Appointment Scheduling with No-Shows and Overbooking: A Multi-Server Model

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High demand for medical appointments

- Patients experience difficulties in accessing medical care.

**Figure:** Merrit et al. (2011): Appointment delay for 1162 medical offices in 15 US metropolitan areas
High demand for medical appointments

"significant delays in access to care negatively impacted the quality of care at this medical facility."

"VA guidelines say veterans should be seen within 14 days of their desired date for an appointment."

Why So Many V.A. Delays?
Too Few Doctors, for Starters.

"Cooking the books" at VA hospitals has exploded into public view since allegations arose that up to 40 patients may have died at the Phoenix VA hospital while awaiting care.
No-Show

- **Patient no-shows**
  - 26% in *Dermatology*, Perio and Niemeier (2011)
  - 21% in *Psychotherapy*, Defife et al. (2010)
  - 30% in *Obstetrics and Gynecology*, Dreher et al. (2008)
  - 31% for *MRI screening*, Green and Savin (2008)
  - 15%-51% in *Mental Health*, Galucci et al. (2005)
  - ...

- **Unattended appointments**
  - Clinic under-utilization
  - Limit the access to other patients
Appointment Overbooking

No-Shows + High Demand → Appointment Overbooking → Clinic Overcrowding
Appointment Scheduling

1. How many patients to schedule?

2. How to allocate appointment slots throughout working day?

3. What is the optimal sequencing of heterogeneous patients?
**Static & Sequential Scheduling**

- **Static (Offline) Scheduling:** The set of customers to be scheduled and their characteristics are known in advance.
  - Kaandorp and Koole (2007)
  - Hassin and Mendel (2008)
  - Klassen and Yoogalingam (2009)
  - Robinson and Chen (2010)
  - Begen and Queyranne (2011)
  - Cayirli et al. (2011)
  - LaGanga and Lawrence (2012)...

- **Sequential (Online) Scheduling:** Requests for appointment come in gradually over time.
  - Muthuraman and Lawley (2008)
  - Zeng et al. (2010)
  - Liu et al. (2010)
  - LaGanga and Lawrence (2012)...

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**Introduction**

Heterogeneous Patients

Homogeneous Patients

Sequential Scheduling

Conclusion
Introduction

Heterogeneous Patients

Homogeneous Patients

Sequential Scheduling

Conclusion

Overview of the Problem

- Patients are heterogeneous
  - Different no-show probabilities
  - Different weights

- Objective: minimize the weighted sum of
  1. Patients’ waiting times
  2. Doctor’s idle time
  3. Doctor’s overtime

- Static Scheduling

- Sequential Scheduling
Contributions

- Sensible practice of appointment overbooking can significantly improve the operational performance.
- Patient heterogeneity affects optimal schedule and should be taken under consideration.
- New sequencing rule is introduced.
- Heuristic solution is proposed for the online problem.
Roadmap

1. Static Scheduling
   a. Heterogeneous Patients
   b. Homogeneous Patients

2. Sequential Scheduling

3. Conclusion
Single Server Model

- Single server.
- $n$ time slots available.
- $m$ customers are scheduled to arrive, $m \geq n$.
- One time slot of service.
- Customer $j$ will show up with probability $r_j = 1 - q_j$ exactly at the beginning of the time slot she was assigned.
Three costs:

1. **Waiting cost:** $w_j$ per time slot patient $j$ has to wait.
2. **Idle time cost:** $c_I$ per time slot of idle server.
3. **Overtime cost:** $c_o$ per overtime slot.

Objective:

$$\min_s E[W(s) + I(s) + O(s)]$$
**Lemma**

Each time slot has at least one customer assigned to it.
**Lemma**

There exists an optimal schedule that assigns all customers from the set $C_1 = \{ j : q_j = 0 \}$ to the first $N_1 = |C_1|$ time slots.
Structural Properties

- Consider for now the problem where
  \[ c_I, c_O \gg w_j \text{ for all } j. \]

- **primary objective**
  Minimization of doctor’s idle + overtime cost
  \[ \min_s E[I(s) + O(s)] \]

- **secondary objective**
  Minimization of patients’ waiting cost
  \[ \min_{s \in A} E[W(s)] \]
  where \( A = \left\{ s' : s' = \arg\min_s E[I(s) + O(s)] \right\} \)
Sequencing Rules

**Proposition**

The appointment schedule within class $\mathcal{A}$ that minimizes expected waiting cost has the structure:

(a) **Customers in set $C_1$ are assigned to slots $1, 2, \ldots, N_1$, no overbooking.**

(b) $m - n + 1$ customers are assigned to slot $N_1 + 1$, prioritized in decreasing order of $w_j$.

(c) Remaining $n - N_1 - 1$ customers are assigned to slots $N_1 + 1, N_1 + 2, \ldots, n$ in increasing order of $z_j = \frac{w_j(1 - q_j)}{q_j}$.

(d) Customer with lowest weight assigned to slot $N_1 + 1$ has $z$ index lower than that of customer assigned to $N_1 + 2$. 

![Diagram of sequencing rules](image)
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![Diagram of scheduling rules](image)
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![Diagram showing the sequencing rules](image-url)
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![Diagram showing appointment scheduling with no-shows and overbooking](image-url)
Sequencing Rules

Vertical Segment - LW

Horizontal Segment - SWPS

C₁
**Proposition**

In an optimal schedule:

- The customers in any vertical segment of the optimal schedule are ordered in decreasing order of $w_j$.
- The customers in any horizontal segment of the optimal schedule are scheduled in increasing order of

$$z_j = \frac{w_j(1 - q_j)}{q_j}.$$
**Proposition**

In an optimal schedule:

- The customers in any vertical segment of the optimal schedule are ordered in decreasing order of $w_j$.
- The customers in any horizontal segment of the optimal schedule are scheduled in increasing order of $z_j = \frac{w_j(1 - q_j)}{q_j}$.
**Corollary**

If $w_j = w$ for all $j = 1, 2, \ldots, m$, then all customers in a vertical segment and in the immediately following horizontal segment have to be scheduled in decreasing order of $q_j$.

*SPS: Smallest Probability of Showing up first*
Offline Scheduling-Homogeneous Customers

- $w_j = w \ \forall j = 1, 2, ..., m.$
- $q_j = q \ \forall j = 1, 2, ..., m.$

**PROPOSITION**

If $m = n + 1$ then the optimal schedule is

- if $\frac{w(1-q)}{q} \leq c_I + c_0$
- if $c_I + c_0 \leq \frac{w(1-q)}{q} \leq c_I + c_0 \left(1 + \frac{1}{1-q}\right)$
- if $c_I + c_0 \left(1 + \frac{1}{1-q}\right) \leq \frac{w(1-q)}{q}$
Numerical Experiments: Fixed $m$

<table>
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<th>Optimal Schedule</th>
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Decomposed Cost as a Function of $q$

- $n = 12$, $m = 16$. 
Numerical Experiments: $m$ subject to optimization

<table>
<thead>
<tr>
<th>Regime</th>
<th>No-Show rate = 20%</th>
<th>No-Show rate = 30%</th>
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<tr>
<td>$w=0.10$</td>
<td><img src="image" alt="Graph" /></td>
<td><img src="image" alt="Graph" /></td>
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<tr>
<td>$w=0.15$</td>
<td><img src="image" alt="Graph" /></td>
<td><img src="image" alt="Graph" /></td>
</tr>
<tr>
<td>$w=0.20$</td>
<td><img src="image" alt="Graph" /></td>
<td><img src="image" alt="Graph" /></td>
</tr>
</tbody>
</table>

**Figure:** Optimal Schedules: $n = 16$, $c_o = 1.5$, $c_i = 1$
Optimal Overbooking level $y$

- Poisson regression
- $x = (n, w, q, 1)$
- Model: $E[y|x] = e^{\beta^T x}$, for some $\beta \in \mathbb{R}^4$.

| Coefficient | Standard Error | $z$ | $P > |z|$ | 95% Confidence Interval |
|-------------|----------------|-----|-----------|------------------------|
| $n$         | 0.15           | 0.02| 9.68      | 0.00                   | [0.12,0.18]          |
| $w$         | -2.70          | 0.20| -13.60    | 0.00                   | [-3.09,-2.31]        |
| $q$         | 8.36           | 0.28| 29.44     | 0.00                   | [7.80,8.91]          |
| $1$         | -3.26          | 0.18| -17.72    | 0.00                   | [-3.62,-2.90]        |

$X_{LR}^2 = 1588.91$  
$P(\chi^2(3) > 1588.91) = 0.0000$

Table: Poisson Regression

$y = e^{\beta_1 n + \beta_2 w + \beta_3 q + \beta_4}$,

where $\beta = (0.15, -2.70, 8.36, -3.26)$. 
Introduction

Heterogeneous Patients

Homogeneous Patients

Sequential Scheduling

Conclusion

Deterministic Vs Lognormal Service Times

$\mathbf{x} = (221121111111), q=0.3$

- Av. Wait. Time - Deterministic
- Av. Wait. Time - Lognormal
- Idle Time - Deterministic
- Idle Time - Lognormal

Cayirli et al. (2006)

Figure: Deterministic Vs Lognormal Service Times
## Deterministic Vs Lognormal Service Times

| w = 0.01    | x* | 3 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 | 3 2 1 2 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 | 4 2 1 2 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 |
| x/ | 3 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 |
| w = 0.05    | x* | 2 1 2 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 | 2 2 1 2 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 | 4 2 1 2 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 |
| x/ | 2 2 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 |
| w = 0.10    | x* | 2 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 | 2 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 | 3 1 2 1 2 1 1 1 1 1 1 |
| x/ | 2 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 |
| w = 0.15    | x* | 2 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 | 2 1 1 1 2 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 | 3 1 2 1 2 1 1 1 1 1 1 |
| x/ | 2 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 |
| w = 0.20    | x* | 2 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 | 2 1 1 1 2 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 | 2 1 2 1 2 1 1 1 1 1 1 |
| x/ | 2 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 |
| w = 0.25    | x* | 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 | 2 1 1 1 2 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 | 2 1 2 1 2 1 1 1 1 1 1 |
| x/ | 2 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 |
| w = 0.30    | x* | 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 | 2 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 | 2 1 2 1 2 1 1 1 1 1 1 |
| x/ | 2 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 |
| w = 0.40    | x* | 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 | 2 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 | 2 1 2 1 2 1 1 1 1 1 1 |
| x/ | 2 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 |
| w = 0.50    | x* | 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 | 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 | 2 1 1 1 2 1 1 1 1 1 1 |
| x/ | 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 |
| w = 0.60    | x* | 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 | 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 | 2 1 1 1 1 1 1 1 1 1 1 |
| x/ | 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 |
| w = 0.70    | x* | 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 | 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 | 1 1 1 1 1 1 1 1 1 1 1 |
| x/ | 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 |

**Table:** Deterministic vs Lognormal Service Times
Sequential Scheduling
Online Scheduling—Proposed Heuristic

Phase I

- The design of the scheduling framework
- Depends on the clinic’s and patients’ characteristics.

Phase II

- Schedule Generation
- Gradual appointment booking based on the framework established in Phase I.
Phase I - Design of the schedule

**Phase I**

*Step 1:* Determine target number of customers to overbook.

*Step 2:* Determine specific time slots for overbooking.

\[
\begin{align*}
\text{Schedule patient } j \text{ at } & \begin{cases} 
1 & \text{if } 0.00 \leq F(Z(z_j)) \leq 0.25 \\
2 & \text{if } 0.25 < F(Z(z_j)) \leq 0.50 \\
3 & \text{if } 0.50 < F(Z(z_j)) \leq 0.75 \\
4 & \text{if } 0.75 < F(Z(z_j)) \leq 1.00 
\end{cases} 
\end{align*}
\]

*Step 3:* Determine appropriate ranges of index values for each slot according to *SWPS*.
Phase I - Design of the schedule

Phase I

*Step 1:* Determine target number of customers to overbook.

*Step 2:* Determine specific time slots for overbooking.

```

Step 3: Determine appropriate ranges of index values for each slot according to SWPS.
```

Schedule patient \( j \) at

\[
\begin{align*}
1 & \quad \text{if } 0.00 \leq F_Z(z_j) \leq 0.25 \\
2 & \quad \text{if } 0.25 < F_Z(z_j) \leq 0.50 \\
3 & \quad \text{if } 0.50 < F_Z(z_j) \leq 0.75 \\
4 & \quad \text{if } 0.75 < F_Z(z_j) \leq 1.00
\end{align*}
\]
Proposed Heuristic: Example

- \( n = 12 \)
- average weight \( \bar{w} = 0.2 \) and average no show probability \( \bar{q} = 0.3 \).
- \( W = \begin{cases} \begin{align*} w_L & \text{w.p. 0.5} \\ w_H & \text{w.p. 0.5} \end{align*} \end{cases} \) and \( Q = \begin{cases} \begin{align*} q_L & \text{w.p. 0.5} \\ q_H & \text{w.p. 0.5} \end{align*} \end{cases} \)
Proposed Heuristic: Example

- \( n = 12 \)
- average weight \( \bar{w} = 0.2 \) and average no show probability \( \bar{q} = 0.3 \).
- \( W = \begin{cases} \begin{align*} w_L & \text{w.p. } 0.5 \\ w_H & \text{w.p. } 0.5 \end{align*} \end{cases} \) and \( Q = \begin{cases} \begin{align*} q_L & \text{w.p. } 0.5 \\ q_H & \text{w.p. } 0.5 \end{align*} \end{cases} \)
- Therefore there are four types of customers. Type \((i, j)\) customer corresponds to one with weight \( w_i \) and no-show probability \( q_j \), \( i, j \in \{ L, H \} \).
- \( Z = W(1 - Q)/Q \) and \( z_{ij} = w_i(1 - q_j)/q_j \)
- \( z_{LH} \leq z_{HH}, \ z_{LL} \leq z_{HL} \)
- Assuming that \( W \) and \( Q \) are independent, \( Z \) takes each one of these values with probability \( \frac{1}{4} \).
Proposed Heuristic: Example

Phase I

- Overbook $y = [e^{\beta_1 n + \beta_2 \bar{w} + \beta_3 \bar{q} + \beta_4}] = 2$ appointments.
- The scheduling framework is the optimal schedule for the homogeneous customers problem with $m = 14$, $w = 0.2$ and $q = 0.3$.

We intend to fill the Horizontal segments according to the SWPS rule.

Step 3 of Phase I, $z_{HH} \leq z_{LL}$

Step 3 of Phase I, $z_{LL} \leq z_{HH}$
### Phase II

<table>
<thead>
<tr>
<th>Proposed Schedule</th>
<th>Baseline Schedule</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assign the first $n$ customers following the structure of Phase I</td>
<td>Assign the first $n$ customers randomly (equivalent to uniform patient preferences)</td>
</tr>
<tr>
<td>Assign the last $m - n$ requests to the overbooking slots specified in Phase I</td>
<td>Assign the last $m - n$ requests to the overbooking slots specified in Phase I</td>
</tr>
</tbody>
</table>

We don’t reject customers. If there is no proper slot available, then schedule to an adjacent slot.
Proposed Heuristic: Example

- We simulate 100,000 samples.
- Each sample consists of 14 consecutive requests for an appointment drown from $Z$.
- We evaluate the proposed schedules compared to the baseline schedules.
- $\Delta_w = w_H - w_L$, $\Delta_q = q_H - q_L$.

<table>
<thead>
<tr>
<th>$\Delta_w$</th>
<th>$\Delta_q$</th>
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Table: Performance of the Proposed Heuristic
Summary

- Overbooking model for scheduling arrivals under no-shows.
- Heterogeneous customers.
- Offline and Sequential Scheduling are considered.
Conclusions

- A sensible practice of appointment overbooking can effectively address the no-show phenomenon.

- No-show rates and patient heterogeneity affect the optimal schedule and should be taken under consideration.

- Front-loaded schedules with repeating patterns.

- Structural properties and a priority rule are introduced for the offline problem.

- A heuristic solution is developed for the sequential problem.
Limitations

In order to focus on no-shows we assumed

- Deterministic service times:
  - Have shown to perform very well (click here).

- Punctuality of arriving customers:
  - Blanco White and Pike (1964) compare patient’s waiting times when customers are punctual or unpunctual and are shown not to differ significantly.


