1 - z^\omega_{p'p} \\
x^\omega_{pc} &\in \{0, 1\} \\
z^\omega_{p'p} &\in \{0, 1\} \\
a_p &\geq 0 \\
w^\omega_p, d^\omega_p &\geq 0
\end{align*}

\[ \forall p \in P, \forall \omega \in \Omega \]

\[ \forall p \in P, \forall \omega \in \Omega \]

\[ \forall c \in C, \forall p, p' \in P, \forall \omega \in \Omega \]

\[ \forall p, p' \in P, \forall \omega \in \Omega \]

\[ \forall p \in P, \forall \omega \in \Omega \]

\[ \forall p, p' \in P \]

\[ \forall c \in C, \forall p \in P, \forall \omega \in \Omega \]

\[ \forall p, p' \in P \]

\[ \forall p \in P \]

\[ \forall p \in P, \forall \omega \in \Omega \]

Binary and non-negativity constraints
Model Simplification

- Stochastic MIP model
  - Large number of constraints
  - Using big M in constraints results in weak relaxations
  - Numerical experiments suggest that LPT sequencing rule is optimal

- Stochastic LP model
  - Assuming LPT and FIFO rules, the MIP model becomes an LP which is tractable for a large number of scenarios
  - LP optimal solution within 0.1% of MIP optimal solution
Trade-off Concept
Trade-off Concept
Results
Results
Results

The diagram shows the total time of Infusion Center operation (hrs) vs. the average waiting time for each patient (mins). The data is categorized into different groups: Baseline, LPT, SPT, and OPT LPT. Each group is represented by different markers and colors, allowing for a clear comparison of the waiting times across different scenarios.
Conclusions

• A simplified version of an infusion center scheduling process can be formulated as a stochastic integer program

• The LPT sequence appears to be optimal after solving the stochastic integer programming model

• Fixing the LPT rule for sequencing patient arrival results in an easy to solve continuous stochastic program
  – Performs slightly better than LPT heuristic
Future Steps

• Development of a heuristic that can be easily implemented by schedulers

• Improve stochastic models

• Enhancing simulation model
  – Addition of oncology clinic
  – 2-day model evaluation

• 2-day model survey
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