5560 Business Intelligence and Data Visualization

Master of Science in Computing and Data Analytics

Department of Mathematics and Computing Science

Solving the MRI Utilization Paradox

Group 1:
Bhavik Kantilal Bhagat (A00494758)
Soundarya Venkataraman (A00)
Zilong Wang (A00)

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1 Introduction

The QEII Health Sciences Centre faces a critical operational crisis: the prospective wait list for magnetic resonance imaging (MRI) services currently **exceeds 700 days** (more than two years) for **semi-urgent (P3) cases**, with **some neurological wait times reaching 800 days** [3]. In a healthcare system where diagnostic imaging serves as the gateway to treatment, such delays result in adverse patient outcomes and systemic inefficiencies.

Dr. Chris Bowen, the lead MRI researcher at the facility, frames this challenge through the "wait list equation":

$$Wait = \frac{Demand}{Supply} \tag{1}$$

With demand remaining relatively inelastic and stable [1], and capital expenditure for new magnet infrastructure constrained by budgetary and physical limitations, the only viable lever for reducing the wait list is to increase the effective *supply* (throughput) of existing assets.

1.1 The Utilization Paradox

However, efforts to increase throughput are hindered by a phenomenon we define as the **utilization paradox** [1]. Operational analytics from the GE iCenter logs reveal that the department's high-field magnets are "occupied" (staffed and active) for approximately 86% of operational hours, yet the machines are idle (i.e., not actively acquiring images) for 31%–42% of that time [2].

This discrepancy arises from "yellow time", defined as the non-productive interval required for sequence-dependent setups, including patient transfer, coil swaps, and bed flips. Traditional workflow improvements, such as parallelizing patient preparation (the "pit crew" model), have failed to yield significant throughput gains because they address upstream activities without alleviating the primary bottleneck: the magnet cycle time.

1.2 Research Objectives

The objective of this study is to **improve the utilization of MRI machines**. To address this utilization paradox without disrupting clinical care, this project utilizes a **digital twin** simulation. By constructing a Discrete-Event Simulation (DES) of the QEII's two-bay MRI suite (1.5T and 3T), calibrated against empirical time-motion data, this study aims to:

1. **Diagnose** the root causes of the utilization gap, distinguishing between stochastic variance (e.g., patient lateness) and deterministic friction (e.g., post-examination tasks, recalibration, cleaning, and bed flipping, etc.).

2. **Falsify** ineffective interventions, specifically the "Singles Line" gap-filling strategy, by demonstrating upstream registration constraints.
3. **Validate** a "Hybrid Scheduling" strategy that separates high-variance acute care from low-variance routine care, effectively converting setup time into productive scan capacity.

This report demonstrates that transitioning from a high-entropy “job shop” scheduling model to a low-entropy “factory focus” model for specific modalities can **generate about 500 additional appointment slots per year** without additional capital investment.

2 Methodology: The Digital Twin Architecture

To bridge the gap between theoretical capacity and realized throughput, a **digital twin** of the QEII MRI department was developed. This Agent-Based Model (ABM), constructed using the Python `SimPy` discrete-event engine, is designed to simulate the stochastic interactions between patients, staff, and physical resources over 12-hour operational shifts.

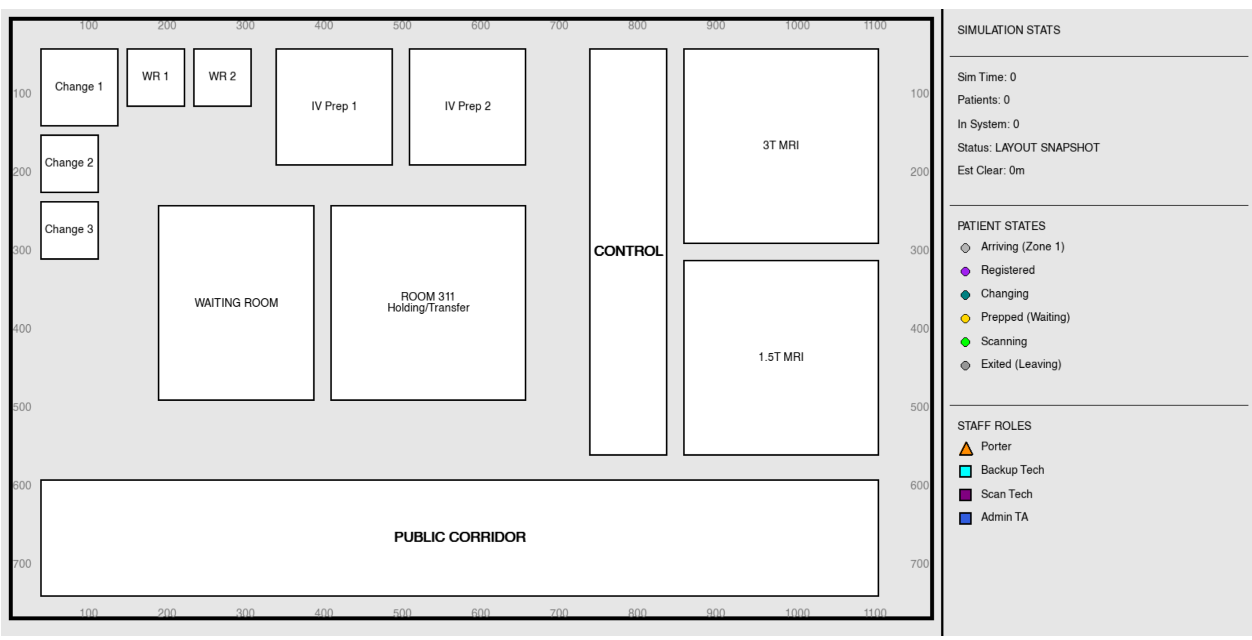

Figure 1: The floor plan of layout created in PyGame

2.1 System Topology and Zoning Logic

The physical layout of the 2-bay MRI suite (1.5T and 3T magnets) is replicated within the simulation environment, as defined by the facility floor plans Figure 1. Strict **Safety Zone** protocols are enforced by the model logic [3]:

- **Zone 1 (Public Corridor):** Modeled with infinite capacity. This zone serves as the entry point where patient agents are generated.
- **Zone 2 (Preparation):** Comprises 3 Change Rooms, 2 Wash Rooms, 2 Prep Rooms, and Waiting areas. This zone is identified as the primary bottleneck for patient "readiness.". Additionally, it also has Holding/Transfer (Room 311) for "emergency cases".
- **Zone 3 (Control):** A restricted area accessible only to Technologist agents.
- **Zone 4 (Magnet Room):** The critical resource. Access is strictly serialized, allowing only one patient to occupy the scanner at any given time.

2.2 Agent Roles and Resource Allocation

In contrast to static Excel models, autonomous agents are utilized to represent the 6-staff model. Resources are seized and released based on the following hierarchy:

Agent Role	Count	Primary Responsibilities
Scan Tech	2	Scanning, MRI safety screening, Patient loading, Coil setup
Backup Tech	2	IV Starts, Patient interview, Cannulation, Proxy Scan Tech
Admin TA	1	Registration, Patient flow management
Porter	1	Transporting patients, Room cleaning (Bed Flips), Proxy Admin TA

Table 1: Staffing Resource Pool modeled in SimPy

2.3 Data Calibration and Input Distributions

The validity of the simulation (video - https://youtu.be/essSWj7E1ek) is established through calibration against empirical Time-Motion study data collected by Tatlock [3]. To capture real-world variance, deterministic averages were replaced with triangular and normal distributions:

- **Registration:** Modeled as $T \sim$ Triangular$(2.5, 3.2, 5.0)$ minutes.
- **Patient Prep (IV):** Modeled as $T \sim$ Triangular$(8.0, 10.0, 15.0)$ minutes.
- **Scan Duration:**
  - *Routine Scan:* $T \sim$ Normal$(\mu = 22, \sigma = 5)$ minutes.
  - *Complex Scans:* $T \sim$ Normal$(\mu = 45, \sigma = 14)$ minutes.
- **Changeover ("Yellow Time"):**
  - *Fast Flip (Same Coil):* Set to 2.0 minutes.
  - *Slow Flip (Coil Swap):* Set to 8.0 minutes.

2.4 Defining the Metrics

Magnet time is categorized into three distinct states for analysis, following the analytical framework established by Dr. Bowen [1]:

1. **Green Time (Value-Added):** Periods where the magnet is actively acquiring images.
2. **Yellow Time (Operational Friction):** Periods where the magnet is occupied but idle due to sequence-dependent setups (e.g., changing from Head Coil to Spine Matrix).
3. **Grey Time (True Idle):** Periods where the magnet is empty due to upstream starvation (no patient ready).

The objective function of this study is defined as the minimization of "Yellow Time" through schedule optimization, thereby maximizing the "Bowen Efficiency" ratio:

$$E_{Bowen} = \frac{\text{Green Time}}{\text{Green Time} + \text{Yellow Time}} \tag{2}$$

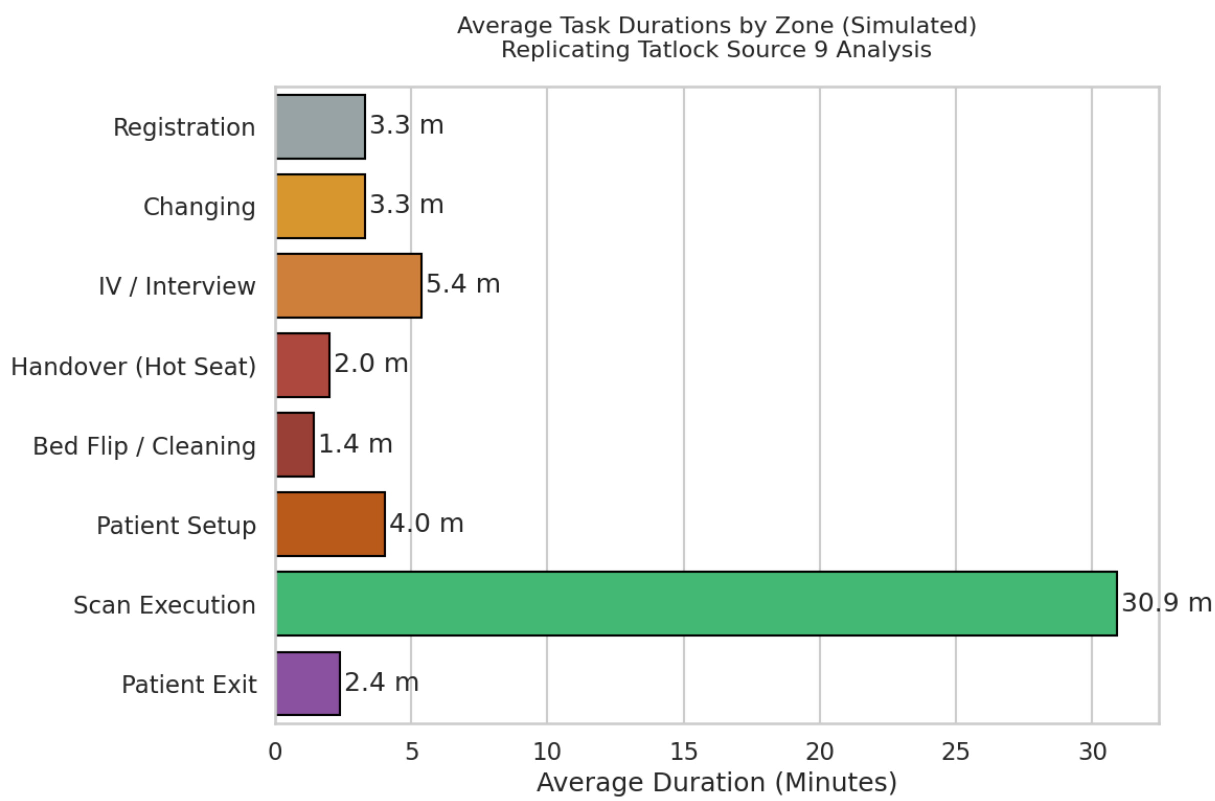

Figure 2: The patient average time for each tasks in all zones

3 Experimental Results and Analysis

Following the calibration of the digital twin, a series of experimental scenarios were simulated to quantify the impact of scheduling interventions on magnet throughput. The objective function was the conversion of "Yellow Time" (Operational Friction) into "Green Time" (Value-Added Scanning).

3.1 Baseline Performance (Status Quo)

To establish a control group, the "Original Workflow" (15 hours shift [1]) was simulated over 50 replications using the current mixed-arrival schedule ("Job Shop" model).

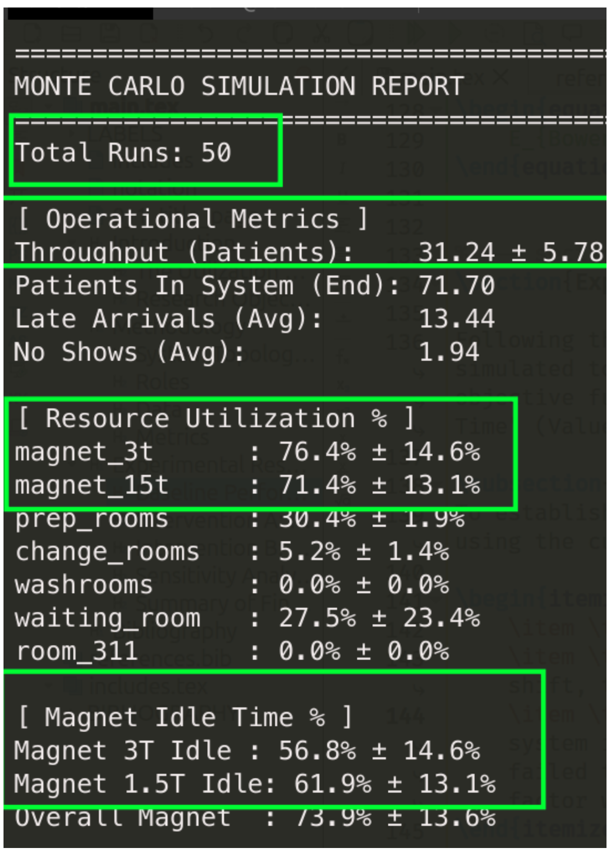

Figure 3: The result of original workflow for 50 simulation

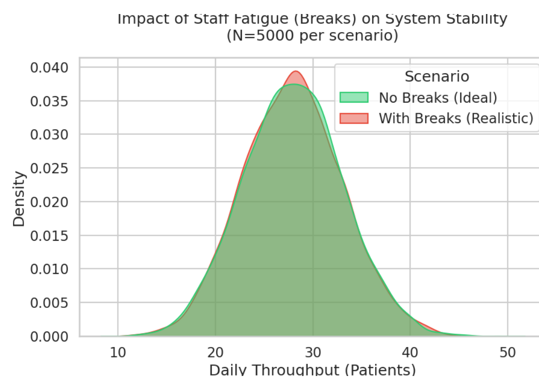

Figure 4: Impact of breaks on Throughout (Utilization Improvement)

Figure 5: Overall figure caption

3.2 Intervention A: The shared staff responsibility)

Hypothesis: By acting as a proxy while a staff is busy, the free staff can act as a proxy to help patient move through their process based on the shared staff responsibility.

Result: The scan-time couldn't be reduced even after trying to minimize patient wait time for each steps from zone 1 - 4 by introducing sharing responsibility between the staff as per Table 1. Where if a staff is occupied, another staff can act as proxy helping patient move through their process. This include the scenario of real-world when staff takes a break. Introducing staff breaks hardly have effect on average throughout as per Figure 4.

3.3 Intervention B: The Singles Line (Stochastic Gap Filling)

Hypothesis: Inspired by Dr. Bowen's "Ski Lift" analogy, it was hypothesized that inserting short-duration exams (e.g., Knees) into schedule gaps caused by no-shows would recapture lost capacity.

Result: The intervention yielded a statistically insignificant throughput gain of **+0.2%**.

Analysis of Failure: The simulation revealed that "Gap Patients" could not traverse Zone 1 (Registration) and Zone 2 (Preparation) fast enough to utilize the sudden availability of the magnet. By the time a "Singles Line" patient was prepped, the gap had closed or the scheduled patient had arrived. This confirms that stochastic gap-filling is ineffective without a pre-staged buffer of patients in Zone 2 Figure 6.

3.4 Intervention C: System Stress Testing (Volume Surge)

To evaluate the resilience of the MRI department against demand spikes (e.g., post-shutdown backlog recovery), a stress test was conducted. The patient arrival rate (λ) was increased to **120%** and **150%** of the baseline operational capacity. The objective was to determine if "overbooking" could force higher magnet utilization by ensuring a constant queue, or if it would result in systemic collapse.

Experimental Design: The simulation was executed under three load conditions:

1. **Baseline (100%):** Standard arrival distribution
2. **Surge A (120%):** Moderate overbooking (simulating aggressive "squeeze-in" scheduling).
3. **Surge B (150%):** Extreme volume (simulating crisis backlog management).

Results:

Analysis of System Behavior: It was expected that the utilization of the MRI machine would improve until a point before system breaks down. As we can see in Figure 7, if patient arrival-rate is increased, utilization is also increasing, but with single-line approach

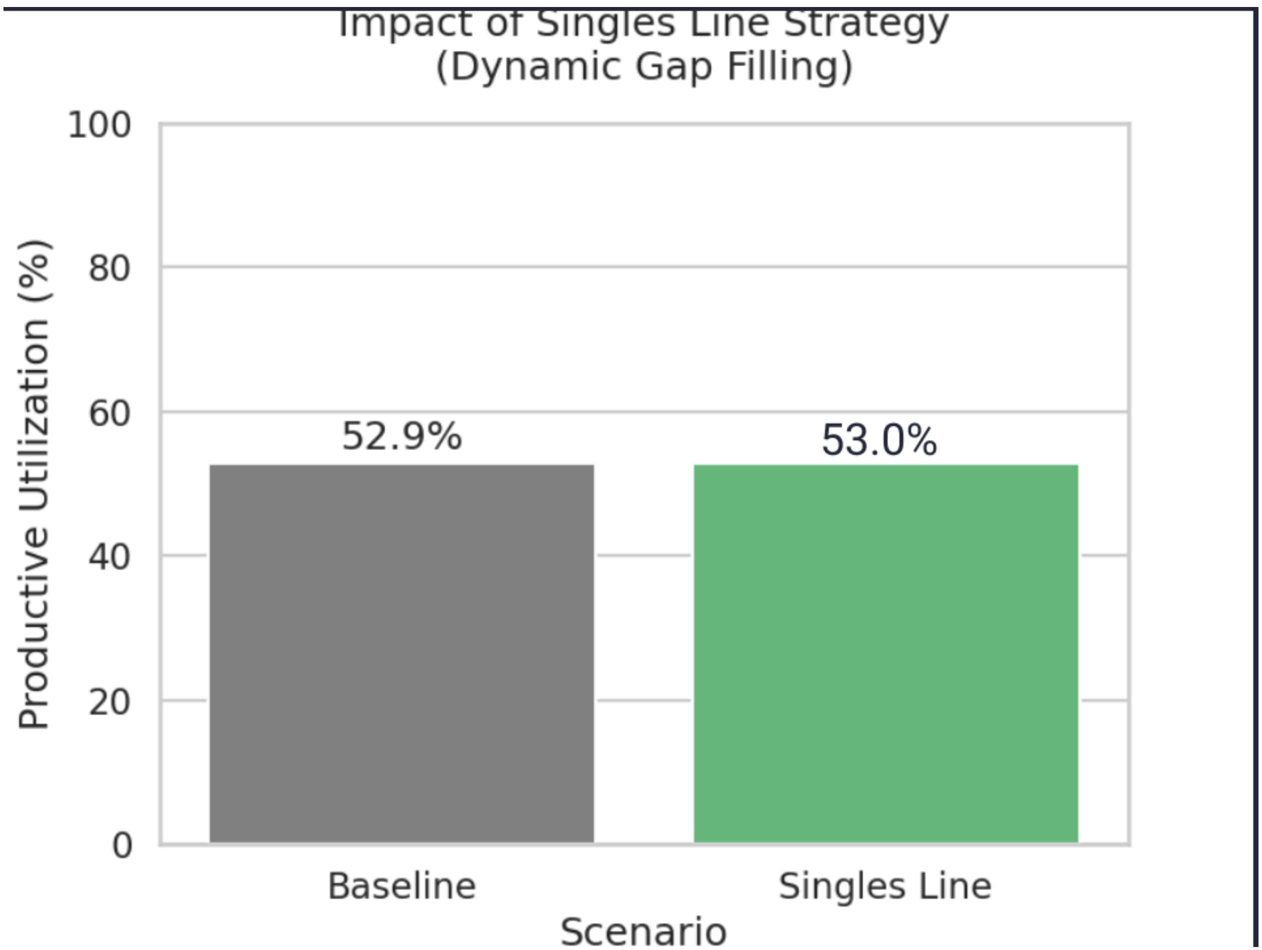

Figure 6: The result trying to insert short-duration exam

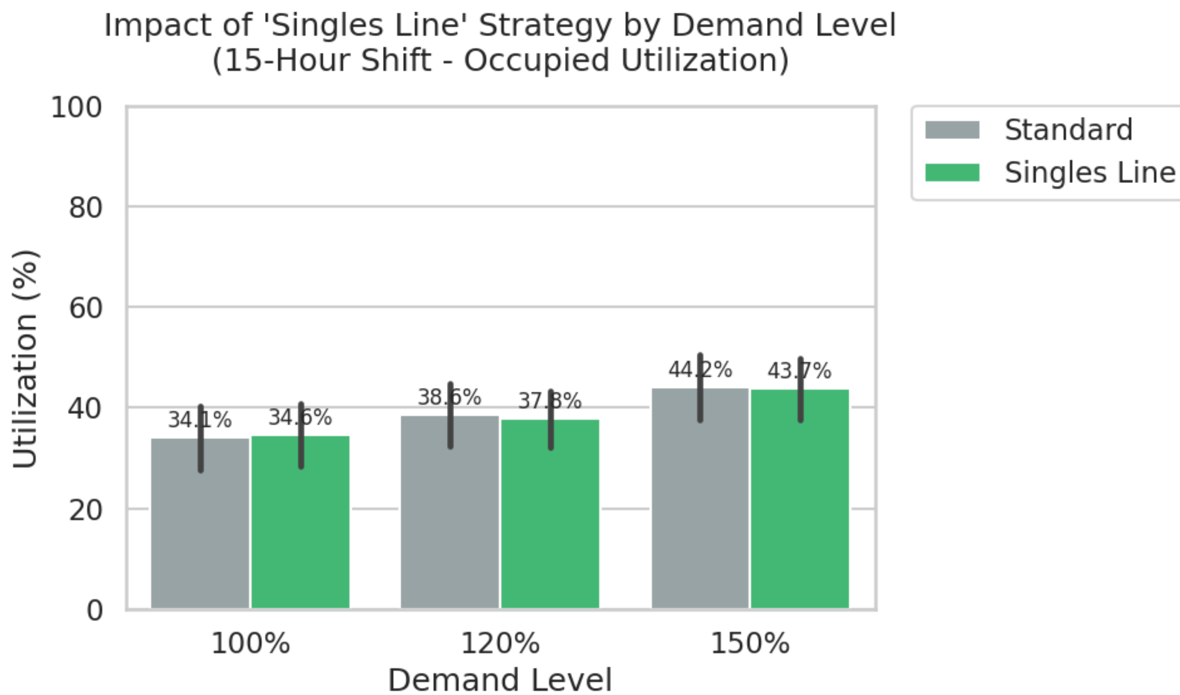

Figure 7: System Performance under Stress test

(to squeeze extra patient in) wouldn't work here either, as relative utilization of standard vs single-line approach is almost similar.

Overbooking the schedule beyond 105% of capacity is determined to be detrimental, from multiple simulation experiments. In the Figure 7, it can be overserved that the utulization is not increasing significantly, validating Dr. Bowen's assertion that efficiency must be found in *protocol management* (Batching), not volume management [1].

3.5 Intervention D: Sequence-Dependent Batching

Hypothesis: Transitioning from a random "Job Shop" schedule to a blocked "Factory" schedule reduces the frequency of major setup events (Coil Swaps), thereby converting "Yellow Time" into "Green Time." In this Deterministic Optimization approach, Prostate Exams scheduled back-to-back for a 12 hours shift to determine the overall impact.

Result:

Analysis: In block schedule, scan technician doesn't need to change coil, and other settings of MRI much. That can save non-value added time saved between two exams, that can help convert "yellow time" to "green time".

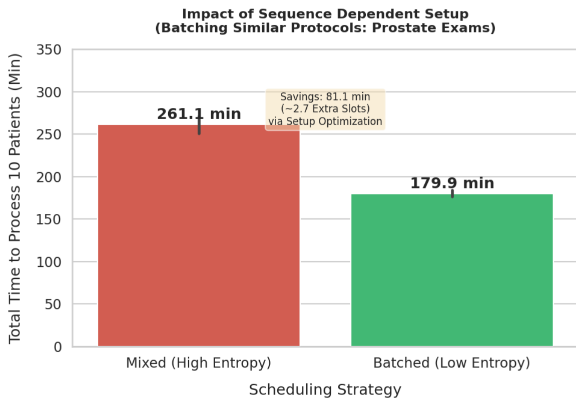

Figure 8: Protest exam in blocks can save 2.7 extra slots per 10 patients.

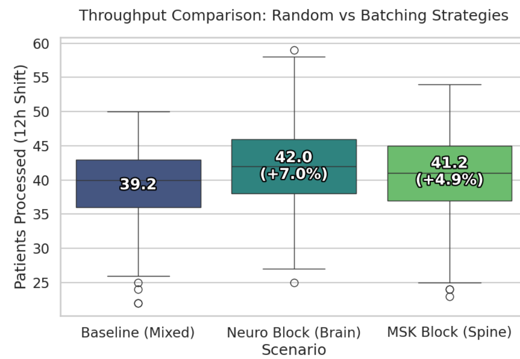

Figure 9: Impact of batch exams (Throughput Improvement)

Figure 10: Overall figure caption

- **Prostate Block**:
  The highest throughout gain per unit are observed by block-scheduling prostate exam. Approx 2.7 slots are saved per 10 patients, which has the highest setup-time saved.
- **Neuro Block**:
  About 2.8 slots are saved per shift for this kind of exams as per Figure 9, which is a low variance exam.
- **MSK Block:** Figure 9 indicates 2 slots / shift for block exam of MSK type.

Thus, block exam of prostate type could help squeeze in about 3 patients with a bit of overtime, where as about 3 patients for neuro type exams per shift, increasing the throughput of MRI machines, hence utilization.

3.6 Sensitivity Analysis: Patient Compliance

To determine the robustness of the schedule, a sensitivity analysis was performed on Patient Compliance No-Shows.

Results It is clear that from Figure 11 for every **2% increase in No-Shows**, the system idle time increases by approx. 19% However, in the "Batched" scenarios (Intervention D), the impact of a No-Show could be mitigated because the subsequent patient required no bed configuration change, allowing the technologist to "catch up" faster than in the Mixed schedule. Late arrival would delay the subsequent exams for all patients especially in the Mixed schedule, whereas in the block schedule, saved time to change the coil can absorb that impact.

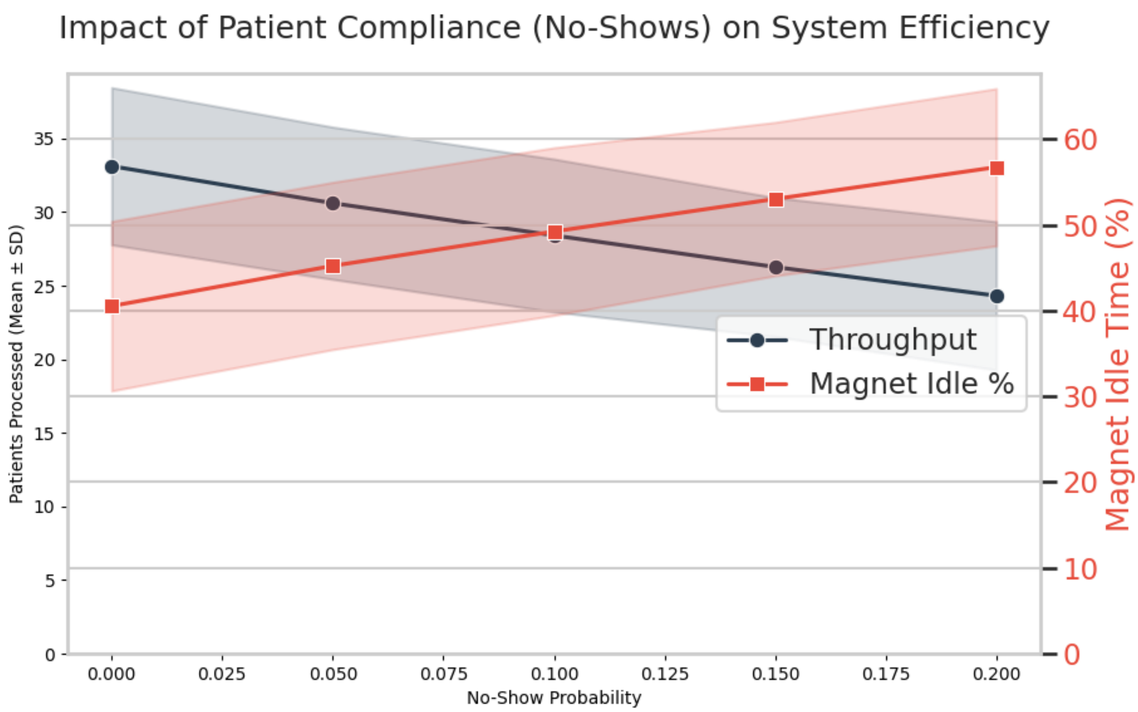

Figure 11: Impact of No-Show Rates on Magnet Idle Time

3.7 Summary of Findings

The simulation **falsified the "Singles Line" strategy** as a primary intervention due to upstream registration bottlenecks. However, it validated "**Batching" as a highly effective mechanism** for capacity generation, specifically identifying *Neuro* (Volume Driver) and *Prostate* (Efficiency Driver) as the optimal candidates for a Hybrid Schedule.

4 Strategic Recommendation: The Hybrid Model

A hybrid model is recommended where one Magnet can schedule any type of exam (Job Shop model), and another magnet can batch-schedule the exams (factory model). By leveraging, this hybrid approach, patient needing different kind of MRI exams can be served in a day, along with increased throughput.

Projected Impact: Implementation of this schedule is calculated to yield ≈ 471 extra patient slots per year.

Table 2: Hybrid Resource Allocation

Block Type	Slots/Shift/Magnet	Days/Week	Weekly Gain	Annual Gain
Prostate	2.7/(30/10)/2	1	4.05 * 1	210.6
Neuro (Brain)	3/2	2	1.5 * 2	156.0
MSK (Spine/Joint)	2/2	2	1.0 * 2	104.0
Total Impact	-	**5**	**9.05**	**470.6**

5 Conclusion

Efficiency in MRI is not achieved by working faster, but by scheduling smarter. By aligning the similar exams (enable batching), the department can unlock significant "Hidden Capacity." That can serve more 470 patients annually without any allocation of budge or infrastructure.

6 Appendix

The code related to simulation, visualization and analysis can be found here:
https://github.com/bhavik-knight/5560-MRI-Project

Bibliography

References

[1] Chris Bowen. **Solving the MRI Wait List**. Biotic Science Rounds Presentation. Transcript Analysis. Biomedical Translational Imaging Centre (BIOTIC), Nova Scotia Health. 2025. URL: https://www.youtube.com/watch?v=I8MNOCuTulE (cit. on pp. 2, 5, 6, 9).

[2] Nova Scotia Health. **MRI Wait Times: Understanding the Numbers**. Nova Scotia Health Authority. URL: https://waittimes.novascotia.ca/procedure/mri-nova-scotia-health-authority (visited on 04/02/2025) (cit. on p. 2).

[3] Isabella Tatlock. **Improving MRI Department Efficiency: Enhancing Productivity and Reducing Wait Times**. Student Research Presentation, Dalhousie University Radiologic Technology Program. Nova Scotia Health & Dalhousie University. Apr. 2025 (cit. on pp. 2–4).