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Title: Simulating a Mass Vaccination Clinic
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ABSTRACT

To react to an outbreak of a contagious disease that requires medication or vaccination, county health departments must setup and operate mass dispensing and vaccination clinics. Carefully planning these clinics before an event occurs is a difficult and important job. Two key considerations are the capacity of each clinic (measured as the number of patients served per hour) and the time (in minutes) spent by patients in the clinic. This paper discusses a simulation study done to support this planning effort. Based on data from a time study of a vaccination clinic exercise, a simulation model was used to evaluate alternatives to the clinic design and operation. Moreover, the study identifies some shortcomings in existing guidelines for mass vaccination clinics.

KEYWORDS: emergency response, mass vaccination clinic, communicable disease, discrete-event simulation, capacity planning

1. INTRODUCTION

The threat of a biological attack on the United States, due to naturally occurring causes or a terrorist act, has compelled public health departments to update and enhance their plans for responding to such an event. This is especially true in densely populated regions and regions of significant importance such as the nation's capital. In the worst-case scenario, terrorists could release a lethal virus such as smallpox into the general population. If this were to happen, every person in the affected area would have to be vaccinated in a matter of days. For example, Montgomery County, Maryland, would need to vaccinate nearly one million people. In order to vaccinate a large number of people in a short period of time, mass vaccination clinics would need to be set up at designated sites within the county. Kaplan *et al.* [1] compare vaccination policies for responding to a smallpox attack, showing that mass vaccination results in many fewer deaths in the most likely attack scenarios.

Carefully planning mass dispensing and vaccination clinics (also known as points of dispensing or PODs) before an event occurs is a difficult and important job. The correct number of staff must be appropriately trained beforehand, and the correct number of staff must be assigned to roles when the clinic begins operations. Two key considerations are the capacity of each clinic (measured as the number of patients served per hour) and the time (in minutes) spent by patients in the clinic (this is known as the time-in-system or flow time or throughput time). Clinic capacity affects the number of clinics that must be opened and the total time needed to vaccinate the affected population. The time-in-system affects the number of patients who are inside the clinic. More patients require more space as they wait to receive treatment. If too many patients are in the clinic, they cause congestion, crowding, and confusion.

The Centers for Disease Control have created guidelines to help county health departments plan their response in such incidents [2]. The guidelines provide some estimates of the time needed to perform specific activities (such as vaccination) and, based on these estimates, suggest the number of staff needed to meet a specific throughput target (118,000 patients per day). One purpose of the study described in this paper was to acquire more data about realistic processing times and to consider the adequacy of the existing guidelines.

Clinic capacity and time-in-system are not the only concerns in planning such clinics. Based on mass prophylaxis operations in 2001, Blank *et al.* [3] describe many of the practical concerns that arise while planning and operating mass dispensing and vaccination clinics.

Simulation modeling has been used to model health care systems such as medical centers, hospitals, and clinical practices [4-8]. Other formal techniques have been applied as well. Malakooti [9] used a cell formation approach to emergency room design. Jain and McLean [10] describe a framework for linking simulation models of disasters. There are no known published reports that describe the modeling or design of mass dispensing and vaccination clinics.

The remainder of this paper is organized as follows: Section 2 presents the methodology used. Section 3 describes the mass vaccination clinic exercise. Section 4 discusses the data analysis. Section 5 presents the simulation model. Section 6 discusses the validation of the model, and Section 7 presents the results of the simulation experiments. Section 8 concludes the paper.

2. METHODS

This study followed a standard simulation study methodology, consisting of the following steps:

1. Define scope of study.
2. Collect data.
3. Analyze data.
4. Build simulation model.
5. Validate simulation model.
6. Run experiments.
7. Present results.

The scope of the simulation study was limited to the clinic operations and the key performance measures of capacity and time-in-system. The transportation of patients to the clinic and the handling of vaccines and other supplies were not considered. Data collection relied upon a time study of the mass vaccination clinic exercise (described in Section 3).

3. MASS VACCINATION CLINIC EXERCISE

Operation Dagwood, a mock mass vaccination clinic exercise, was performed on June 21, 2004 by the Montgomery County Department of Health and Human Services (MCDHHS). This drill was created to simulate the emergency procedures in store for mass vaccination in the event of a widespread outbreak of the smallpox virus. The clinic was setup at John F. Kennedy High School in Silver Spring, Maryland. No actual vaccinations were given. Nurses at the vaccination station simulated the smallpox vaccination step by poking each patient's arm with coffee stirrers.

In this full-scale exercise, 152 workers and volunteers worked as professional, command, and administrative staff. Physicians, Registered Nurses, health professionals and pharmacists as members of the Volunteer Medical Reserve Corp went through the clinic as patients first before taking their posts in the clinic as workers. Montgomery County Fire and Rescue provided an ambulance crew, and Montgomery County Law Enforcement provided security at the clinic.

Volunteers from the local workforce and community served as patients. County workers and especially Public Health staff were encouraged to participate with their families. A number brought elderly family members and children, and the volunteers included individuals with physical disabilities. A local newspaper covered the exercise as well [11].

3.1. CLINIC OPERATIONS

Approximately 530 people participated in the exercise as patients between 12:30 pm and 3:00 pm. These participants arrived at one of four staging areas, where selected individuals were instructed to play out special roles. These roles included patients with mental health problems, patients with various medical symptoms, patients who had contact with the smallpox virus, and patients with little or no ability to speak English. Hereafter, these symptoms and scenarios, as well as the exercise as a whole, will be referred to as if actual as opposed to simulated. Although this description refers to a specific clinic configuration, this configuration is based upon CDC guidelines, and other county health departments are planning to use the same type of clinic.

After gathering at the staging areas, patients were transported on school buses to the clinic. Each bus held up to 50 patients. At the clinic, after receiving a timestamp sheet, each patient proceeded to the triage station, which was outside the clinic building. At this station three triage staff asked patients if they had any symptoms of smallpox (a rash or fever) or if they knew they had been in contact with the smallpox virus. Escorted by other staff, symptomatic patients went to a holding room to await medical consultation. Patients exposed to the smallpox virus went to a quarantine room to await medical consultation. After seeing a doctor, patients from these areas were sent to the hospital or sent to enter the clinic. See Figure 1.

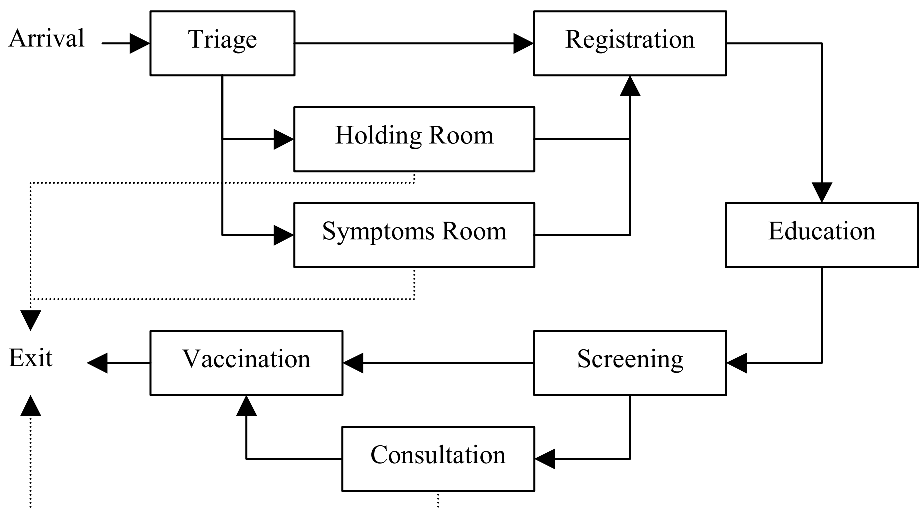

Figure 1. Flowchart of patient flow (dashed lines show patients who exit without receiving vaccinations).

After entering the clinic, each patient received registration forms and information on smallpox at the registration station. The registration station had four tables, each with two registration staff. After this, each patient went to the education station.

The education station was a set of classrooms. At the beginning of the exercise, there were four classrooms showing the video in English, and one classroom showing a Spanish language version. During the exercise, clinic staff opened two additional classrooms (both showing the English language video). In each classroom, a group of patients watched an informational video about the smallpox vaccine and completed their registration forms. The education station staff managed the classrooms and checked the registration forms for completeness. After this, each patient walked to the screening station.

Figure 2. Photo of queue for screening

At the screening station, patients waited in a single line to see medical personnel. A staff person helped direct traffic at the head of the line, and the screening staff held up signs when they were ready for a new patient. The number of screening staff varied from 9 to 11 throughout the day. The screening staff checked each patient's registration form. Staff directed patients who had possible complications based on their medical history to visit the consultation station. The others signed a consent form and went directly to the vaccination station.

At the consultation station, each patient met with a doctor to discuss possible complications. The number of consultation staff was six. Some patients decided to skip the vaccination. These patients received an information sheet and then left the clinic. The others signed a consent form and joined the line for the vaccination station.

At the vaccination station, patients waited in one line to see vaccination personnel. There were 14 stations with vaccination staff. Vaccination staff verified that the consent form was signed and witnessed and then vaccinated the patient in one arm. The patient and another staff member reviewed an information sheet about what to do after the vaccination, and then the patient left the clinic.

3.2. DATA COLLECTION

Researchers from the University of Maryland, along with student volunteers, conducted a time study to collect data on clinic performance during the exercise. As mentioned above, each patient received a time stamp form upon arriving at the clinic. This form was stamped with the time (hour and minute) of their arrival. While walking through the clinic from one station to the next, each patient passed by one of five additional time stamp tables, where the time stamp form was stamped again in a defined spot. The time stamp forms were collected at the last time stamp table. Stamping was done using electronic timers that printed not only the hour and minute but also a code that indicated which timer was used and counted the number of patients stamped with that timer. The six time stamp tables (each staffed by two students) were positioned throughout the clinic as follows:

1. Arrival (outside the clinic)
2. Registration (inside the clinic after triage and before registration)
3. Education (after registration and before education)
4. Screening (after education and before screening)
5. Vaccination (after screening and before vaccination)
6. Exit (inside the clinic after vaccination)

Figure 3. Photo of time stamp table

In addition, video cameras were used to record the processes at each station. These recordings were made with the clock displayed on tape. Two vaccination locations were filmed for the duration of the exercise. Another video camera recorded various aspects of the exercise, including triage, the holding rooms, registration, and consultation. The time study team also collected data on the bus arrivals, noting what time they arrived and how many patients were on each one. The average arrival rate was 213 patients per hour.

The distance between different stations was measured. A group of volunteers were timed while walking 100 feet to provide data on walking speeds.

MCDHHS also collected data that was useful to the time study, including the total number of patients vaccinated, the number infected with smallpox, and the number sent to the hospital for other reasons. MCDHHS data management volunteers collected this data every 30 minutes. This data was gathered by counting registration forms picked up from the various stations.

Although the time study was carefully planned, the data collected was not complete and may have included some inaccuracies due, in part, to the limited number of people, time, and equipment available to conduct the time study. Still, the data were sufficient for constructing a valid simulation model.

4. DATA ANALYSIS

The first step in data analysis was to enter the collected time stamp data into an electronic spreadsheet. This yielded data about how long each patient spent at each station and the total time in the clinic. A researcher watched all of the videotape to determine the distribution of the processing time at each station except the education station. Data about the education station was gathered during the exercise itself. The walking speeds used in the simulation model are a triangular distribution based on information from the U.S. Manual on Uniform Traffic Control Devices, the Canadian Uniform Traffic Control Devices for Canada, and Coffin [12].

Searching the time stamp data for outliers provided estimates on the number of patients that went to the holding rooms and the number of patients that went to the consultation station. For instance, if most of the patients who arrived at the screening station around 1:00 pm then arrived at the vaccination station 10 minutes later, then those patients who arrived at the screening station at the same time but arrived at the vaccination station 30 minutes later must have spent time at consultation.

Table 1 lists the mean processing time determined from the data that was collected from the exercise. Note that some of these are significantly different from the processing times suggested in the CDC guidelines for large-scale smallpox vaccination clinics. A different set of processing times leads to a significant difference in the number of staff needed at each station.

Table 1. Processing time data.

Station	**Measured from exercise (minutes)**	**Given in CDC guidelines**
Triage	16 secs	1 min
Registration	7 secs	0.5 to 2 min
Education	22 mins, 7 secs	30 min
Screening	1 min, 43 secs	5 to 10 min
Consultation	3 mins, 42 secs	5 to 15 min
Vaccination	3 mins, 36 secs	0.5 to 2 min
Symptoms	1.2 min	10 min
Contacts	3.8 min	10 min

5. SIMULATION MODEL

The research team designed and built a discrete-event simulation model of the mass vaccination clinic using Rockwell Software's Arena® 5.00. The initial model was meant to simulate the exercise that occurred. Patient arrived in batches that corresponded to the actual bus arrivals. In the model, each patient was represented as an entity that progressed through different queues and processes. The model included animation for visualizing the movement of patients through the clinic. This is shown in Figure 4.

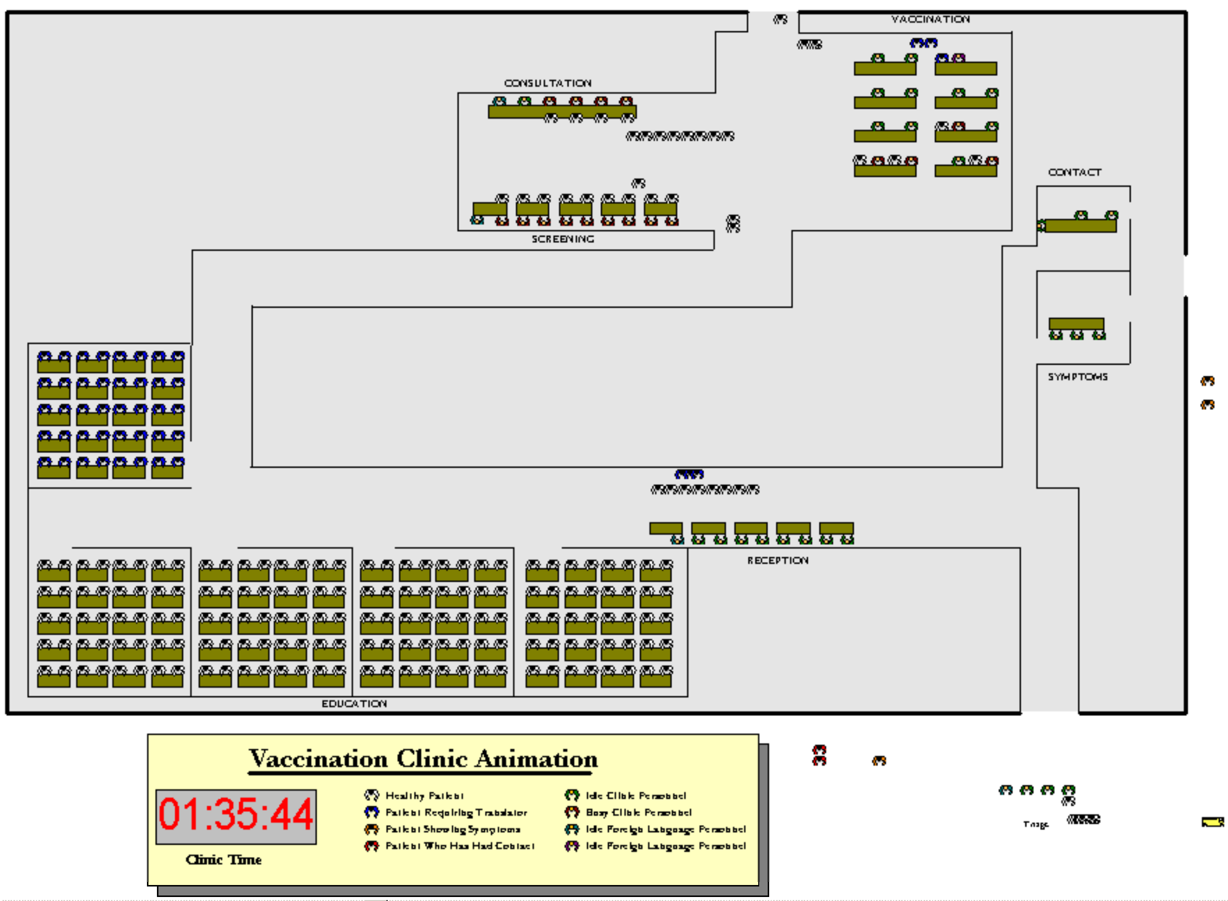

Figure 4. Clinic simulation model

In the simulation model, each patient's arrival to each station was noted and recorded. The processing times at each station were random variables, using gamma distributions that were the best fits as determined by the simulation software. Patients were randomly sent to the holding rooms or to consultation using probabilities that corresponded to the actual clinic (see Table 2).

In the simulation model, patients at the education station were batched into temporary class groups (30 in the baseline), each of which visited a classroom for the education process. After they finished, the class groups were separated into the original patients, who then moved to the screening station.

Table 2. Patient routing probability.

From	To	Percentage
Triage	Registration	92.06
Triage	Symptoms Room	4.77
Triage	Holding Room	3.17
Symptoms Room	Registration	67.00
Symptoms Room	Hospital	33.00
Holding Room	Registration	65.00
Holding Room	Hospital	35.00
Screening	Consultation	26.17
Screening	Vaccination	73.83
Consultation	Vaccination	94.07
Consultation	Exit	5.93

6. MODEL VALIDATION

For validation purposes, timestamp stations were simulated in the model to resemble as closely as possible those present in the exercise. The timestamp stations in the model were used to record minutes from the beginning of the simulation, which could then be compared with the timestamp data taken during the exercise. The timestamp operation in the model was instantaneous (in the exercise, the timestamp operations required only a few seconds.)

Table 3 and Figure 5 show the average time that a patient spent at each station. The simulation results are given as confidence intervals on the mean time. These results show that the measured and simulated times are close.

Table 3. Validation results.

Station	**Measured from exercise (minutes)**	**95% confidence interval from simulation (minutes)**
Triage	2.18	4.35, 4.75
Registration	2.43	0.16, 0.17
Education	31.23	28.18, 29.65
Screening	16.77	20.08, 22.48
Vaccination	8.87	8.98, 9.98
Total in system	60.02	62.27, 65.03

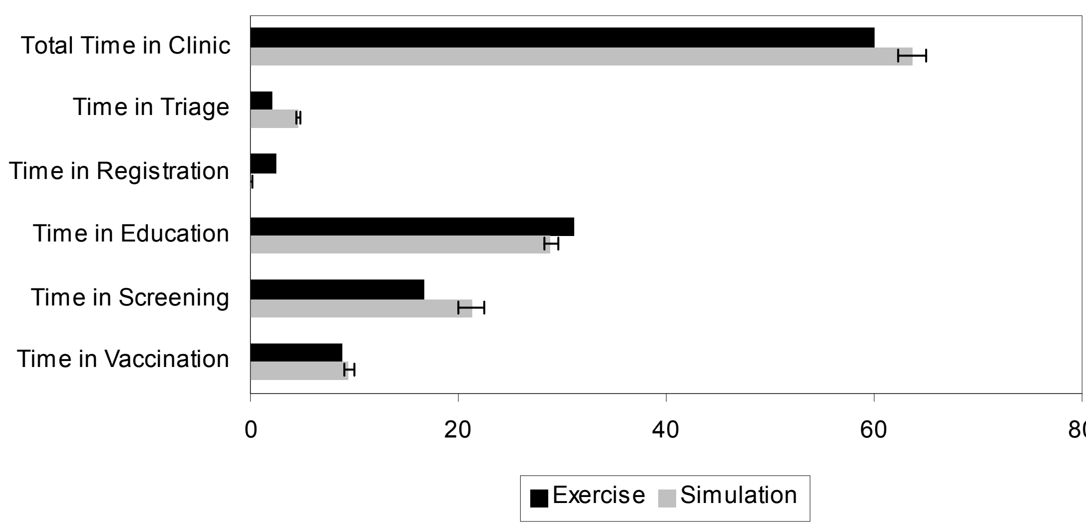

Figure 5. Flow time comparison for exercise and simulation.

There are various reasons why the results from the simulation model do not match more closely the clinic's performance from the actual exercise. In the exercise, patients may have spent extra time inside the clinic (in activities such as casual conversations or visiting the restrooms). Some congestion occurred at some timestamp tables. Patient walking speeds varied widely. The operation of some stations was not consistent.

7. SIMULATION EXPERIMENTS

The purpose of the simulation experiments was to evaluate how changes would affect the clinic performance. These experiments considered the performance of the clinic under the steady-state conditions that would occur in a large event, when the clinic would be operating for several days. Therefore, in these models, buses arrived randomly. The mean interarrival time was set to specify different patient arrival rates. The interarrival time distribution was varied.

The first step was to improve the capacity of the clinic by addressing a problem with the vaccination station. In the exercise, the average time to vaccinate a patient was 3 minutes, 36 seconds. However, this time included the time needed for the patient to walk from the head of the vaccination queue to the vaccination table. This wasted time can be eliminated by having the next patient wait in a spot next to the vaccination table. This reduces the average time to vaccinate a patient to 3 minutes, 16 seconds. With 16 vaccination staff, this change increases the clinic capacity from 267 patients per hour to 293 patients per hour.

For comparison purposes, a baseline clinic model was created. Table 4 specifies the number of staff at each station, based on the CDC guidelines. (For education, this is also the number of classrooms.) Each classroom held 30 patients. Each arriving bus brought 50 patients.

Table 4 also shows how the capacity of each station affects the clinic capacity. Because not all arriving patients go through all of the stations, the clinic capacity (patient arrivals per hour) is not simply the minimum station capacity. Each station places a constraint upon the clinic capacity by dividing the station capacity by the fraction of the patients that visit that station (on average). This fraction can be determined from the routing percentages given in Section 5. Based on this, the clinic capacity is 307 patients per hour. If the patient arrival rate were to exceed this, some stations in the clinic would not be able to serve all of the patients that arrive to that station, which would lead to unstable behavior.

Table 4. Baseline clinic staffing.

Station	Number of Staff	Station Capacity (patients per hour)	Percentage of Patients Served	Constraint on Clinic Capacity (patients per hour)
Triage	2	463	100.0	463
Registration	9	4444	97.3	4567
Education	8	600	97.3	617
Screening	16	558	97.3	574
Consultation	7	111	25.5	437
Vaccination	16	294	95.8	307
Symptoms	1	49	4.8	1037
Contact	1	16	3.2	498

In addition to capacity, the other key clinic performance measure is the average total time in clinic. This was evaluated at five different arrival rates, shown in Table 5.

Table 5. Patient Arrival Rates.

Arrival Rate (patients per hour)	Percent of Clinic Capacity
150	49
250	81
275	89
290	94
300	98

A critical parameter in the model was the distribution of bus interarrival times. Experiments were done to quantify the impact of arrival variability. We measure the variability by the squared coefficient of variation (SCV). Experiments were done with the following interarrival time distributions: exponential (SCV = 1), gamma (SCV = 0.25), and constant (SCV = 0). Figure 6 shows the results. The top line corresponds to the exponential distribution, the middle line to the gamma distribution, and the bottom line to the constant interarrival times. This clearly shows that a key cause of congestion is the variability in the bus interarrival times.

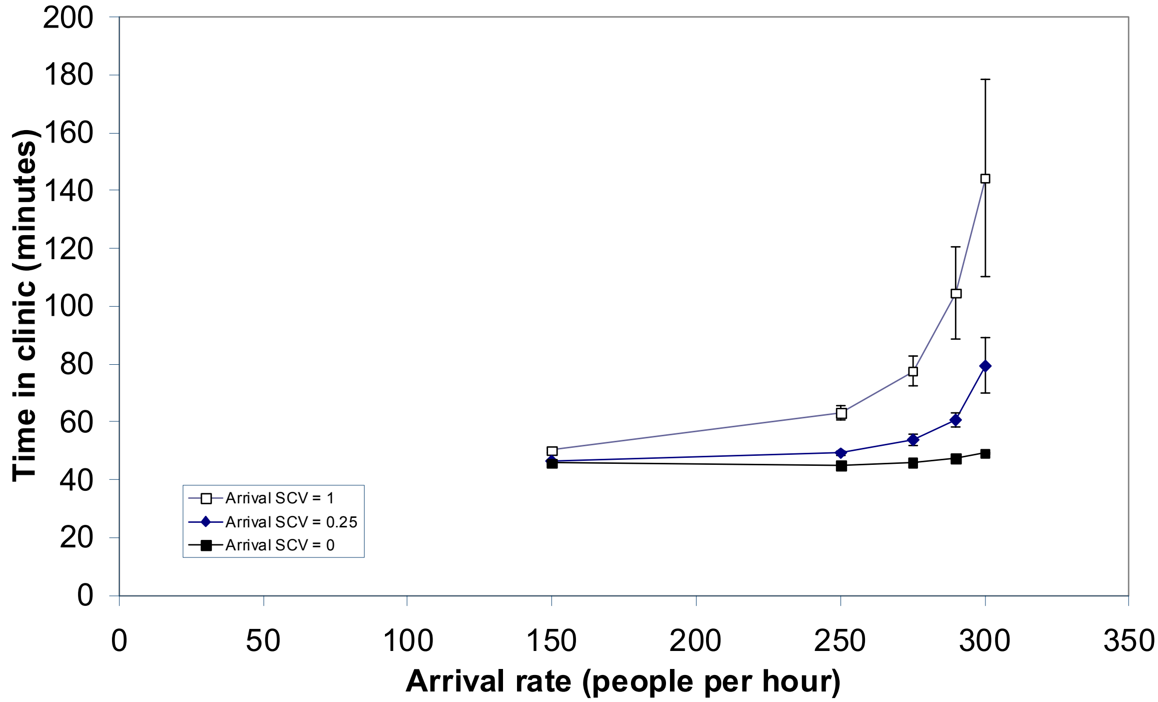

Figure 6. Time in clinic versus arrival rate for different bus interarrival time distributions.

We also considered reducing batching (by changing the number of patients per classroom) and reducing the number of registration and screening staff. Batching at education is causes delays in the clinic. Reducing this batch size should reduce congestion, while increasing it should increase congestion. However, the simulation results showed that changing classroom size to 20 or 40 did not reduce time in clinic significantly at the highest arrival rates, as shown in Figure 7.

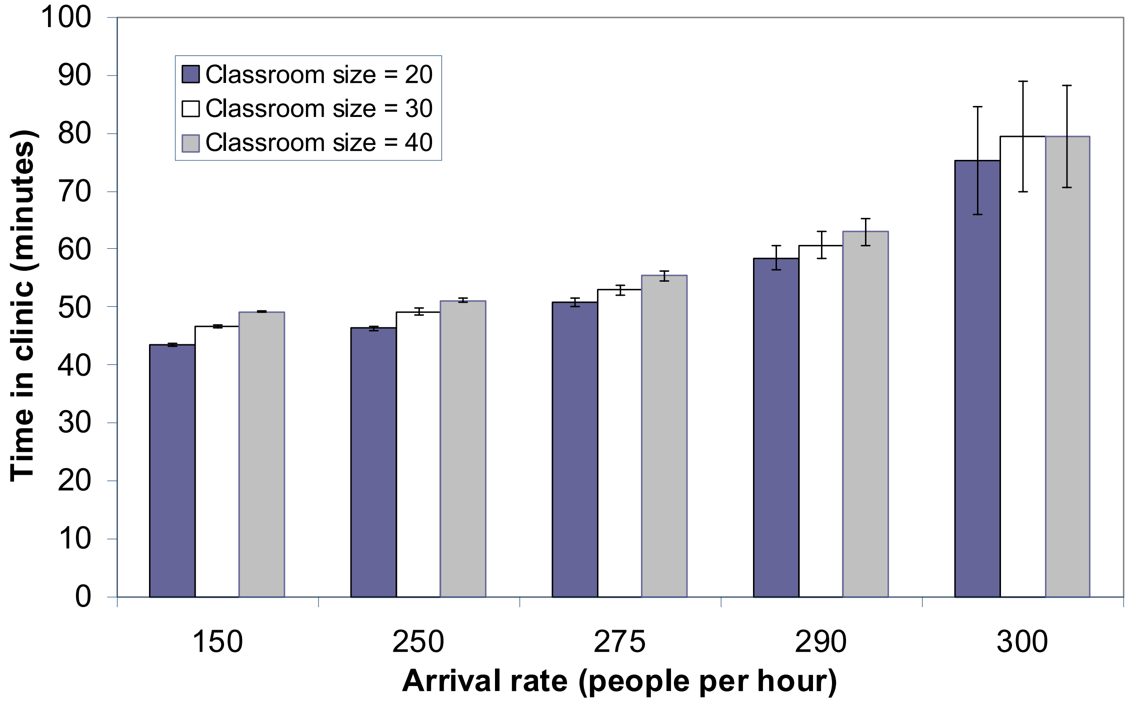

Figure 7. Time in clinic versus arrival rate for different classroom batch sizes.

In the baseline model, the utilization of the screening staff is at most 52%, and the utilization of the registration staff is at most 7%. This indicates that too many staff members are working at these stations. Reducing the number of staff at these stations should cause a slight increase in congestion. To evaluate the impact, a reduced staffing model was created. In this model, the screening station has only ten staff members (instead of 16), and the registration station has only one staff member (instead of 9). At the highest arrival rate, the utilization of the screening staff increased to 84%, and the utilization of the registration staff was 59%. The increase in time in clinic was not significant. At the highest arrival rate, the time in clinic was 80.4 minutes (with a 95% confidence interval half-width of 9.3 minutes). Thus, clinic staffing can be reduced by 14 staff members while maintaining the same clinic capacity and with practically no increase in congestion.

8. SUMMARY AND CONCLUSIONS

This paper discussed the use of discrete-event simulation models to evaluate mass vaccination clinic performance. Simulation models can measure the queues that occur during clinic operation and can determine the average time that patients spend in the clinic. This allows county health departments to plan operations that reduce the number of patients in the clinic, which avoids unnecessary congestion, crowding, and confusion. Simulation models also provide animation of the clinic operations to help planners visualize what would happen.

Congestion in mass dispensing and vaccination clinics is caused by variability, and there are multiple sources of variability. The experimental results presented here show that the arrival time variability has a more significant impact on clinic performance than the variability due to the number of patients in a classroom.

The simulation models created are based on a time study of a mass vaccination clinic exercise. This time study provides the county health departments with more data about the time needed to perform clinic activities and allows them to generate better estimates of the staffing required to meet a given throughput target. Further work is needed to acquire the best possible estimates of processing times (especially for those operations that require scarce resources such as nurses) and also to develop clinic designs whose performance is robust with respect to the actual processing time distributions.

Simulation provides the best estimates of queueing due to the batch processes and the general processing time distributions that characterize mass dispensing and vaccination clinics. Simulation studies such as the one described here are most appropriate as part of planning a county's response to an event, since conducting the study requires time to collect and analyze data, build and validate the model, and conduct experiments to evaluate alternatives.

The authors are conducting research to build adaptable simulation models of common clinic designs. These parametric models will eliminate the need to construct a new simulation model from scratch.

Finally, simulation models that comprise multiple dispensing and vaccination clinics, staging areas, and the transportation system used to move patients to and from clinics could be built using the clinic simulation models (or simplified versions of them).

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