Helping the Captive Audience: Advance Notice of Diagnostic Service for Hospital Inpatients

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Hospital Diagnostic Service is Essential to Patient Care

- Canada expenditures
  - Total hospital expenditures exceed $80 billion in 2022
  - Medical imaging alone accounts for 4.4%, i.e., $3.52 billion, in 2022
  - Average annual growth rate in total hospital expenditures since 2005 is about 4% (Canadian Institute for Health Information, 2024)

- US expenditures
  - Medicare Part B expenditures on hospital imaging services reached $3.53 billion in 2006 *(U.S. GAO 2008)*.
  - 2006: 51.0 million CT scans and 14.6 million MRI scans in U.S. hospitals.
  - 2019: 71.3 million CT scans and 29.4 million MRI scans *(OECD 2021)*.

Hospital Diagnostic Service Management

- Efforts in improving patient scheduling
  - Improving timeliness for outpatients (OPs) and emergency patients (EPs).

- However, hospital inpatients (IPs) may not be the focus of these efforts.

IP scheduling is a *"pro forma scheduling"* ... *"with schedulers entering incorrect or imaginary appointments as placeholders"*

--- *Efficient Radiology*, Daniel Rosenthal and Oleg Pianykh (2021)

Current Practice

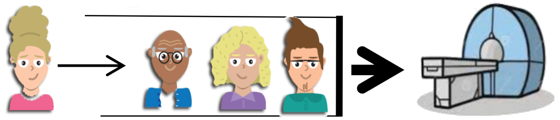
- IPs are scheduled arbitrary appointment times, but are not honored.
  - Service provider calls for IPs whenever she has time and the diagnostic equipment becomes available.

- IPs are perceived as always on standby and readily available.
  - IPs are "captive audience" (*Rosenthal and Pianykh 2021*).

- This approach "has little basis" *and* "creates numerous problems" (*Rosenthal and Pianykh 2021*).
  - Conflict with other IP care activities, or nursing/supporting staff availability.
  - May lead to distrust among these providers and patients.

Classic Scheduling Paradigms

- Allocation scheduling



- IPs added to a waitlist with no specific service time.
- IPs have to stand by until their services.

- *Gerchak et al. 1996, Huh et al. 2013, Wang and Truong 2017, Liu et al. 2019 …*

Min patient convenience

Max provider flexibility

Can we achieve a better tradeoff?

- Advance scheduling

- Patients are provided specific service times.
- Providers must honor scheduled times.

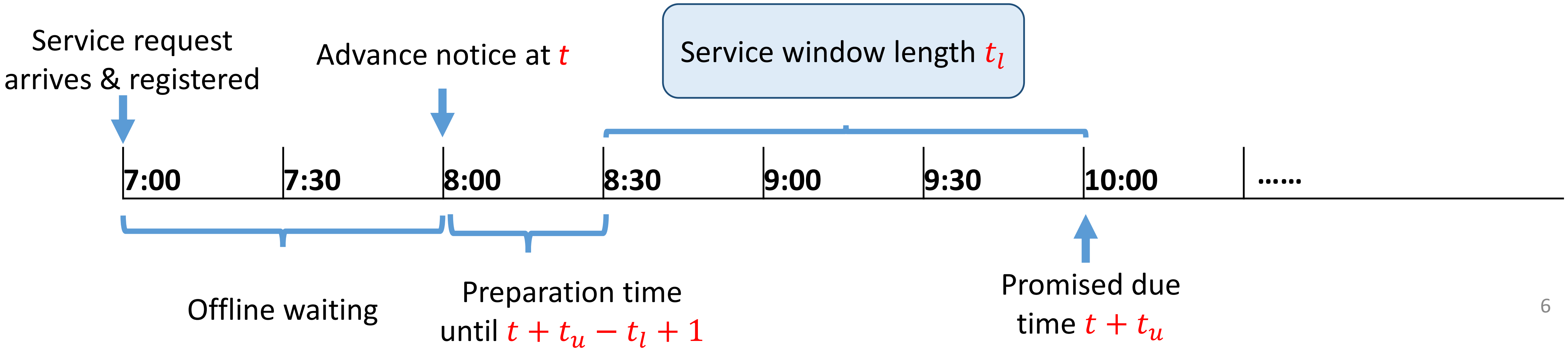
- *Liu et al. 2010, Truong 2015, Samiedaluie et al. 2017, Wang et al. 2018, Diamant et al. 2018, Keyvanshokooh et al. 2021, Zacharias et al. 2022 …*

Max patient convenience

Min provider flexibility

A New Scheduling Paradigm – Advance Notice

- We propose **advance notice** for IPs.
  - Guarantee that IP exams are completed within t_u intervals after the notice
  - Not starting their exams until $(t_u - t_l + 1)$ intervals after the notice
  - The length of service time window is t_l
- It reduces IP standby time (no last-minute notice) and also grants provider service flexibility (no specific service time).



Feedback from Practitioners on Advance Notice

- Mayo Clinic is fairly positive because they tried something similar.
  - The radiology staff will leave a note to inpatient nurses in advance, notifying that they plan to pick up the inpatient for exams in the next 15 minutes to 1 hour.

- Dr. Daniel Rosenthal shared that they have also implemented "something somewhat similar" (at Mass General), but in a "less structured" way, by "[providing] the inpatient floors with information about the usual time that a call should be expected".
  - Dr. Rosenthal is Senior Vice Chairman, Department of Radiology & Professor of Radiology, Harvard Medical School. He coauthored the book "Efficient Radiology: How to Optimize Radiology Operations".

- Largely based on staff experience and intuition, without scientific or data support.

(Brief) Literature Review

- Dynamic scheduling
    - Advance scheduling: *Patrick et al. 2008, Liu et al. 2010, Truong 2015,Diamant et al. 2018, Keyvanshokooh et al. 2021, Zacharias et al. 2022, Chambers et al. 2023*
    - Allocation scheduling: *Gerchak et al. 1996, Huh et al. 2013, Wang and Truong 2017, Liu et al. 2019*

- Diagnostic service management
    - Follow either the advance or allocation scheduling frameworks*: Green et al. 2006, Kolisch and Sickinger 2008, Patrick and Puterman 2007, Saure et al. 2020*

- Other OM literature
    - Dynamic inventory control for perishable product: *Nahmias 1975, Chen et al. 2014, Li and Yu 2014, Li et al. 2016, Sarhangian et al. 2018*
    - Curbside pickup: *Cavdar and Isik 2020, Farahani et al. 2020*

Problem Formulation as an MDP

- Diagnostic service
  - Operate *M* servers within a time horizon of *T* periods
  - Each server can serve one patient in a period.

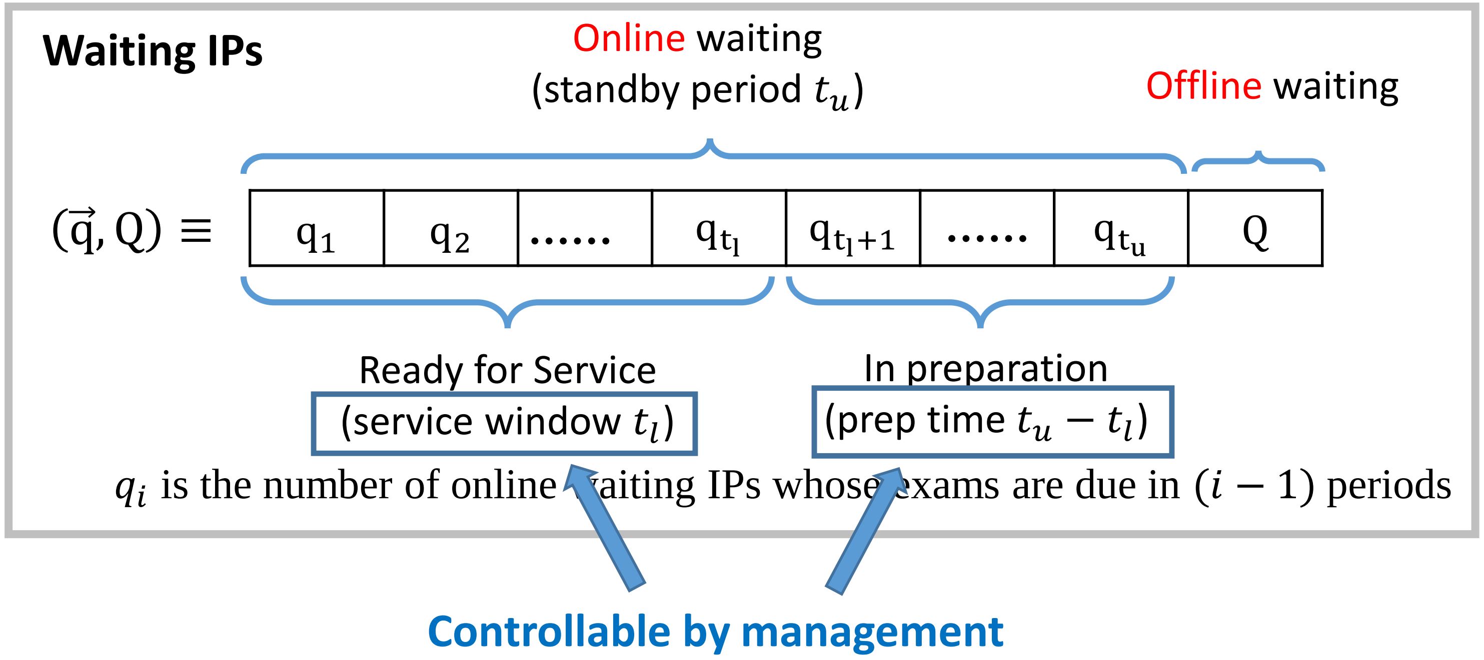
- Stochastic demand from OPs, IPs, and EPs at each interval
  - OPs random: scheduled ahead but with uncertainty in arrival time and duration of check-in and preparation procedures
  - IPs and EPs random: random arrivals

- Priorities
  - EPs and OPs served in the same interval as they arrive, but IPs can wait.

(*Kolisch and Sickinger 2008, Green et al. 2006*)

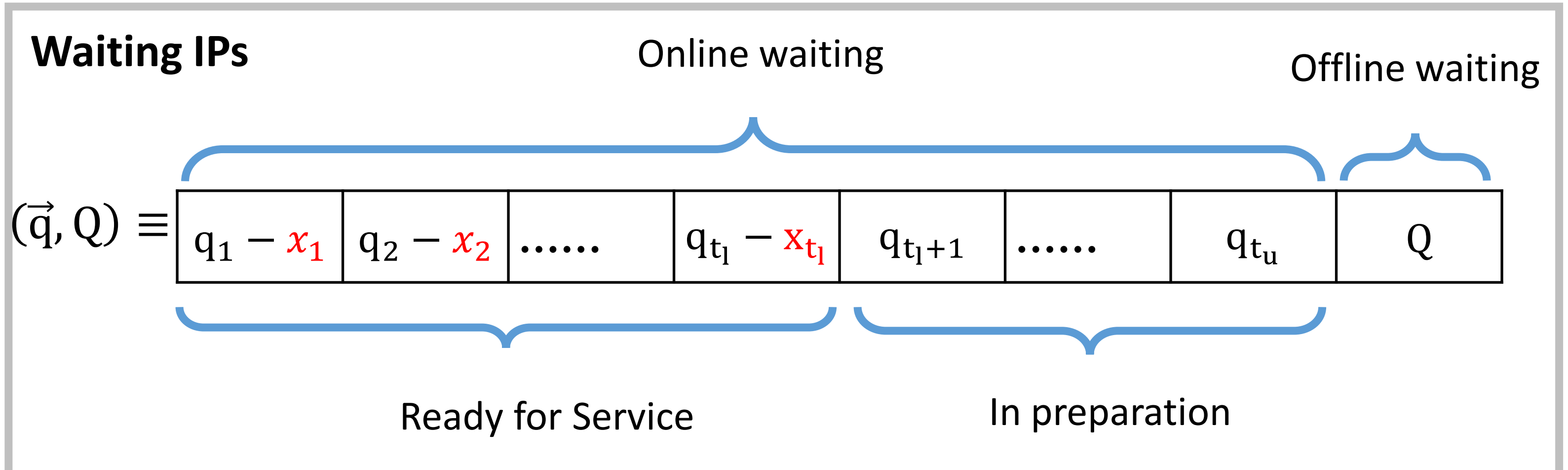
As Each Interval Starts, the Provider Observes:

- Offline waiting IPs (**Q**) who have not received advance notice
- Online waiting IPs ($\vec{q}$) who have received advance notice



First Decision $\vec{x}$: Who to Serve

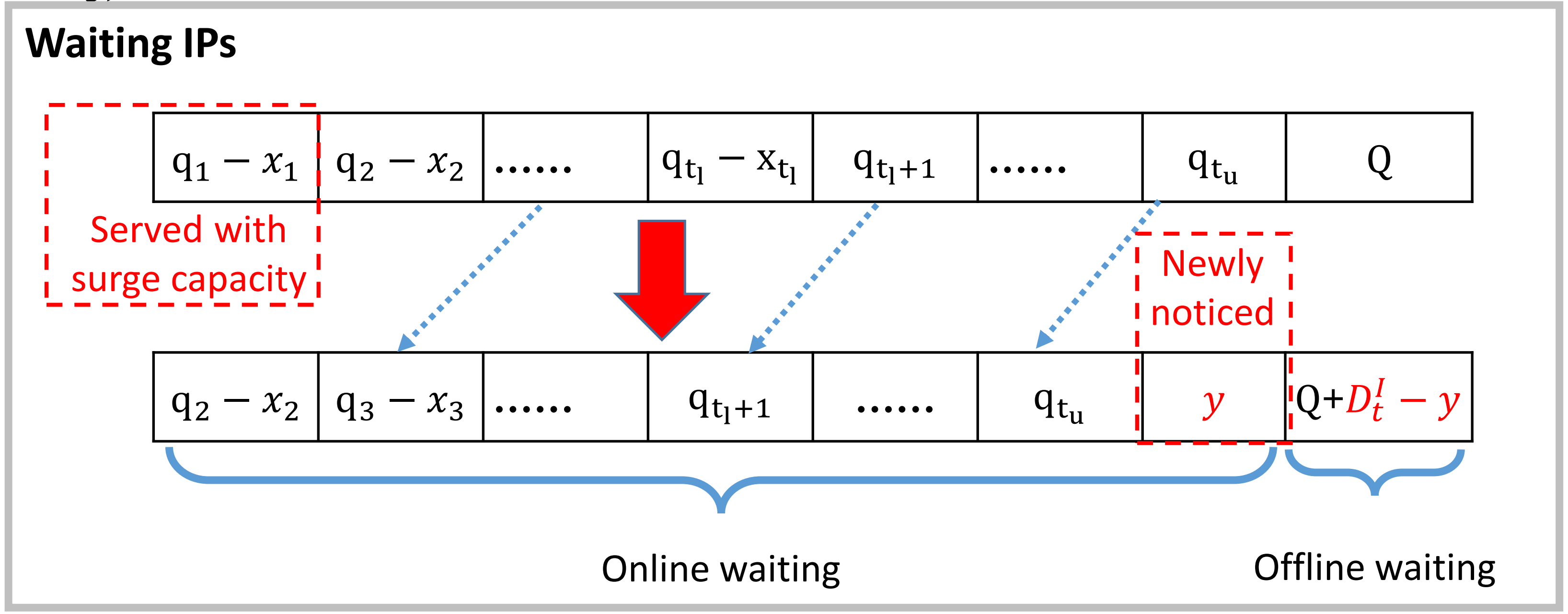
- New demands from OPs (D_t^O) and EPs (D_t^E) realized and served
- Use the remaining capacity to serve online waiting IPs
  - Remaining capacity $S_t \equiv (M - D_t^O - D_t^E)^+$
  - IP exams $\vec{x} \equiv (x_1, x_2, \dots, x_{t_l}), x_i \le q_i, i = 1,2,\dots,t_l$; $\sum_{i=1}^{t_l} x_i \le S_t$



$q_i - x_i$ is the remaining online waiting IPs whose exams are due in $(i-1)$ periods

Second Decision y: How Many Advance Notices to Send

- The remaining IP exams due in the current period ($q_1 - x_1$), if any, are served by using surge capacity
- Observe D_t^I new IP requests
- At the end of the period, send out y advance notices to offline waiting IPs ($y \leq Q + D_t^I$)



Cost Structure, Objective, and Formulation

- Maximize the total discounted “rewards” of serving IPs
  - Revenue (r) of serving each IP
  - Cost (w_{on}) of online IP waiting per interval
  - Cost (w_{off}) of offline IP waiting per interval
  - Cost (p) of using surge capacity to serve each “overdue” IP and to serve remaining IPs at the end of the horizon

- The problem can be formulated as a Markov Decision Process model
  - First decision: who to serve, i.e., $\vec{x}$
  - Second decision: how many advance notices to send, i.e., y

Structural Results - Service Strategy $\vec{x}$

- Cost of online waiting > offline waiting

Assumption 1

$$w_{on} > w_{off} \geq 0.$$

- Service provider does not use surge capacity unless it is absolutely necessary.

Assumption 2

$$\frac{w_{on}}{1-\gamma} \leq p$$

Optimality of the FCFS service strategy

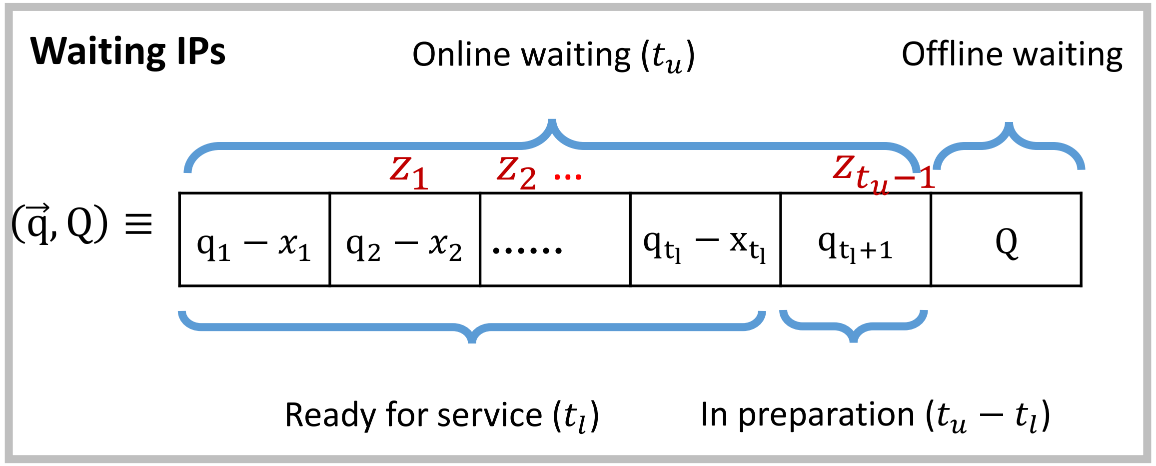
The optimal service strategy is to serve online waiting IPs on a FCFS basis, i.e., use up all available capacity and serve those with most imminent promised due time first.

Structural Results - Advance Notice y

- Structural analysis on advance notice decisions
  - Via a simple and yet novel variable transformation

  - Reveal the hidden *antimultimodular* structure of the problem

Monotonicity and Bounded Sensitivity of y^*



❑ The optimal number of advance notices (y^*)

- y^* increases as offline waiting IPs (Q) increase
- y^* decreases as online waiting IPs (z_i) increase
- Online waiting IPs who have imminent promised due time (*smaller i*) have smaller impacts on y^*

❑ Bounded sensitivity

- If Q or z_i changes by 1, y^* changes no more than 1
- we only need to check two possible neighboring solutions around a known solution → efficient solutions!

Case Study

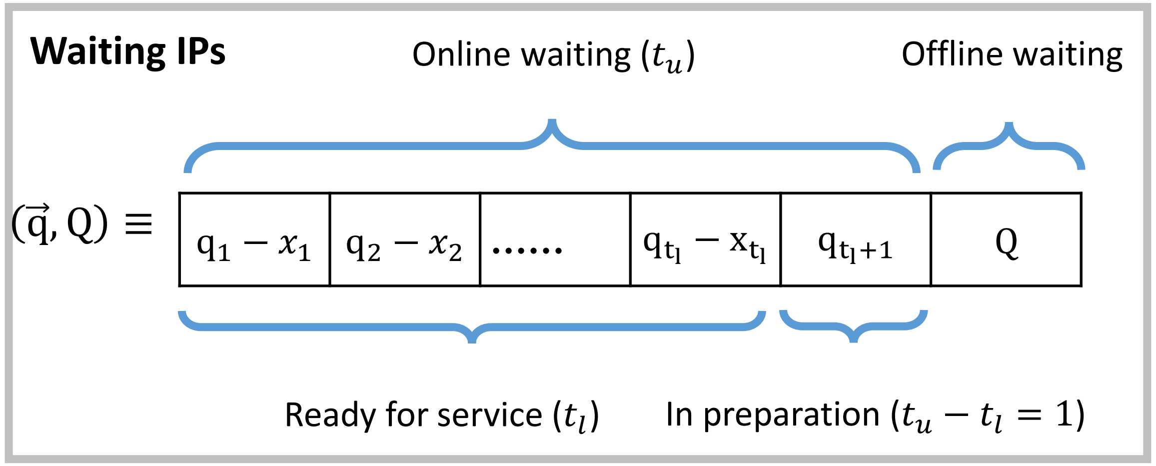
- 9-month data from a computed tomography (CT) practice in Mayo Clinic
  - Operates *M=4* scanners and serves IPs, OPs and EPs.
  - Day shift consists of *T=18* service intervals (each 30 minutes based on median exam duration)
  - We derive empirical demand distribution based on historical data (non-stationary arrivals)

- Cost parameters based on empirical studies in literature *(Sistrom and McKay 2005, Liu et al. 2018, Hathaway et al. 2021)*
  - Revenue per patient $r = \$416$
  - Cost of surge capacity usage $p = \$76.5$
  - Cost of online waiting per interval $w_{on} = \$3.18$
  - Cost of offline waiting per interval $w_{off} = \$0.57$

Value of Advance Notice

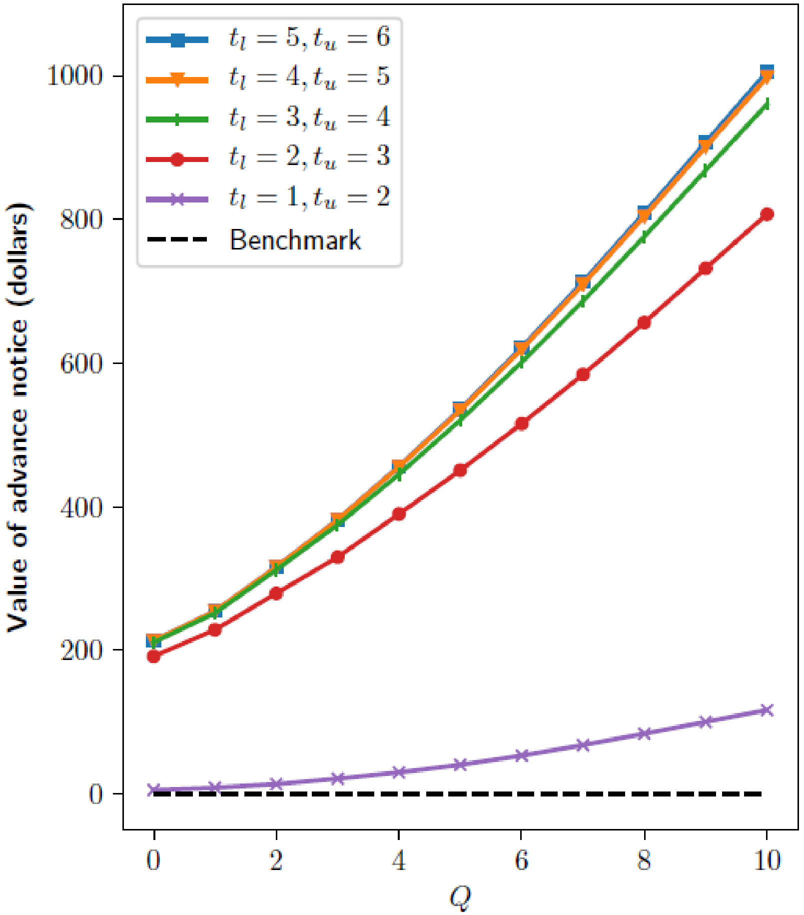
- In benchmark model, we set $t_l = 1$, t_u=2, and treat all waiting as online waiting.
  - Everyone is standing by, send notice 1 period ahead, and allow 1 period transportation time
  - Likely provides a performance upper bound of current practice.
- In our advance notice model, we set the prep time, i.e., $t_u - t_l$, as one period (i.e., 30 mins) based historical data.
- Compare the cumulative rewards for different starting Q's, while fixing $\boldsymbol{q} = \boldsymbol{0}$.
  - There may be physician orders sent over night.

Impact of Service Window t_l



- As t_l increases, benefits turn more significant.
  - More service flexibility for provider with larger t_l.
  - Provable result.

- Marginal benefit of increasing t_l is diminishing.
  - Larger t_l requires longer IP standby.
  - Enables providers to use a small t_l to achieve good improvement.



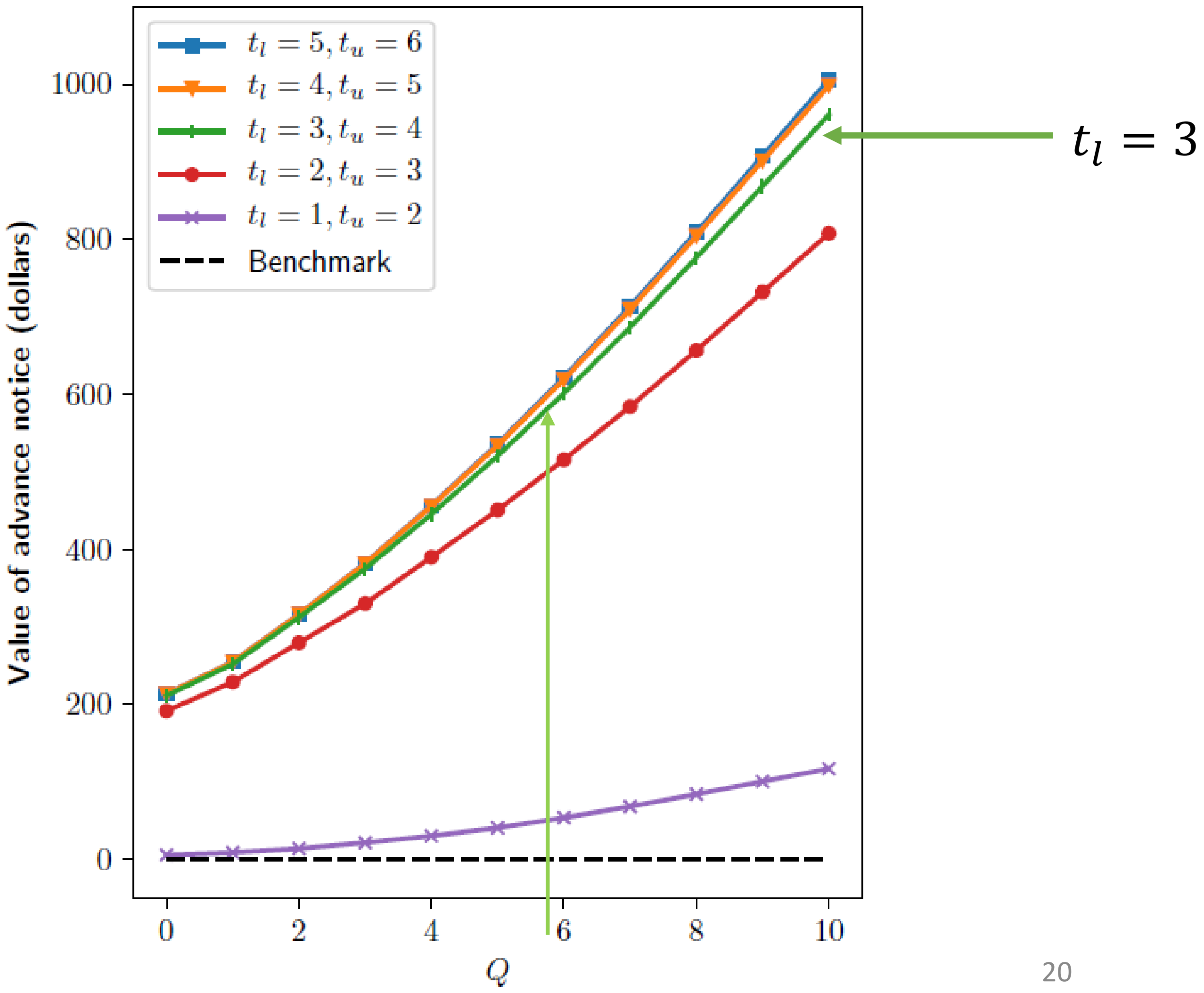
How much improvement?

- With a little flexibility in service time window (e.g., $t_l = 3$ or equivalently 1.5 hours), the financial improvement can be $211-961 per day or equivalently $55,000-$250,000 per year for M=4 scanners.

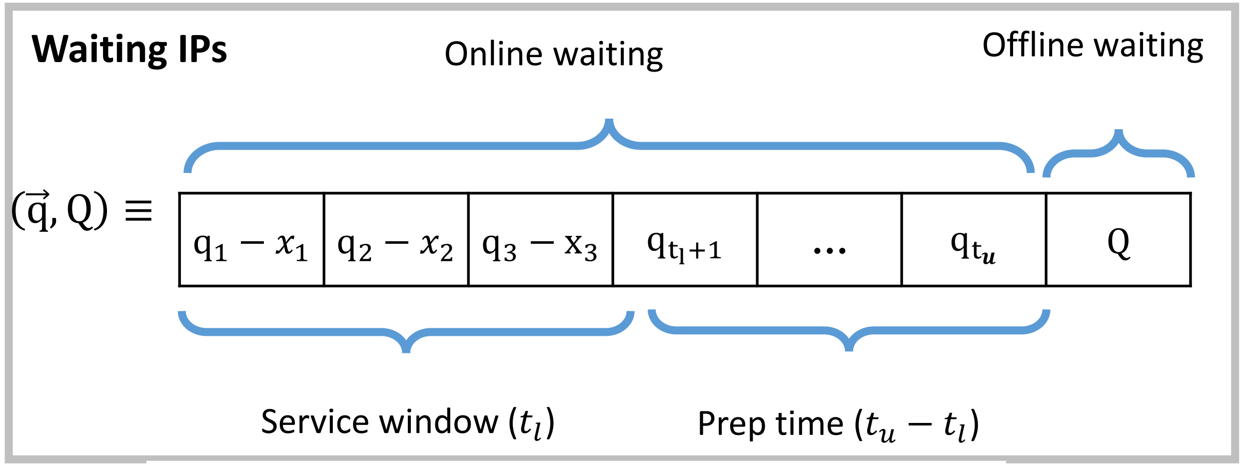
- With $Q = 5 \sim 6$, annual cost savings amount to $135,000-$156,000.

- The annual total expected discounted reward under the current benchmark policy amounts to $1.05M-$1.12M.

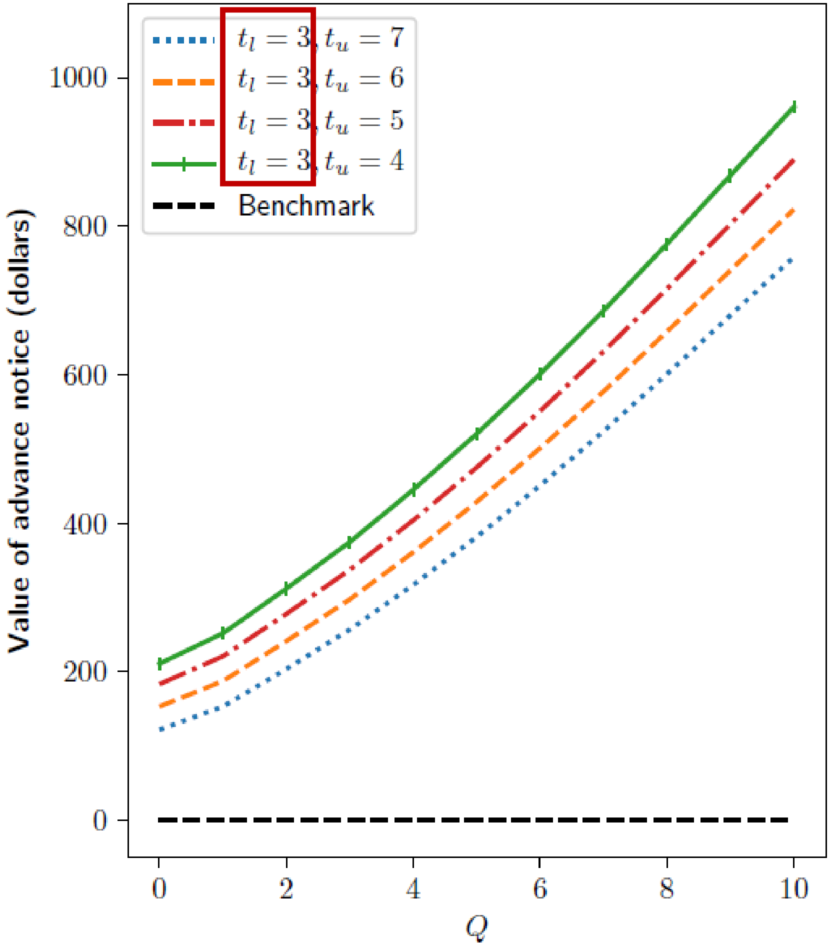
- Improvement @ 13-14%.



Impact of Prep Time $t_u - t_l$



- Fixing the service window t_l,, the value function drops as lead time $t_u - t_l$ increases.
  - Neither patients or providers benefit from long notice.
  - Should not rush to send advance notice.
  - Reducing lead time (e.g., transport time) can be an improvement lever.



Takeaways

- We propose a new scheduling paradigm: ***advance notice.***
  - Strike a fine balance between advance and allocation scheduling.

- Formulate an MDP model and derive structural properties.
  - Reveal its hidden antimultimodular structure via variable transformations.
  - Prove the monotonicity and bounded sensitivity of optimal decisions.

- Demonstrate significant values of advance notice in a Mayo Clinic case.
  - A little flexibility (in the service window) can go a long way.
  - Reduce prep time is a useful improvement lever.

- Advance notice offers a promising approach to improving general appointment-based services, e.g., maintenance, tech support, and online delivery.

Thank you!

Q & A

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Working paper available @