DISCRETE EVENT SIMULATION: SIMULATING A VACCINATION CLINIC WITH TWO ARRIVAL STREAMS, BALKING, AND RENEGING

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1. Abstract

This paper introduces a discrete event simulation (DES) model using SimPy to optimize a vaccine clinic handling both walk-in and scheduled appointments. The objective is to determine the optimal number of receptionists and nurses needed to maximize patient vaccinations while minimizing employee free time, which impacts staffing costs. Key metrics such as wait times, service times, vaccination throughput, and staff free time were analyzed over 100 simulation runs to determine the optimal staffing configuration. Our results indicate that the optimal solution is achieved with two receptionists and five nurses, resulting in a 93.91% vaccination rate, 55.49 patient balks, 16.32 reneges, 31,336 seconds of receptionist free time, and 32,810 seconds of nurse free time.

2. Introduction

Efficient vaccination clinic operations are crucial for public health, especially during large-scale immunization efforts like those prompted by the COVID-19 pandemic. This paper presents a DES model using SimPy to optimize a vaccine clinic that incorporates both walk-in and scheduled appointment arrival streams, prioritizing scheduled arrivals. The model also incorporates balking and reneging. The model evaluates key metrics such as wait times, service times, vaccination throughput, and staff free time. The objective is to determine the optimal number of receptionists and nurses to staff in the clinic that maximizes patient vaccinations while minimizing staffing costs, providing insights and recommendations for enhancing clinic efficiency.

3. Literature Review

Substantial research has explored using DES to optimize vaccination clinic operations. Aaby et al. (2005) evaluated clinic capacity and patient flow times for mass vaccination clinics, finding significant discrepancies in CDC guidelines that could lead to staffing inefficiencies. They recommend reducing batching and adjusting staffing levels to improve efficiency. Sala et al. (2023) studied a COVID-19 vaccination center in Bergamo, Italy using DES with FlexSim Healthcare software. They optimized operations, identifying an optimal configuration with 20 workstations processing 2921 patients daily, highlighting the effectiveness of DES tools in enhancing clinic performance. Abdoli et al. (2021) examined double-booking and walk-in policies for appointment scheduling using DES with Arena software. Their findings suggest double-booking is more productive with high arrival rates, while walk-ins are better for lower rates, highlighting that policy choice depends on demand fluctuations. While these studies offer valuable insights into efficient vaccination clinic operations, a gap remains in the literature regarding the integration of both walk-ins and scheduled appointments in vaccination clinics, as well as considering patient behaviors such as balking and reneging. Addressing this gap will provide a more comprehensive understanding of patient dynamics and further contribute to the goal of producing more efficient and effective vaccination clinic operations.

4. Methodology and Implementation

The clinic was set up so that patients arrive and join a check-in queue to meet with a receptionist. After checking in, patients join a vaccination queue to be vaccinated by a nurse. The times to check in with the receptionist and to vaccinate each patient were randomized using a normal distribution via the Numpy library, with mean times of one minute for check-in and three minutes for vaccination. Patients were divided into scheduled appointments and walk-ins, with scheduled patients prioritized to jump to the front of the check-in queue upon arrival. To facilitate this, receptionists were set as a PriorityResource in the SimPy library, with scheduled patients given a priority of -1 and walk-ins a priority of 0. Nurses were set as a Resource in SimPy without priority. A scheduled patient was fixed to arrive every 15 minutes. Walk-in patients were further randomized into rushed and relaxed categories using binomial randomization from the Numpy library, with 25% classified as rushed. Rushed patients would balk, or leave the check-in queue without entering, if it contained five or more patients, and would renege, or leave without being vaccinated, if their total time in the clinic exceeded five times the mean check-in plus vaccination time. Relaxed patients would balk if the queue had 15 or more patients and would renege if their clinic time exceeded fifteen times the mean check-in plus vaccination time. Realistic patient flow rates were accounted for by setting high flow periods from 7-9am, 11am-2pm, and 5-7pm, and low flow periods from 9-11am and 2-5pm. Patient arrival rates were randomized using a normal distribution with an average of one patient per minute during low flow times and two patients per minute during high flow times. The simulation time was set to 12 hours.

The simulation was run 100 times with 1-10 nurses and 1-10 receptionists with the goal of finding the optimal number of nurses and receptionists to maximize patient vaccination while minimizing unnecessary staffing costs. To measure unnecessary staffing costs, the total time that nurses and receptionists spent idle was tracked throughout the simulation. To measure vaccination rates, each patient was logged as they went through the clinic to determine if they were successfully vaccinated, balked, or reneged. The percent vaccination rate was measured for each of the simulations. Next, three different scenarios were chosen for further analysis based on the data from the initial simulation. For each scenario, each one was run 100 times and the average vaccination rate, average idle time for nurses, and average idle time for receptionists was tracked.

5. Results and Discussion

The output from the initial simulation, which was run 100 times with one to ten nurses and one to ten receptionists, was analyzed, and the resulting graphs are presented in Figures 2, 3, and 4. Figure 2 indicates that having at least two receptionists and between four to six nurses results in vaccination rates ranging from 80% to the high 90s, with significant improvements seen with the addition of nurses. However, the vaccination rate begins to plateau beyond six nurses, with only slight increases observed. The graph also shows that having three receptionists generally achieves a higher percentage of vaccinated patients compared to two receptionists.

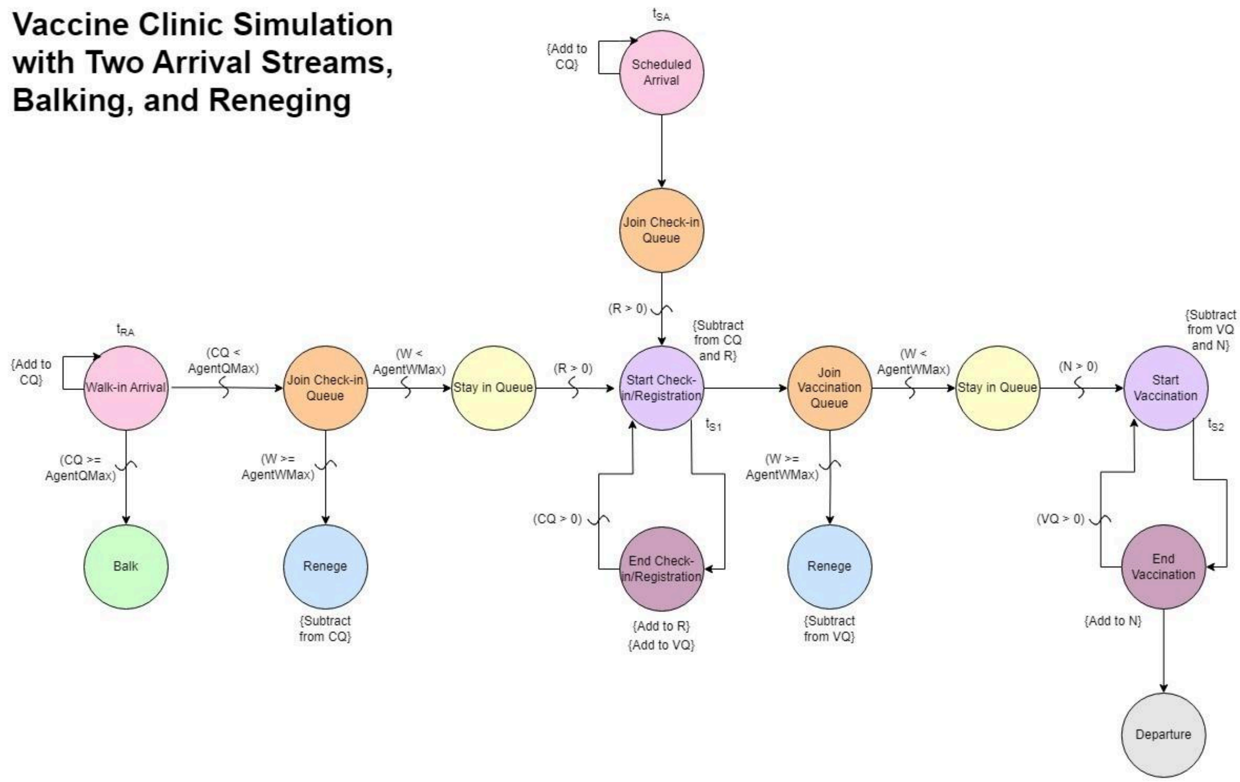
Because employee free time is an important consideration in addition to the percentage of patients vaccinated, the free time of two and three receptionists across one to ten nurses was investigated to determine whether the optimal number of receptionists would be two or three given that having more than three receptionists would not significantly improve the vaccination rate and would significantly increase receptionist downtime. Figure 3 shows that three receptionists experience significantly more downtime than two receptionists. Thus, while having three receptionists results in higher vaccination rates, this increase in idle time more strongly negatively impacts the objective of minimizing staff costs compared to having two receptionists. Now, choosing to have two receptionists and varying the number of nurses while assessing nurse free time to determine the optimal range of nurses, Figure 4 reveals that nurse free time starts to increase sharply after five nurses are available. Given this evidence, we assessed the following scenarios for further simulation runs: two receptionists and four nurses, two receptionists and five nurses, and two receptionists and six nurses. Running these simulations will determine the optimal staffing that best balances high vaccination rates while minimizing unnecessary staff downtime.

The results table for the scenarios with two receptionists and four to six nurses, based on 100 simulation runs (Figure 5), shows that with four nurses, the vaccination rate is 83.92%, with 57.04 patients balking and 132.59 patients reneging. Increasing to five nurses improves the vaccination rate to 93.91% and significantly reduces reneges. With six nurses, the vaccination rate further increases to 95.16%, but nurse free time rises sharply to 80,203 seconds. Receptionist free time remains stable across all scenarios. Based on this evidence, two receptionists and five nurses is the optimal solution, as it best balances a high vaccination rate and low employee free time.

6. Conclusion

This study demonstrates the use of discrete event simulation (DES) to optimize staffing in vaccination clinics, balancing patient throughput and staffing costs. Our model, which incorporates both walk-in and scheduled appointments as well as patient behaviors such as balking and reneging, reveals that two receptionists and five nurses offer the best balance. This optimal configuration effectively enhances clinic efficiency and can significantly improve vaccination clinic operations, thereby supporting better public health outcomes.

Appendix



Key	
CQ	Number of patients in check-in queue
VQ	Number of patients in vaccination queue
t_{RA}	Time until next walk-in patient arrives
t_{SA}	Time until next scheduled patient arrives
R	Number of check-in/registration employees available
N	Number of nurses available
t_{S1}	Time to check-in/register patient
t_{S2}	Time to vaccinate patient
AgentQMax	Longest check-in/registration line patient will join (balking value)
AgentWMax	Longest time patient will wait in check-in/registration line (reneging value)
	Use random number generators to determine tRA, tS1, and tS2 for each event
	Use fixed interval to determine tSA

Figure 1. Event Graph Illustrating the Process Flow of the Vaccine Clinic Simulation.

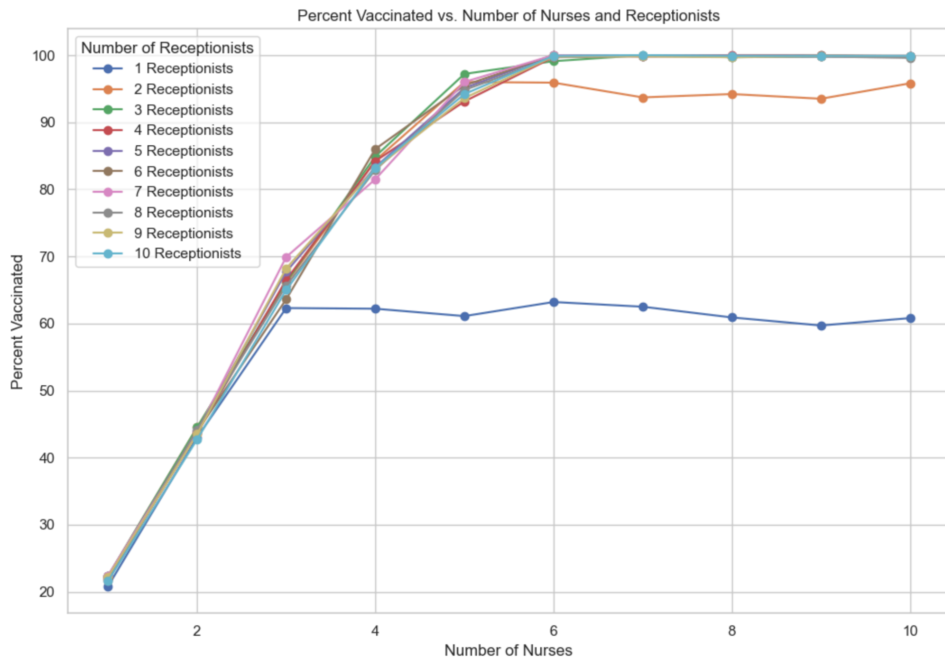


Figure 2. Percentage Vaccinated vs. Number of Nurses and Receptionists.

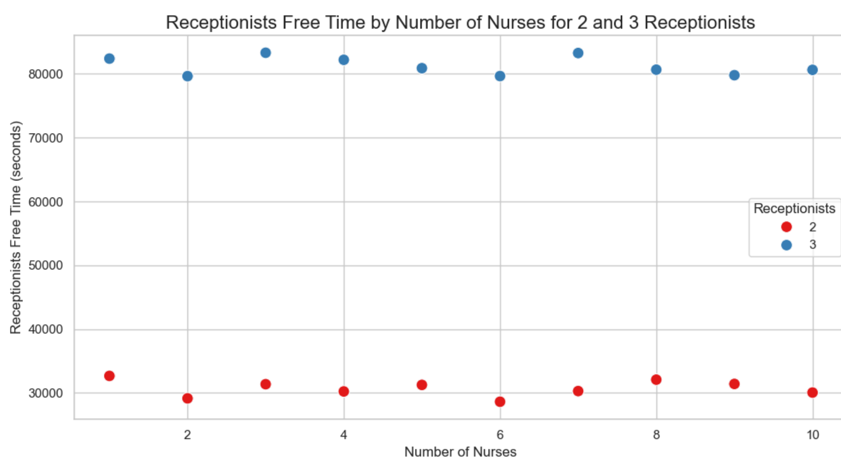


Figure 3. Receptionists' Free Time by Number of Nurses for 2 and 3 Receptionists.

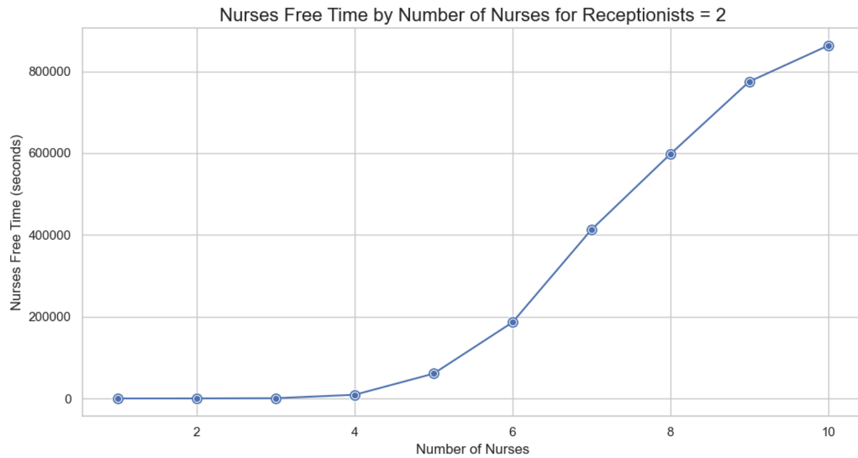


Figure 4. Nurses' Free Time by Number of Nurses for 2 Receptionists.

Nurses	Vaccinations	Balks	Reneges	% Vaccinated	Receptionist Free Time (s)	Nurse Free Time (s)
4	988.91	57.04	132.59	83.92	31006	5136
5	1105.66	55.49	16.32	93.91	31336	32810
6	1119.45	56.98	0.00	95.16	30993	80203

Figure 5. Simulation Results for 2 Receptionists and 4-6 Nurses (Run 100 times).

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