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

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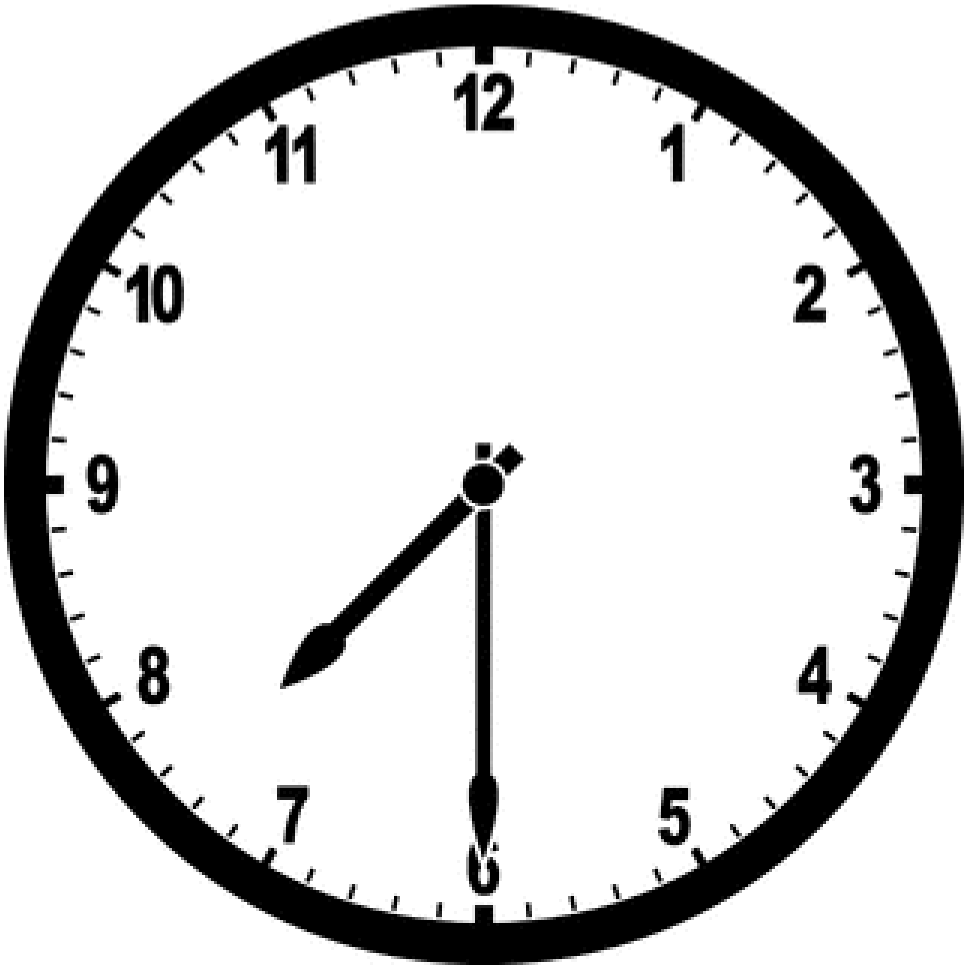
Infusion Center Challenges

- 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

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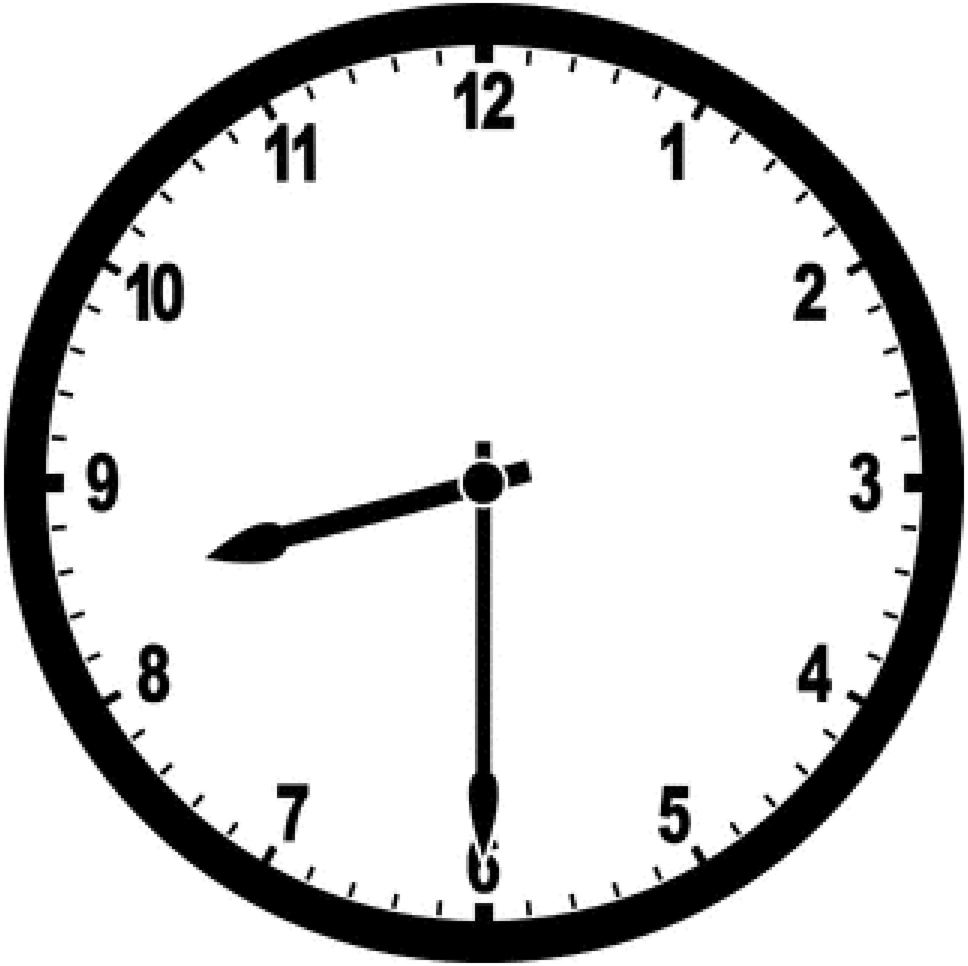
Appointment 2: Clinic



7:30 am – Lab Draw

8:30 am – Clinic

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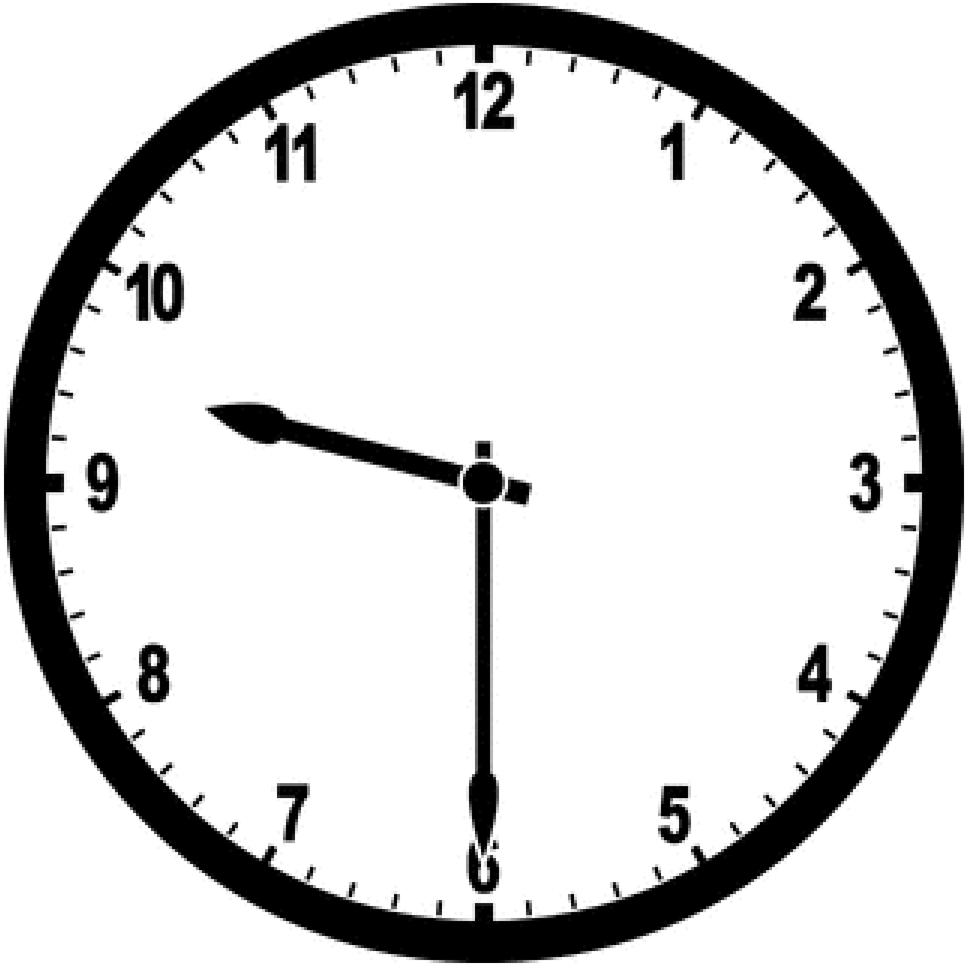
Appointment 3: Infusion



7:30 am – Lab Draw
8:30 am – Clinic
9:30 am – Infusion

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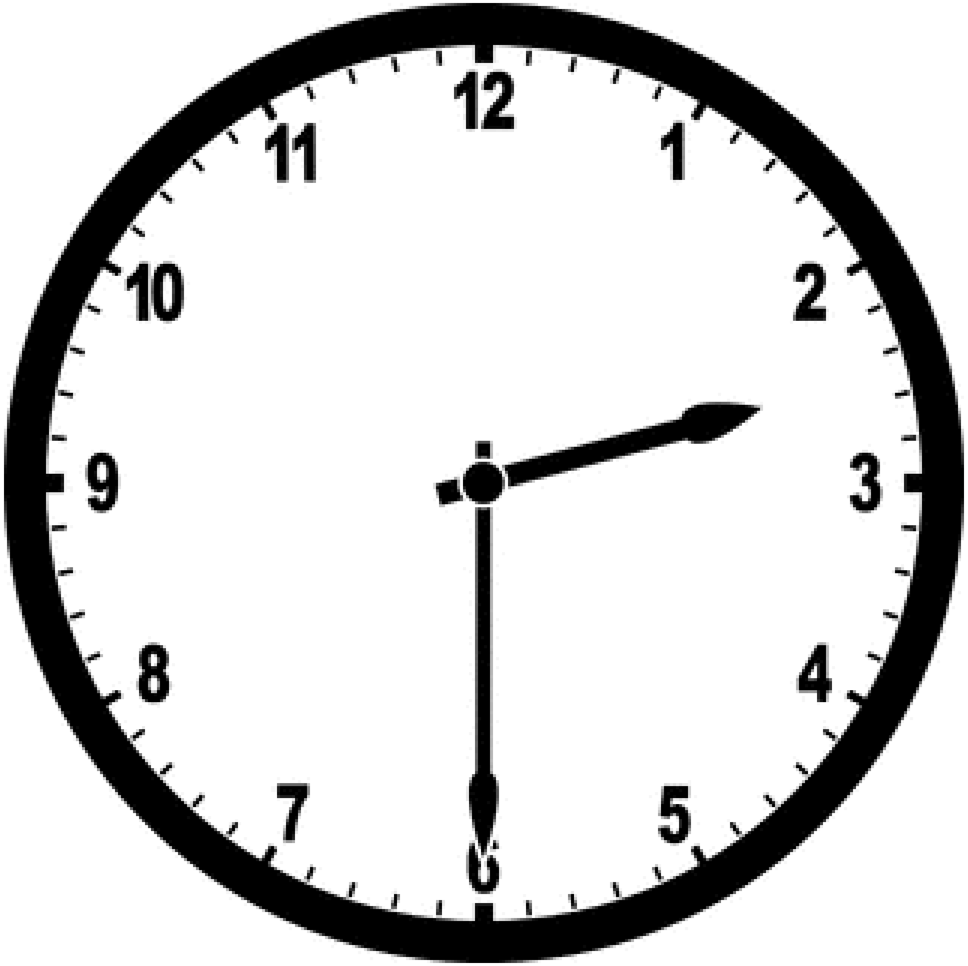
Mrs. J Leaves



7:30 am – Lab Draw
8:30 am – Clinic
9:30 am – Infusion
2:30 pm – Discharge

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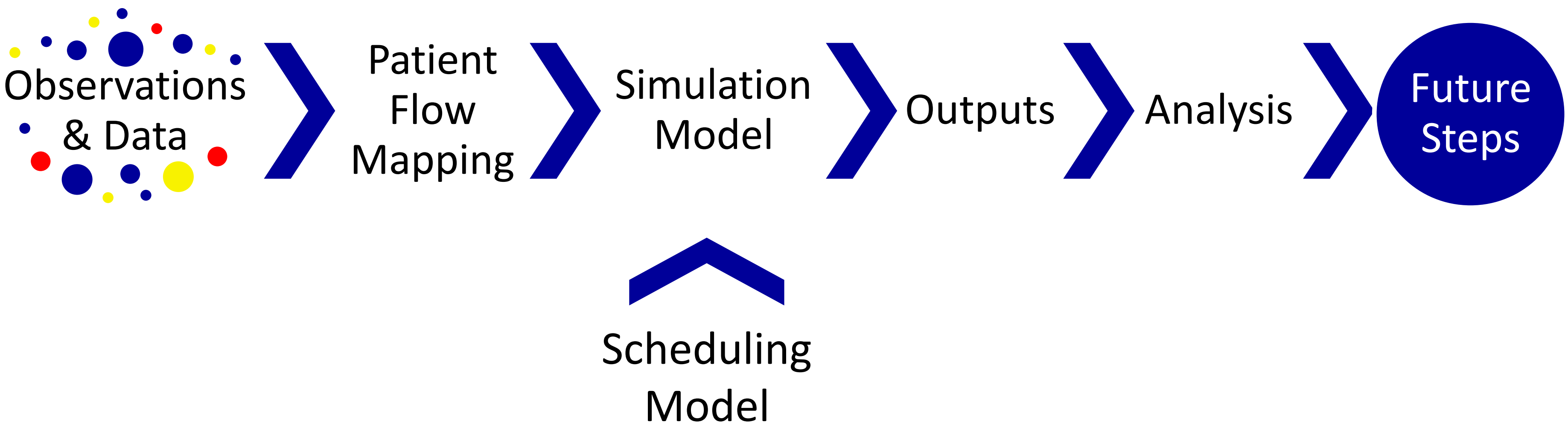
During her visit to the Cancer Center…

- 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

Approach



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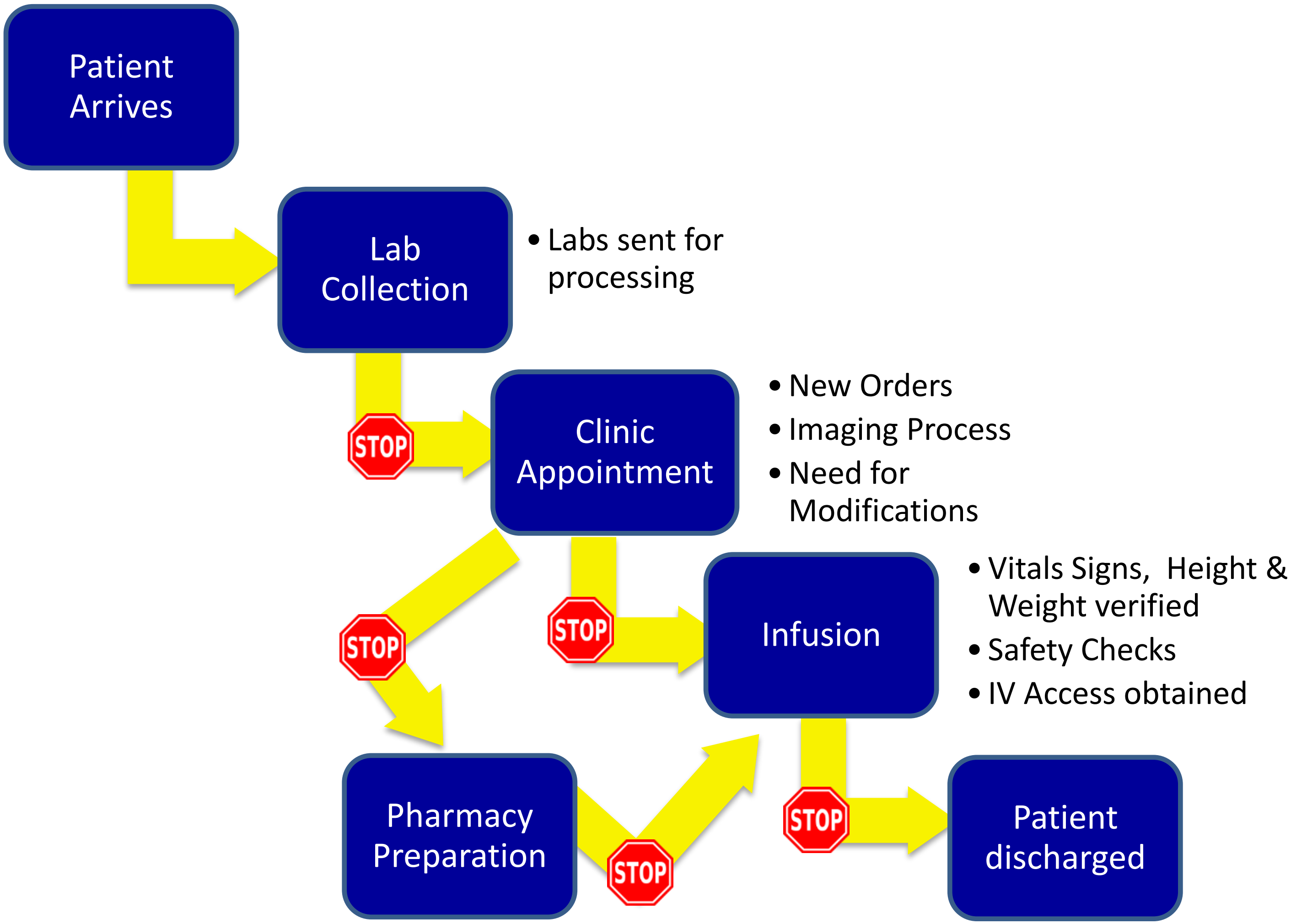
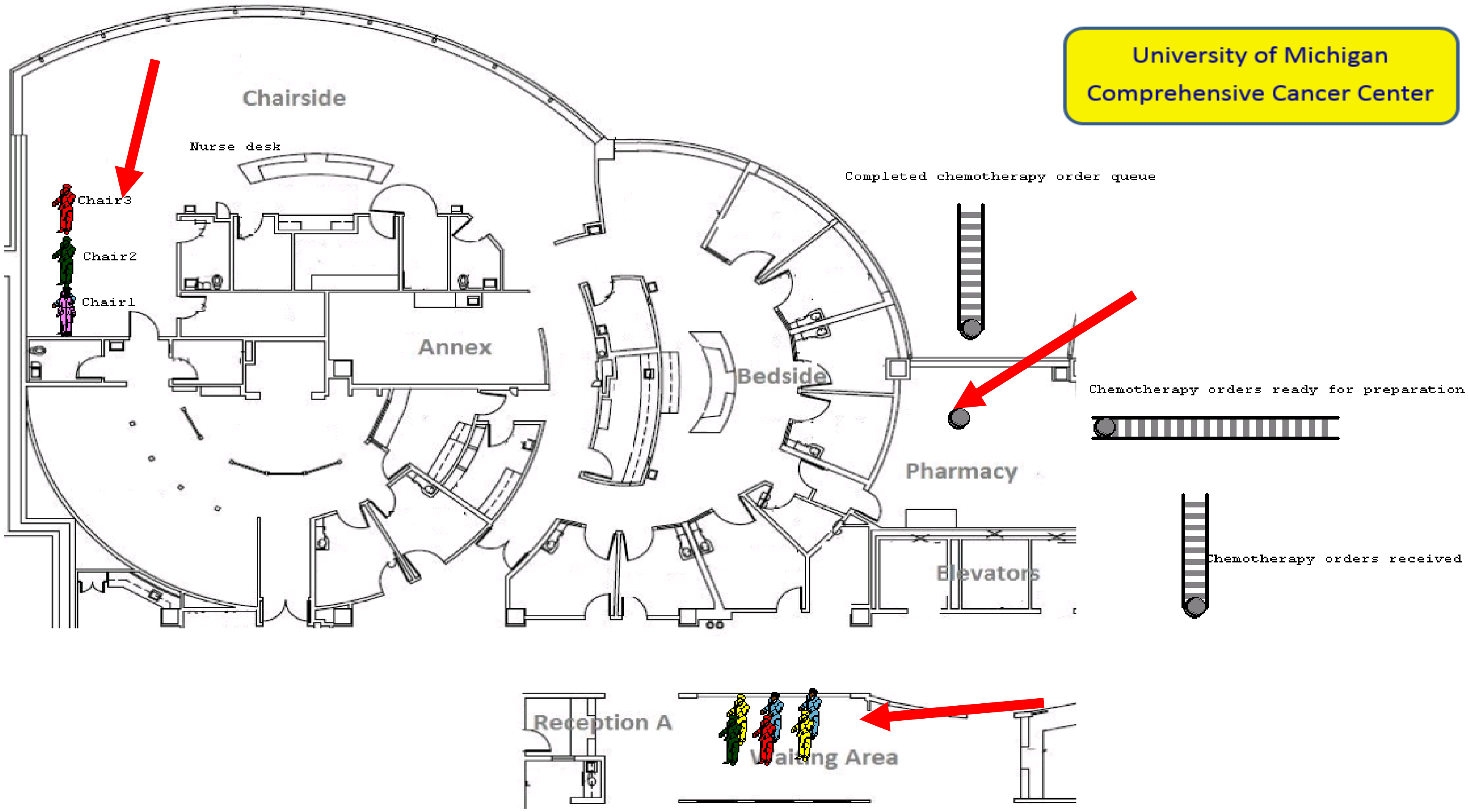
Patient Flow



Computer Simulation Model

University of Michigan
Comprehensive Cancer Center



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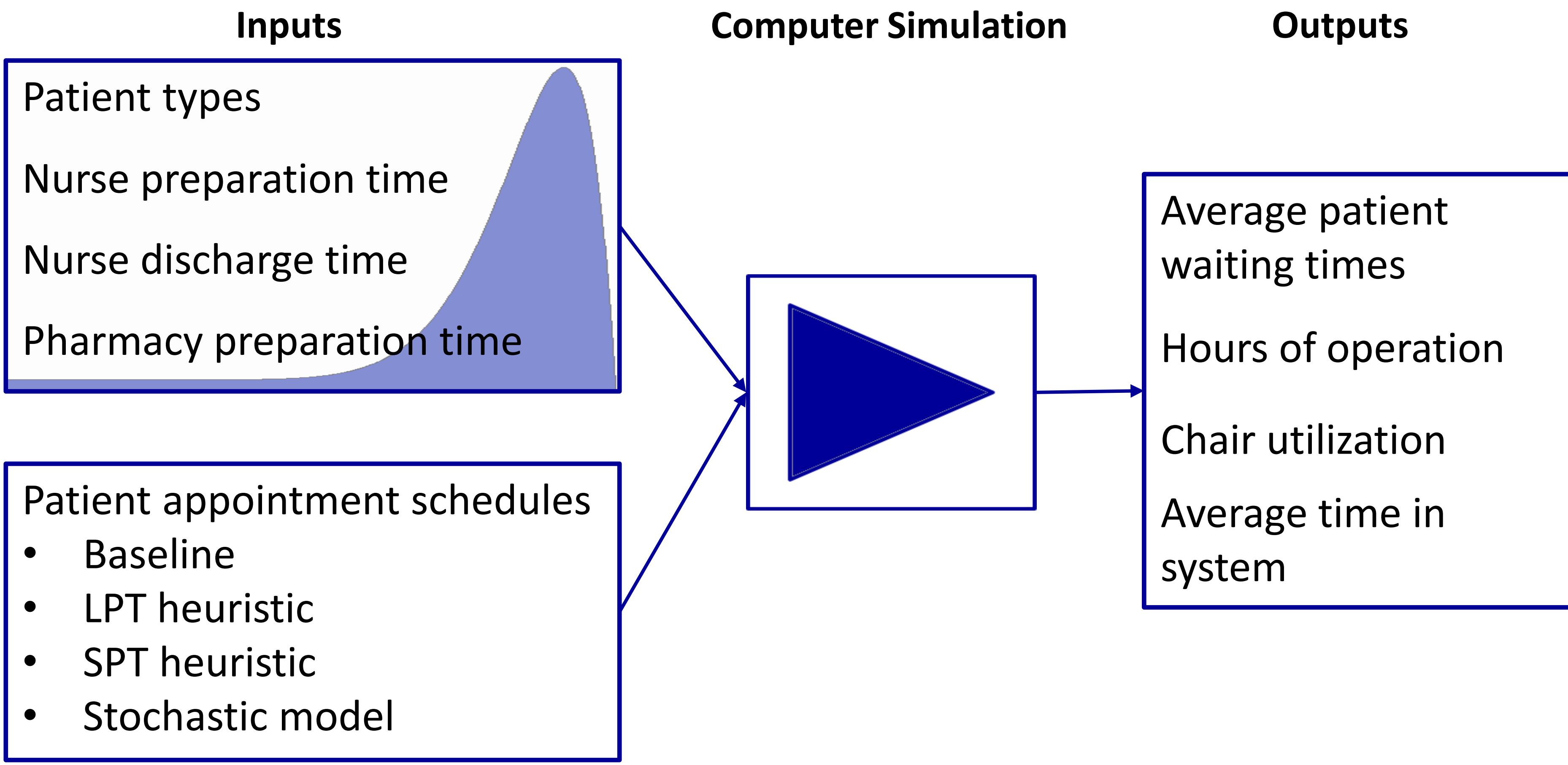
Computer Simulation Model
Inputs - Outputs



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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^ω : waiting time of patient p in scenario ω

d_p^ω : exit time of patient p in scenario ω

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

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

L^ω : end of day in scenario ω

Parameters

s_p^ω : preparation time of patient p in scenario ω

t_p^ω : infusion time plus discharge time of patient p in scenario ω

m : number of scenarios

λ : weight in the objective function

M : large number

Stochastic Scheduling Model Formulation

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

Objective Function: Trade-off between the total expected waiting time and the expected end of day

Stochastic Scheduling Model Formulation

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

$$\text{subject to} \quad \sum_{c\in C} x_{pc}^\omega = 1 \qquad \forall p \in P,\ \forall \omega \in \Omega$$

Each patient should be assigned to exactly one infusion chair

Stochastic Scheduling Model Formulation

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

$$\text{subject to} \quad \sum_{c\in C} x_{pc}^\omega = 1 \qquad \forall p\in P,\ \forall\omega\in\Omega$$

$$a_p + w_p^\omega + s_p^\omega + t_p^\omega = d_p^\omega \qquad \forall p\in P,\ \forall\omega\in\Omega$$

Value of exit time of patient p in each scenario

Stochastic Scheduling Model Formulation

$$
\begin{array}{lll}
\min\limits_{a,z,x^\omega,d^\omega,w^\omega,E^\omega} & \lambda \sum\limits_{p\in P}\sum\limits_{\omega\in\Omega} \frac{1}{m} w_p^\omega + (1-\lambda)\sum\limits_{\omega\in\Omega}\frac{1}{m}L^\omega & \\
\text{subject to} & \sum\limits_{c\in C} x_{pc}^\omega = 1 & \forall p \in P,\ \forall \omega \in \Omega \\
& a_p + w_p^\omega + s_p^\omega + t_p^\omega = d_p^\omega & \forall p \in P,\ \forall \omega \in \Omega \\
& a_p + w_p^\omega + M(3 - x_{pc}^\omega - x_{p'c}^\omega - z_{p'p}) \geq d_{p'}^\omega & \forall c \in C,\ \forall p, p' \in P,\ \forall \omega \in \Omega
\end{array}
$$

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

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Stochastic Scheduling Model Formulation

$$
\begin{aligned}
\min_{a,z,x^\omega,d^\omega,w^\omega,E^\omega} \quad & \lambda \sum_{p\in P}\sum_{\omega\in\Omega} \frac{1}{m} w_p^\omega + (1-\lambda)\sum_{\omega\in\Omega}\frac{1}{m}L^\omega \\
\text{subject to} \quad & \sum_{c\in C} x_{pc}^\omega = 1 && \forall p\in P,\ \forall\omega\in\Omega \\
& a_p + w_p^\omega + s_p^\omega + t_p^\omega = d_p^\omega && \forall p\in P,\ \forall\omega\in\Omega \\
& a_p + w_p^\omega + M(3 - x_{pc}^\omega - x_{p'c}^\omega - z_{p'p}) \ge d_{p'}^\omega && \forall c\in C,\ \forall p,p'\in P,\ \forall\omega\in\Omega \\
& a_p + w_p^\omega + M z_{pp'} \ge a_{p'} + w_{p'}^\omega + s_{p'}^\omega && \forall p,p'\in P,\ \forall\omega\in\Omega
\end{aligned}
$$

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

Stochastic Scheduling Model Formulation

$$
\begin{array}{lll}
\min\limits_{a,z,x^\omega,d^\omega,w^\omega,E^\omega} & \lambda \sum\limits_{p\in P} \sum\limits_{\omega\in\Omega} \frac{1}{m} w_p^\omega + (1-\lambda) \sum\limits_{\omega\in\Omega} \frac{1}{m} L^\omega & \\
\text{subject to} & \sum\limits_{c\in C} x_{pc}^\omega = 1 & \forall p \in P,\ \forall \omega \in \Omega \\
& a_p + w_p^\omega + s_p^\omega + t_p^\omega = d_p^\omega & \forall p \in P,\ \forall \omega \in \Omega \\
& a_p + w_p^\omega + M(3 - x_{pc}^\omega - x_{p'c}^\omega - z_{p'p}) \geq d_{p'}^\omega & \forall c \in C,\ \forall p, p' \in P,\ \forall \omega \in \Omega \\
& a_p + w_p^\omega + M z_{pp'} \geq a_{p'} + w_{p'}^\omega + s_{p'}^\omega & \forall p, p' \in P,\ \forall \omega \in \Omega \\
& L^\omega \geq d_p^\omega & \forall p \in P,\ \forall \omega \in \Omega
\end{array}
$$

All patients should be discharged to end the day

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Stochastic Scheduling Model Formulation

$$
\begin{array}{lll}
\min\limits_{a,z,x^\omega,d^\omega,w^\omega,E^\omega} & \lambda \sum\limits_{p\in P}\sum\limits_{\omega\in\Omega} \frac{1}{m} w_p^\omega + (1-\lambda)\sum\limits_{\omega\in\Omega}\frac{1}{m}L^\omega & \\
\text{subject to} & \sum\limits_{c\in C} x_{pc}^\omega = 1 & \forall p \in P,\ \forall \omega \in \Omega \\
& a_p + w_p^\omega + s_p^\omega + t_p^\omega = d_p^\omega & \forall p \in P,\ \forall \omega \in \Omega \\
& a_p + w_p^\omega + M(3 - x_{pc}^\omega - x_{p'c}^\omega - z_{p'p}) \geq d_{p'}^\omega & \forall c \in C,\ \forall p, p' \in P,\ \forall \omega \in \Omega \\
& a_p + w_p^\omega + M z_{pp'} \geq a_{p'} + w_{p'}^\omega + s_{p'}^\omega & \forall p, p' \in P,\ \forall \omega \in \Omega \\
& L^\omega \geq d_p^\omega & \forall p \in P,\ \forall \omega \in \Omega \\
& (a_{p'} - a_p) + M(z_{p'p}) \geq 0 & \forall p, p' \in P \\
& z_{pp'} = 1 - z_{p'p} & \forall p, p' \in P
\end{array}
$$

Definition of variable $z_{p'p}$

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Stochastic Scheduling Model Formulation

$$
\begin{array}{lll}
\min\limits_{a,z,x^\omega,d^\omega,w^\omega,E^\omega} & \lambda \sum\limits_{p\in P}\sum\limits_{\omega\in\Omega} \frac{1}{m} w_p^\omega + (1-\lambda)\sum\limits_{\omega\in\Omega}\frac{1}{m} L^\omega & \\
\text{subject to} & \sum\limits_{c\in C} x_{pc}^\omega = 1 & \forall p\in P,\ \forall\omega\in\Omega \\
& a_p + w_p^\omega + s_p^\omega + t_p^\omega = d_p^\omega & \forall p\in P,\ \forall\omega\in\Omega \\
& a_p + w_p^\omega + M(3 - x_{pc}^\omega - x_{p'c}^\omega - z_{p'p}) \geq d_{p'}^\omega & \forall c\in C,\ \forall p,p'\in P,\ \forall\omega\in\Omega \\
& a_p + w_p^\omega + M z_{pp'} \geq a_{p'} + w_{p'}^\omega + s_{p'}^\omega & \forall p,p'\in P,\ \forall\omega\in\Omega \\
& L^\omega \geq d_p^\omega & \forall p\in P,\ \forall\omega\in\Omega \\
& (a_{p'} - a_p) + M(z_{p'p}) \geq 0 & \forall p,p'\in P \\
& z_{pp'} = 1 - z_{p'p} & \forall p,p'\in P \\
& x_{pc}^\omega \in \{0,1\} & \forall c\in C,\ \forall p\in P,\ \forall\omega\in\Omega \\
& z_{p'p} \in \{0,1\} & \forall p,p'\in P \\
& a_p \geq 0 & \forall p\in P \\
& w_p^\omega, d_p^\omega \geq 0 & \forall p\in P,\ \forall\omega\in\Omega
\end{array}
$$

Binary and non-negativity constraints

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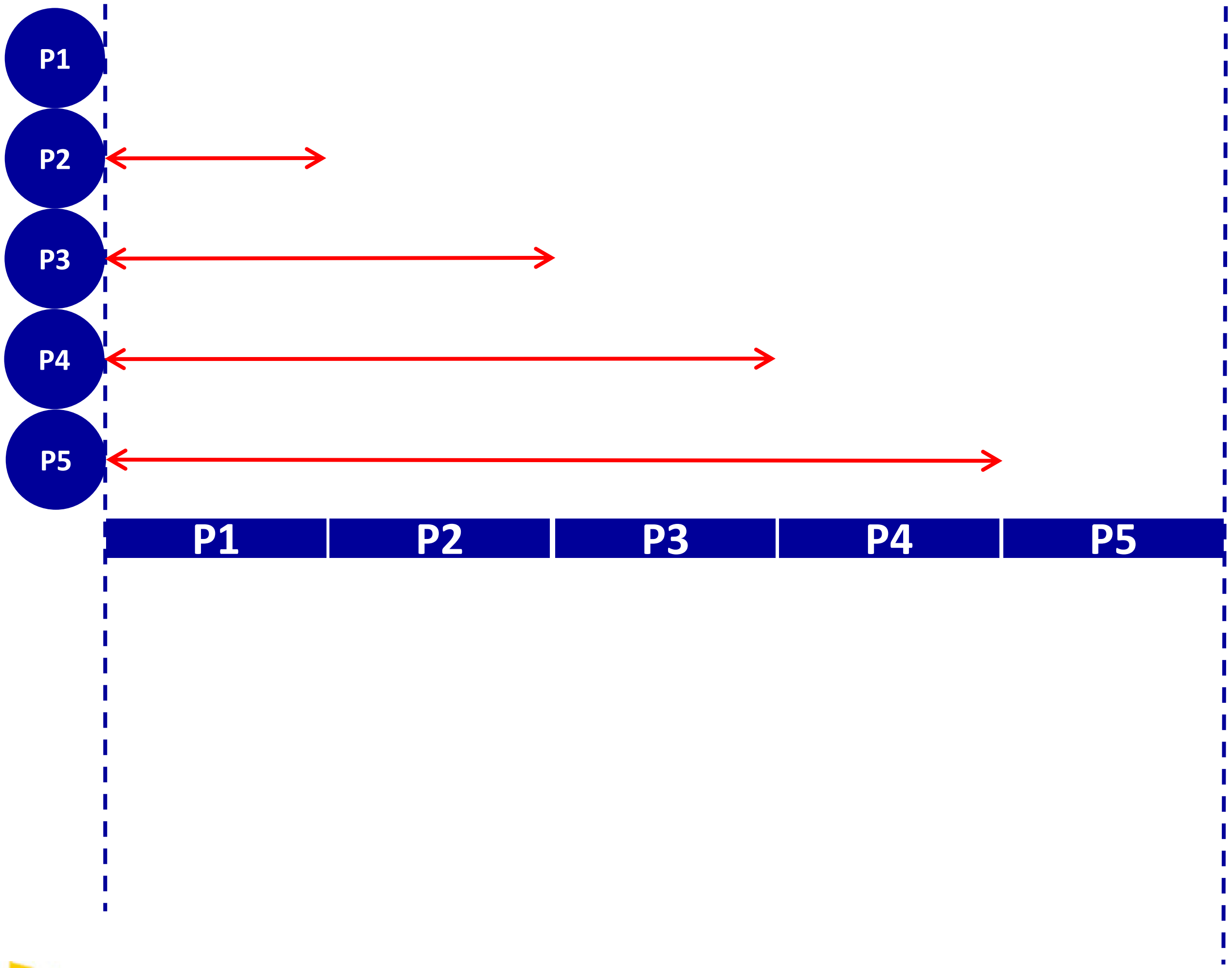
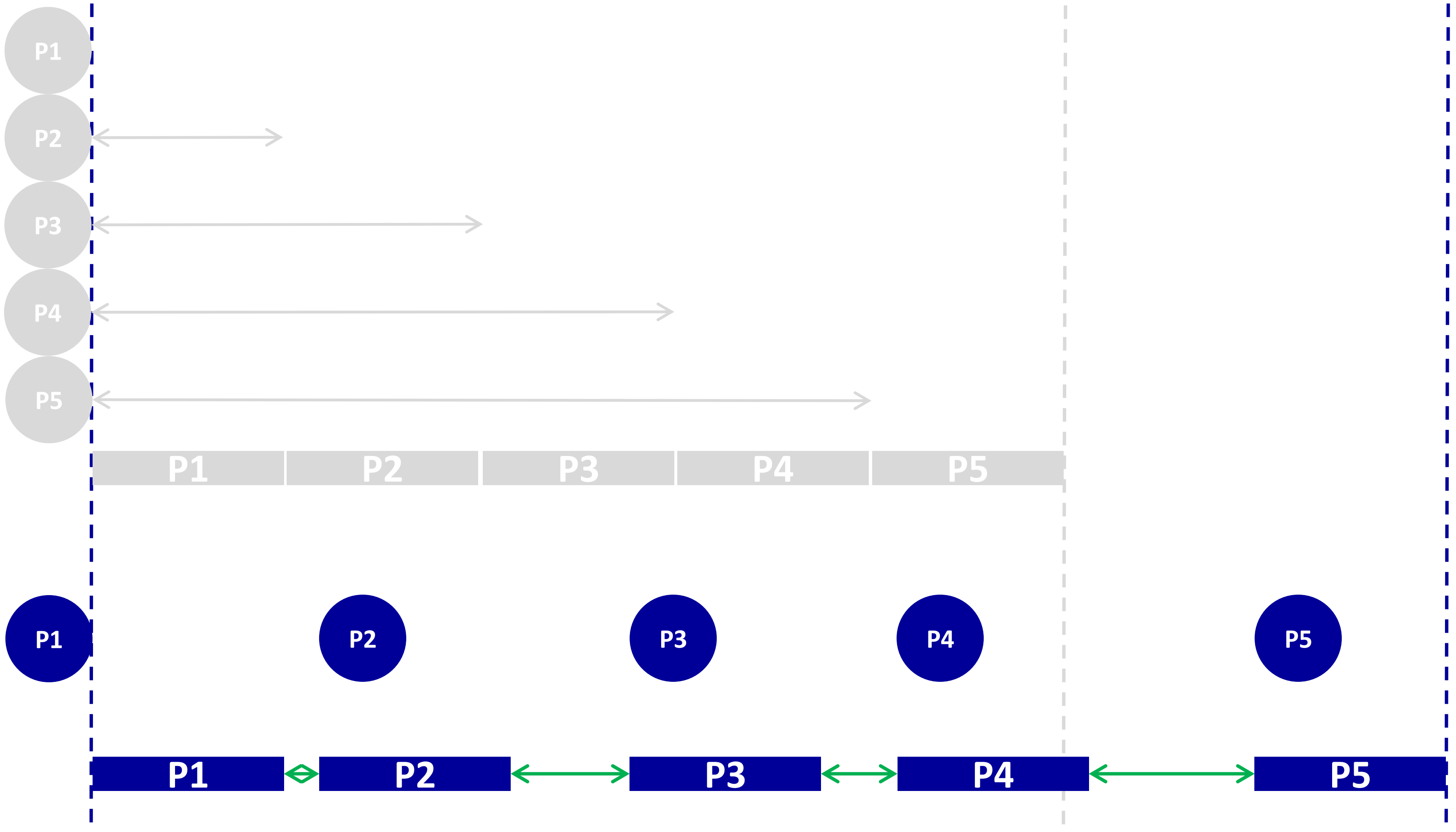
Model Simplification

- 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



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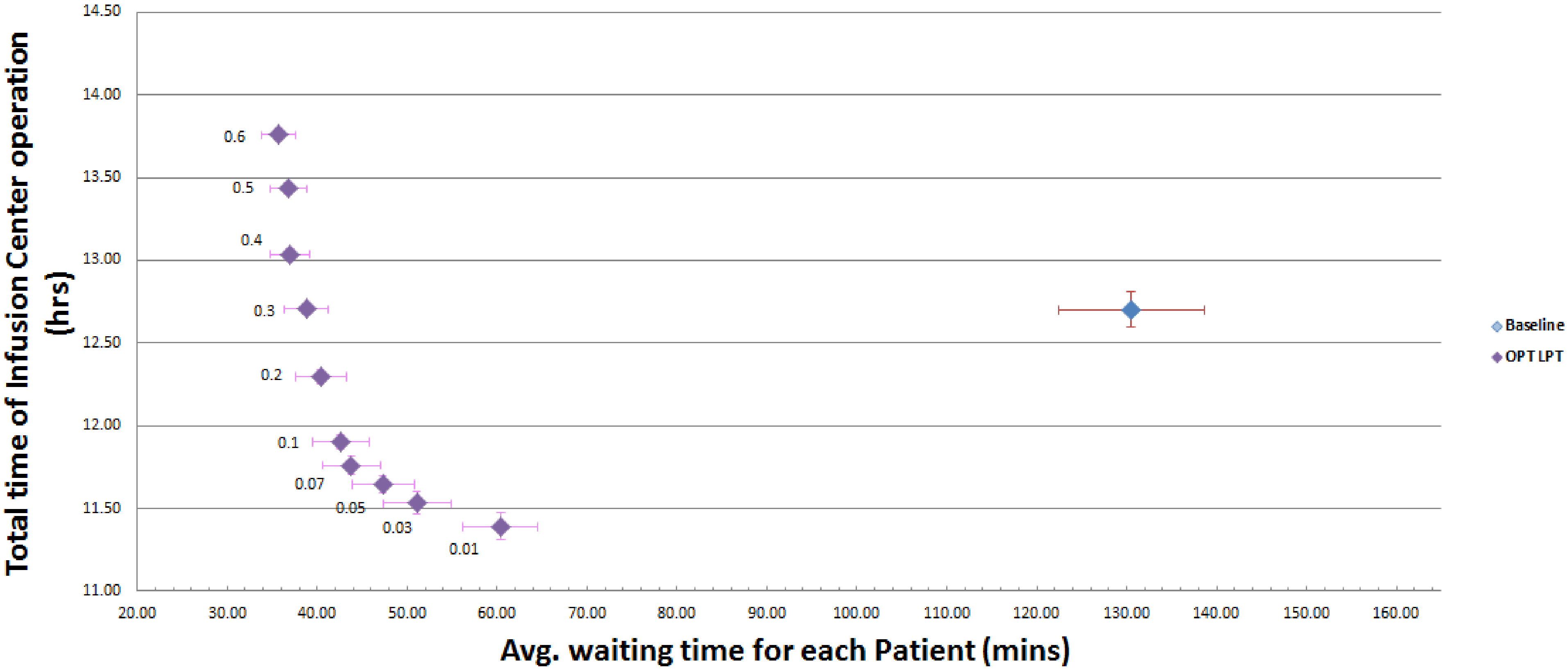
Results



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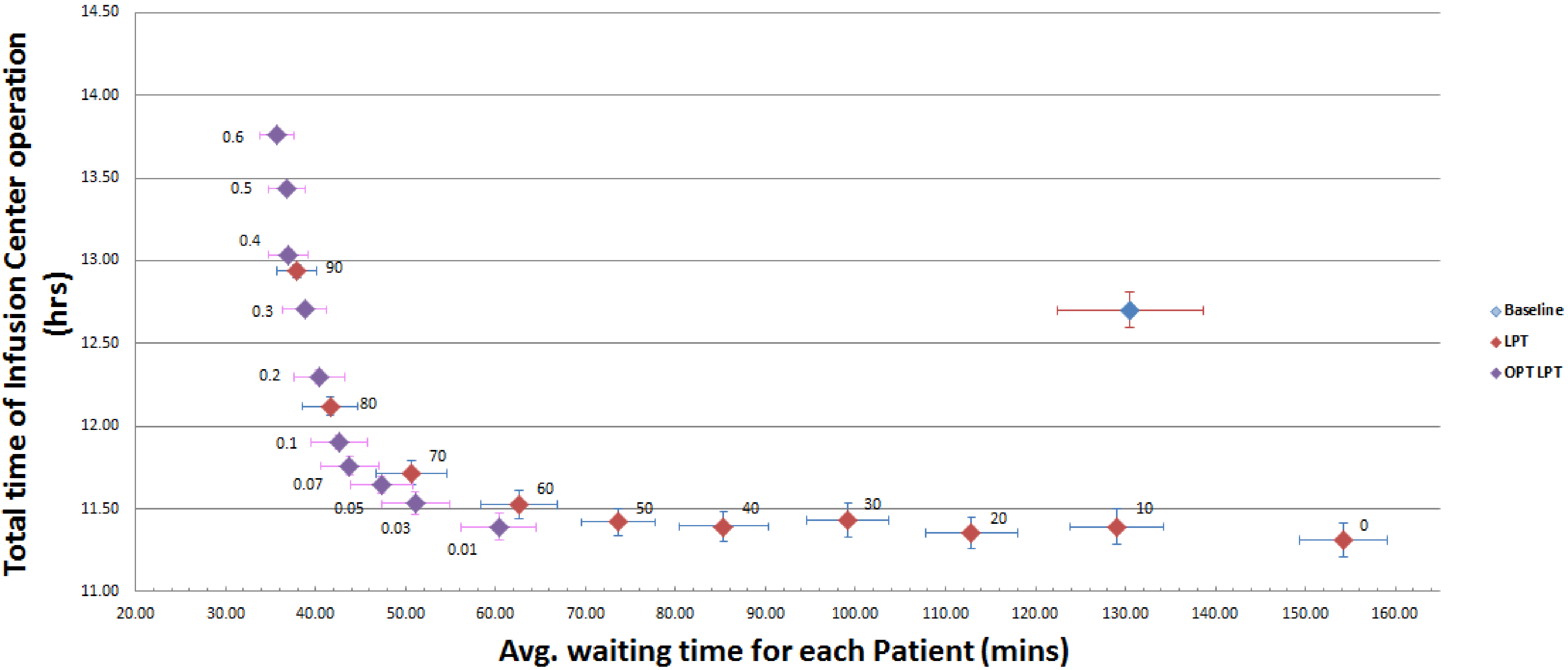
Results



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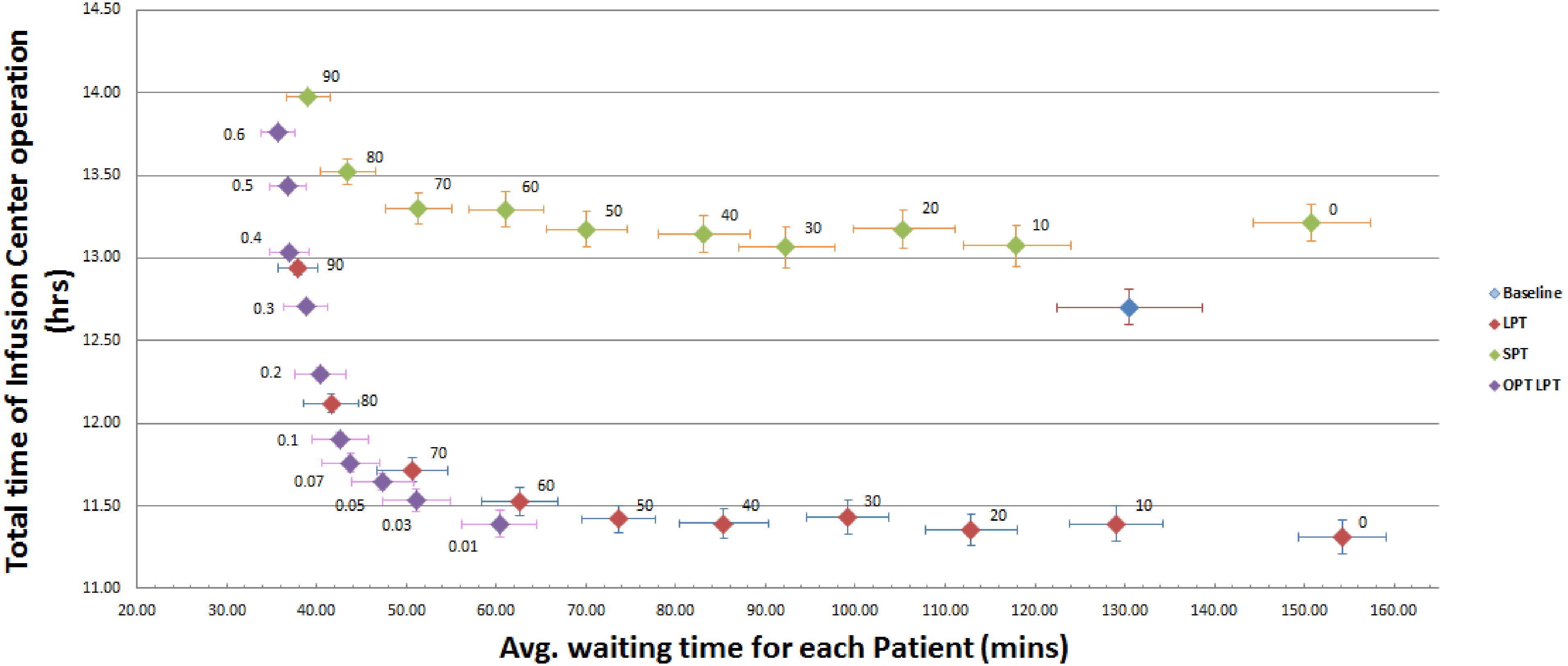
Results


Total time of Infusion Center operation (hrs)
14.50
14.00
13.50
13.00
12.50
12.00
11.50
11.00
20.00
30.00
40.00
50.00
60.00
70.00
80.00
90.00
100.00
110.00
120.00
130.00
140.00
150.00
160.00
Avg. waiting time for each Patient (mins)
Baseline
LPT
SPT
OPT LPT
90
80
70
60
50
40
30
20
10
0
0.6
0.5
0.4
0.3
0.2
0.1
0.07
0.05
0.03
0.01

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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