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REVIEW ARTICLE

Optimizing patient flow, capacity, and performance of COVID-19 vaccination clinics

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ABSTRACT

Mass vaccination plays an important role in increasing immunization against COVID-19 and decreasing morbidity. Drive-through and traditional walk-through centers have been set up in most cities in the United States and other countries to vaccinate large numbers of people in a short period of time. This article focuses on a pair of mass vaccination clinics conducted on a mid-sized, public university campus. Applying tools from Industrial Engineering, including time study, flow charts, and Queuing Theory, the team identified improvements that resulted in a 40% reduction in the duration of the second clinic while vaccinating almost the same number of patients with no increases in overall staffing. The work resulted in a model for designing mass vaccination clinics in the future and demonstrates that engineers have the ability to support healthcare personnel to increase the performance of the vaccination centers. The inclusion of engineering in the planning and execution of these vaccination clinics can help maximize clinic capacity, reduce the staff and resources needed, and reduce the patients' waiting time.

1. Introduction

The worldwide pandemic caused by the SARS-CoV-2 virus demands coordinated and collaborative efforts to reduce spread and prevent morbidity and mortality. Central to these efforts is the widespread distribution of COVID-19 vaccines, approved by the United States Food and Drug Administration under emergency authorization. Vaccinations are among the most successful means to control illness in the general population and are an essential step in reducing the spread of the virus (Frederiksen et al., 2020). While vaccines offer personal protection against a disease, they also protect the population, thus assisting those who are unable to receive the COVID-19 Vaccine due to compromised health conditions, age, availability, or accessibility (Randolph and Barreiro, 2020). Herd immunity is a proportion of the population inoculated to effectively stop the transmission of the virus (Mallory et al., 2018). The Centers for Disease Control and Prevention (CDC) does not yet have a recommendation of what percentage of the population needs to be vaccinated to reach herd immunity, but researchers estimate at least 67% of the population needs to be vaccinated (Randolph and Barreiro, 2020). Unfortunately, efforts to provide vaccines to citizens of the United States have been stalled by uncertainty about them (Chou and Budenz, 2020), lack of financial resources, and logistical limitations in supply and distribution (Savoia et al., 2021).

Due to limited vaccine supply, many states opted for a phased roll-out of the vaccine. In Montana, phase 1a included front-line health care workers and nursing home residents; phase 1 b included residents above 70 years of age, those 16 − 69 years of age with a preexisting high-risk medical condition, Native Americans, and other persons of color (Montana.gov, 2021). Reports of disparities in infection and vaccination rates in racial and ethnic minorities (Artiga et al., 2020) prompted the state of Montana to include Black, Indigenous, and other Persons of Color (BIPOC) in their 1 b priority eligibility criteria. An estimated 7% of Montana's 1 million residents identify as Native Americans and another 4% as persons of color (U.S Census Bureau., 2020).

In recognition of limitations experienced by the local Health Department, the student health center at Montana State University (MSU) was asked to distribute vaccines to students and faculty who meet the 1 b priority category. University enrollment of students who identified themselves as Native Americans or persons of color on registration documents in the academic year 2020–21 was 18%. Administrators at the student health center contacted the College of Nursing to design and implement a large-scale vaccination campaign. In turn, the dean of the College of Nursing created a team of university leaders representing nursing, medicine, medical assistance, engineering, communications, and facilities management. In a collaborative, interprofessional effort, a vaccine clinic was created to

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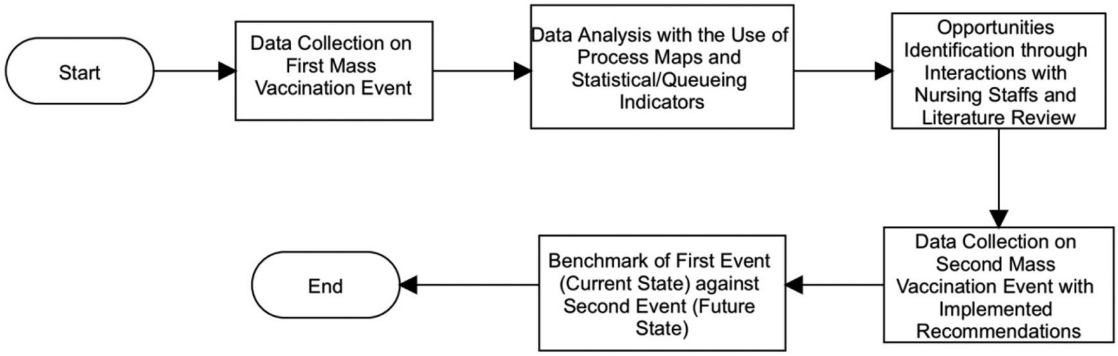


Figure 1. Research process flowchart.

administer 806 first doses of the Pfizer-BioNTech COVID-19 vaccine over the course of 7.5 hours and 776-second doses three weeks later in 4.5 hours.

This article presents observations from an industrial engineering analysis of the vaccine clinic design and processes. Once the engineering team was invited to this project, the following questions emerged:(1) How to estimate staffing requirements for a mass walk-through vaccination clinic? (2) How to minimize patients' waiting time in the clinic? (3) How to improve the vaccination process to reduce overall waste and increase staff utilization? With these questions in mind, the main goal of this research was to minimize (eliminate if possible) patients' waiting time and predict future clinic requirements and capacities.

A multidisciplinary team comprised of three Industrial Engineering students, two Industrial Engineering faculty, and one Nursing faculty performed the study and analysis. The study was performed in 4 phases, the first one was the observation and collection of data in the first vaccination clinic, the second phase was the assessment of the first clinic and presentation of proposed changes for the second clinic, the third phase was the observation and data collection of the second clinic, and the last one was the assessment of the second clinic, comparison of both clinics and propose changes for future clinics. Figure 1 depicts a flowchart of the research process.

This study is significant since it presents a model for using industrial engineering tools in planning and improving a mass vaccination event to inform future large-scale vaccination efforts and demonstrates the ability of to support healthcare personnel to increase the performance of the vaccination centers. To the knowledge of the authors, no previous study has applied tools from Industrial Engineering to improve patient flow, capacity, and performance in a COVID-19 walk-through clinic. Due to the improvements identified in this study, it was possible to reduce the duration of the second clinic by 40% while vaccinating almost the same number of patients with no increases in overall staffing.

2. Literature review

Interdisciplinary approaches to healthcare capitalize on collaborations between nursing and engineering to improve patient care, increase system efficiency, and to improve the quality of services (Zhou et al., 2021). Engineering tools are often employed in attempts to improve healthcare systems. The most common tools used are based on the Lean Six Sigma principles to decrease patient wait times (Mandahawi et al., 2010), reduce hospital stays (Heuvel et al., 2005), improve nursing workflow (Nino et al., 2020), and reduce medical errors (Dickson et al., 2009).

Other industrial engineering tools employed in the improvement of healthcare systems include those focused on examining processes, including process flow charts or process mapping. Studies using process mapping (often as part of a Lean Six Sigma approach) have provided benefits in the in-patient hospital setting, including reducing the length of hospital stay after surgical intervention (Improta et al., 2017) or improving patient flow through an emergency department (Eitel et al., 2010), In the outpatient setting, process mapping has been used to improve treatment algorithms for patients with chronic diseases, such as diabetes (Kutz et al., 2018). Similarly, value stream mapping identifies areas of waste in a system to improve process flow (Teichgräber and de Bucourt, 2012). In healthcare, it has been employed in various settings from identifying patients who are likely to be admitted to the hospital from the emergency department (King et al., 2006) to improving the handling of surgical specimens (Hung et al., 2015).

Models used in the healthcare setting can be effective in analyzing the workflow of personnel. One such tool is a time study, where an observer records the movements and duration of tasks (Lopetegui et al., 2014). Time studies have been used in healthcare to document the efficiency of nursing care (Yen et al., 2018), physician workflow (Young et al., XXXX), medication administration (de Hond et al., 2021), and patient wait times (Aburayya et al., 2020). A related model is queuing theory is used in healthcare systems as a way to estimate patient arrival procedures, time spent in accessing services, and characteristics of how they are moved through the line (Peter and Sivasamy, 2021). These principles have been applied to improve waiting time in outpatient settings (Peter and Sivasamy, 2021) and in emergency departments (Litvak et al., 2001 Nov). They can also be used to estimate the number of nurses required to deliver patient care (Yankovic and Green, 2011) and thus have practical implications in staffing and managing patient flow in an outpatient or clinic setting.

While a few reports of the use of industrial engineering tools applied to the COVID-19 pandemic have been published, they focus on managing hospital protocols during an uptick in COVID cases (Bhandari et al., 2021), on improving contact tracing measures to control the spread (Braune et al., 2021), or on estimating the amount of time a diagnostic test may take (Majedkan et al., 2020). Application of the Six Sigma principles to managing the COVID-19 pandemic suggest that a narrow focus on cost reduction renders hospitals unable to deal with large-scale crisis situations (Kuiper et al., 2022). However, to the best of the authors' knowledge, there is no published account of applying industrial engineering tools in the implementation of a mass vaccine walk-through clinic. To prevent surges in hospitalization, vaccinating the public is imperative.

3. Materials and methods

A multidisciplinary team of nurses, physicians, communications specialists, facilities managers, and pharmacists planned two clinics designed to administer the Pfizer-BioNTech COVID-19 vaccine three weeks apart in the winter of 2021. Engineering was invited to contribute to the design of the vaccination process. The main goal during the planning of this process was to eliminate vaccine waste and prevent unused doses. Due to the sensitivity of the vaccine to heat and light (Center for Disease Control and Prevention, 2021), precautions must be taken to ensure that waste is minimized. A Kanban system with a first-in-first-out (FIFO) lane was chosen to achieve this goal. The main idea of Kanban is that each workstation produces the expected component only when it is needed, and this is determined by a visual signal provided by a card or an empty box (Aguilar-Escobar et al., 2015). The Kanban creates a pull material flow that generates an efficient vaccine administration that contributes to reducing vaccine damage.

To reduce the possibility of vaccine waste, a FIFO lane was used to connect the vaccination stations and the vaccine preparation area. As Roser and Nakano (Roser and Nakano, 2015) indicate, in a FIFO lane, the first component that goes in the inventory is the first one to go out, and there is a maximum capacity of components in the lane. When the FIFO lane is full, the preceding processes stop. On the other hand, an empty FIFO will starve the succeeding process.

Naturalistic observation (Proctor and Van Zandt, 2018) in combination with interviews (Bryman and Cassell, 2006) of the nursing volunteers and staff were used to gain knowledge of each of the processes at both vaccination clinics, with the goal of improving processes for future clinics. The naturalistic observation allowed the researchers to discern the main purpose of each process. Researchers observed patient arrivals, how they moved through the clinic, who guided them, and what occurred at each phase of the process.

Time study analyses were performed to make informed decisions related to personnel capacity and the number of staff needed. Gangala, Modi (Gangala et al., 2017) define cycle time (CT) in a manufacturing environment as "the time taken to do any particular task from the starting point of one process on a particular machine until the end of the last process in the sequence for the production of a part" (p. 510). In the context of the vaccination event, the CT for each process was measured from the moment a patient arrived at a particular station until staff was ready to receive the next patient. The data gathered in the time study was the input to the queuing analysis.

A process flowchart was created with the information collected in the clinics. Flowcharts are a type of diagram that shows the work process or procedures of a system (Gulati and Vatanawood, 2019) and help to communicate concepts between persons by using graphical representations (Chapin, 2003). This graphical tool allows visualization of the different routes that patients and the vaccines follow. Another process mapping tool, value stream mapping (VSM), was also used for system design and analysis. VSM has proved successful in healthcare settings being that it provides insight into systems opportunities (Kovacevic et al., 2016). A VSM is a fundamental tool to deal with disconnection that can be present in healthcare settings (Henrique et al., 2016). VSM is considered an important improvement methodology that allows the visualization of the entire process, material, and information flow with a timeline (Seth et al., 2017). Even though VSM presents valuable information in a condensed graphical way, it has symbols and representations that are not part of common knowledge. Because of this, this study used a basic flow chart with the main process parameters to share the performed analysis with the interdisciplinary team that managed the vaccination clinics.

Queuing Theory (QT) was the core tool used to perform the analysis. QT has been used in manufacturing to evaluate how resources constrained settings to perform at different demand levels, making it an ideal fit to model patient flow in a healthcare setting (Hu et al., 2018). QT looks to calculate various queue characteristics like the mean waiting time, average queue length, and others (Hu et al., 2018). Although QT has been successfully used in various industrial settings, there have been limited examples in complex systems such as healthcare (Verma et al., 2020). Many authors use QT due to its simplicity in the calculation, minimal data needs, and the possibility to be done in spreadsheets (Cochran and Roche, 2009). The focus of this study was to estimate the time that patients spent in each process and during their entire visit at the vaccination clinic, the utilization of each station, and the patients' waiting times. The main goal of this study was to minimize (eliminate if possible) patients' waiting time and predict future clinic requirements and capacities.

4. Results

This section is divided into the first clinic design and assessment, the improvements made to the second clinic, and a comparison between the two of them. The following subsection focuses on the design and assessment of the first clinic.

4.1. First clinic

The first clinic layout, flow, and staff were based on estimates obtained from the health service's experience

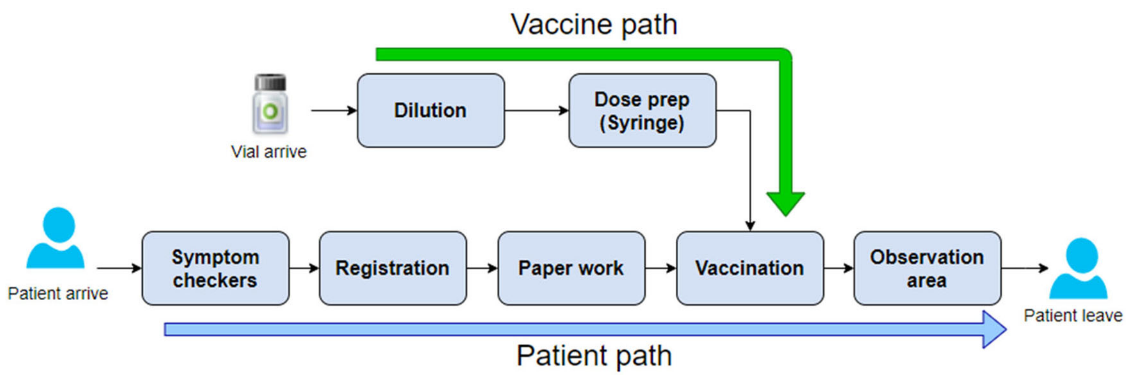


Figure 2. Process flowchart.

administering vaccines one at a time in an office clinic setting. An online scheduler was developed with 20 appointment slots every 10 minutes that allowed qualifying students, staff, and faculty to sign up for an appointment. The clinic was scheduled to start a 9:00 a.m. on a Saturday, concluding at 4:30 p.m. Patients were asked to arrive 10 minutes early to their appointment.

Since there was no historical data or previous COVID clinics to base the design on, it was decided to start the new design with patient flow at the center. The following subsection describes the steps taken to create a patient-centered design.

4.1.1. Patient flow

A process flowchart (Figure 2) and a VSM were created with data gathered from nursing personnel interviews. The flowchart depicts patients' paths during their vaccination and the direct and indirect processes needed to accomplish it.

As shown in Figure 2, patients were received by a group of six nursing students who performed a symptom check which included asking about current COVID-19 symptoms, recent contacts, and a temperature check. In addition, patients were asked to don a new surgical facemask to reduce the probability of COVID-19 contamination during the vaccination. Patients were then directed to registration.

Registration was staffed by six volunteers who confirmed patient identity, collected basic demographic information, and provided vaccine information paperwork. Once registered, patients were sent to a waiting area with 15 chairs, spaced out to maintain social distance.

In the waiting area, nursing students provided peer education to answer questions and address patient anxiety. When one of the 22 individual vaccine stations was available, the patient proceeded to a station staffed by a nursing or medical student.

At the vaccination stations, patients answered questions about allergies, previous adverse reactions to vaccinations, and other screening questions to ensure eligibility for receiving the vaccine. Additional education was provided at each station, and the vaccine was administered.

Patients then went to an observation area of 80 socially distanced chairs, where they were monitored by nursing and medicine students and faculty according to Pfizer-BioNTech COVID-19 protocols for 15–30 minutes. Finally, patients were discharged with information regarding scheduling their second dose.

Once the patient flow was designed, the research team focused on the vaccine preparation process, which was the other critical activity that happened in parallel as patients flowed through the initial steps of the process. The following subsection describes in detail the vaccine preparation process.

4.1.2. Vaccine preparation

The FIFO lane (Figure 3) was made of five lines of three baskets. All the baskets were covered with tin foil to protect the vaccines from the UV lights. Each basket was sent to a vaccination station with three doses inside. In other words, the FIFO lane controlled the production of doses in the vaccine preparation area.

Two runners were designated to distribute the vaccines among the vaccination stations. The addition of the runners played a key role in the efficiency of the vaccination preparation and administration of vaccines. The vaccinators indicated when they were out of vaccines with a red signal paddle, and the runners brought a full basket to their stations. The runners' job avoided the need of the vaccinator or the nurse working on dose preparation to replenish the vaccines.

To ensure a distraction-free environment, the vaccine preparation area was separated from public view. A pharmacist from the student health center oversaw nursing faculty who diluted and drew up doses. An industrial engineering faculty directed the timeline of this station. Pfizer-BioNTech COVID-19 vaccines are sent to providers in frozen vials that contain 5 to 6 doses. The vials need to be thawed in the refrigerator or at room temperature. Once a vial has been removed from the refrigerator, it must be diluted within 2 hours with 0.9% sodium chlorine (normal saline, preservative-free) following aseptic techniques (Center for Disease Control and Prevention, 2021). Doses of 0.3 mL of mixed vaccine were drawn into syringes. Unused vaccines must be discarded after 6 hours. Based on this specification, two processes were needed in the vaccine preparation area: the dilution of the vials and the dose preparation. Three identical stations were allocated to both processes. These two processes started an hour before the beginning of the clinic to ensure adequate doses in all the vaccination stations and

Figure 3. FIFO Lane.

Table 1. Time study data first clinic.

Process	Mean (minutes)	Standard deviation (minutes)
Symptom checking	0.694	0.226
Registration	1.268	0.372
Paperwork	4.925	1.472
Vaccination	5.367	1.870
Dilution	4.207	1.503
Dose prep	7.207	1.359

some vaccines in the FIFO lane. The planned head start was to have 120 vaccines ready at 9:00 am.

After designing the first clinic with patient flow and vaccine preparation at the center of the design, approval and buy-in were obtained from the health providers. The research team then assessed the clinic's performance and proposed opportunities for improvement. The following two subsections present the assessment of the first clinic and proposed changes for the second clinic.

4.1.3. First clinic assessment

The information gathered in the time studies is presented in Table 1. With this data and QT, all the process parameters were calculated. A spreadsheet was developed to run all the QT calculations. The implementation of this spreadsheet saved a good amount of time and allowed the formulation of future scenarios by modifying some of the parameters, including the patient's arrival rate, the number of stations in each process, utilization, and others.

Figure 4 summarizes the main information obtained in the queuing analysis. Based on this analysis, there was an installed capacity of 150 patients per hour, but the average utilization was around 46%. However, the dose preparation process was at 72% utilization which suggests that an increased capacity at this station could positively affect the capacity at other stations.

The results from the QT Analysis reflect what was observed at the first clinic. The vaccination stations were waiting for patients due to the low utilization, while the dose preparation stations were working continuously. In addition, there was patient congestion from a large number of patients waiting at the opening of the clinic. This situation created an overflow of patients that produced stress and a lack of control at the beginning. This study also noticed that patients arrived in groups generating waves of patients throughout the process. As a result, the different stations switched from being full to being almost empty in a matter of minutes. This situation continued during the day and could be attributed to the scheduling system.

The paperwork area was overloaded at the beginning of the clinic with not enough chairs. Additional chairs were placed in front of the vaccination stations. Patients filling paperwork, patients, and staff in the vaccination stations, people providing information to the patients, way runners, supervisors, and other staff were all in the same area, causing confusion and disorder. In addition, some of the patients doing paperwork did not receive information about the vaccine, slowing down the process at the vaccination administration station due to unanswered questions and anxieties.

4.1.4. Proposed changes for second clinic

After evaluating the first clinic, the industrial engineering team suggested changes to improve clinic capacity and efficiency. Changes proposed included clinic layout, staffing ratios, and alterations in the schedule. To alleviate the confusion and congestion at the registration area in the first clinic, this study moved the registration area to a hallway, which allowed patients to complete paperwork in an area separate from clinic operations (Figure 5).

Different layouts for the vaccine preparation area were proposed and evaluated with the team that managed the clinic (Figure 6). These new layouts aimed to decrease walking and have a reduced working area to promote process standardization. This standardization was intended to reduce cycle time while preserving or increasing the quality since it was observed in the first clinic that each station managed the process differently.

Several scenarios were generated with the QT spreadsheet. Figure 7 shows a portion of the QT spreadsheet, while Table 2 describes the queueing theory variables. The information required to run this tool is patient arrival rate, processing times (te), the standard deviation of the processing times (St Dev), and the number of stations. The rest of the calculations were performed by the QT spreadsheet.

With the proposed changes, this study estimated that the second clinic, held three weeks after the first, could administer 810 vaccinations in 4.5 hours, using an arrival time of 3 patients per minute. With this information, this study calculated the minimum staff and stations required for each process. Two main scenarios were presented: the first one was designed to guarantee less than 85% utilization at each station. This number was planned to allow the staff to work in a constant but not overloaded way and to be able to address natural variability experienced during the process. The second scenario was designed to limit the patients' waiting time in any given process to no more than 20 seconds ($CTq < 20$ seconds). This scenario was presented to take care of the concerns presented by the healthcare staff about patients waiting in line. Both scenarios are shown in Table 3.

Because the clinic offered an educational opportunity for nursing and medicine students, the clinic lead elected to continue with mostly the same number of people used in the first clinic. However, increases in clinic layout and placement of personnel, including increasing the number of

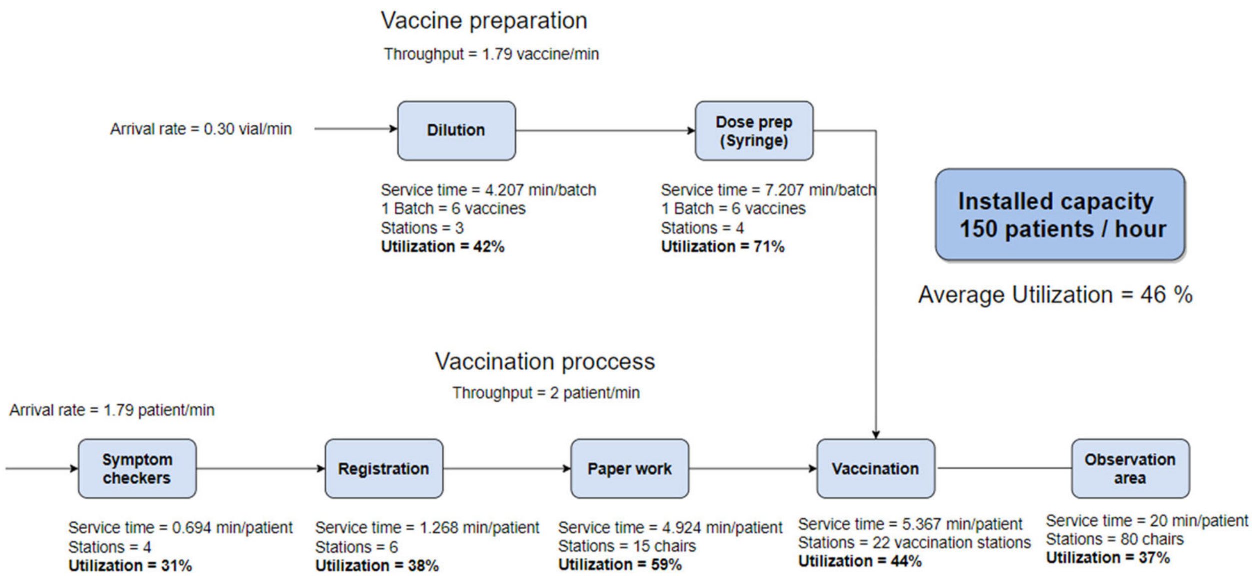


Figure 4. Flowchart with main parameters according to Queuing Theory Analysis.

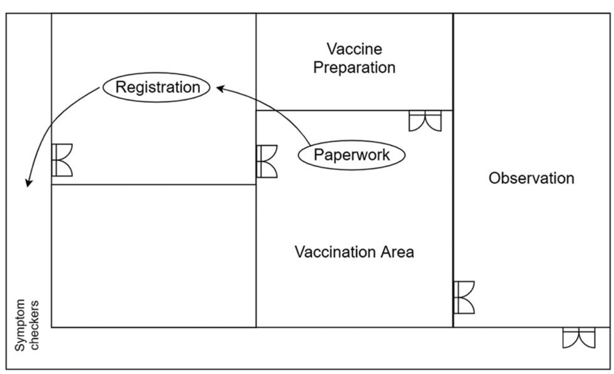


Figure 5. Proposed layout change.

stations for dose preparation and paperwork, allowed for a reduction in the duration of the clinic.

To reduce variability in the patients' admission it was requested that patients be instructed to show up at their appointment time rather than 10 minutes early. In addition, to alleviate the rush at the beginning of the day, it was arranged to start the second clinic with 20 patients for the first two appointment slots. The following section describes the design and assessment of the second clinic.

4.2. Second clinic

The second clinic was implemented three weeks following the first with the proposed changes to the layout and an increase in the scheduling from 20 patients per 10 minutes slots to 30 patients per 10 minutes slots. Registration was moved to the hallway as proposed, and the paperwork area was moved to the room where registration was previously located. Figure 8 presents the layout implemented in the second clinic; it also shows patients' path through the vaccination clinic.

4.2.1. Second clinic assessment

Despite the instructions to arrive at their appointment time, many patients still arrived 10 to 30 minutes early. During the clinic's first hours, the nurses in the symptom checking area asked patients to wait until their appointment time. This situation promoted a queue and increased the system's variability since patients in the queue were admitted at the time slots, creating patient batches entering the clinic. This situation was communicated to the clinic organizers, and the staff was instructed to allow patients upon arrival; variability was reduced and the queue disappeared. In addition, it was observed that patients arrived at the symptom checking area from different entry points creating some sense of disorder.

The registration staff implemented a visual signal that informed patients to proceed to their location. This implementation helped patients quickly identify the empty stations and distributed them more evenly among the stations. It was scheduled to receive 20 patients instead of 30 in the 2 first slots to reduce the rush at the beginning of the clinic. Nevertheless, It was observed that this ramp-up schedule was not necessary.

The separation of the paperwork from the vaccination area helped with the organization of the clinic and reduced the vaccination time by guaranteeing that every patient received the side effect and immunity information. The area contained 24 chairs with their respective social distancing. Every chair was disinfected after its use. A two-sided card (red/green) indicated if the chair was clean/available or needed to be sanitized. Student nurses trained as peer educators approached each patient, explained to them the vaccine side effects, and answered questions. The attention of the patients during the paperwork process reduced the requests for information in the vaccination stations.

The proposed layout was implemented in the vaccine preparation area (Figure 6D). This change reduced the physical space used and the walking distance. There were two main work areas instead of the three that the first clinic had. Two running nurses handled both stations instead of the previous three. In addition, one diluter was used for every two nurses doing dose preparation (a third diluter supported about half of the clinic). In the first clinic, there was one diluter for every dose preparation nurse, which

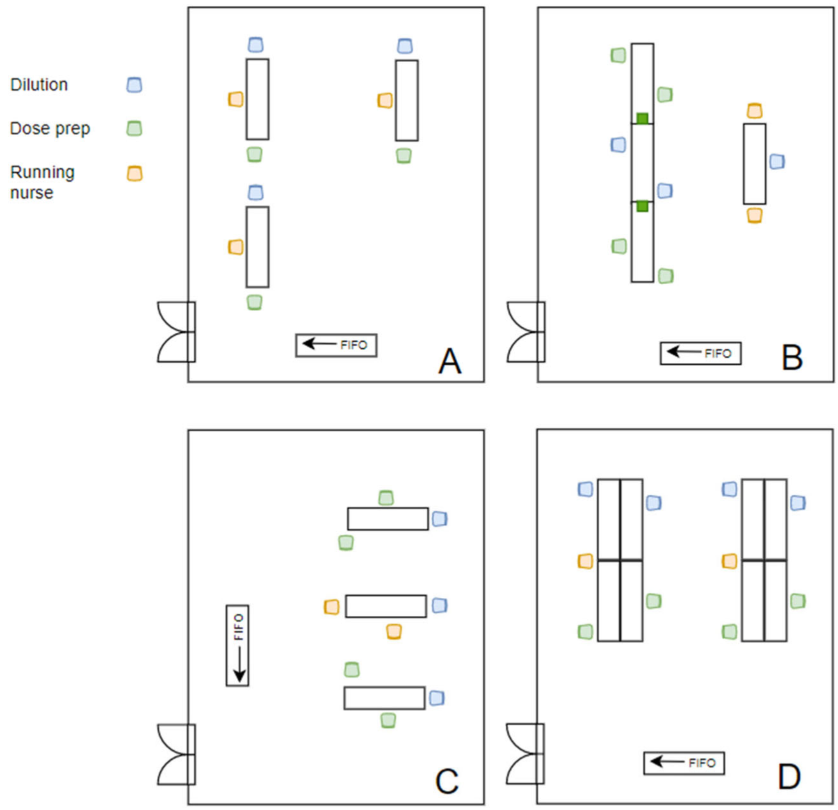
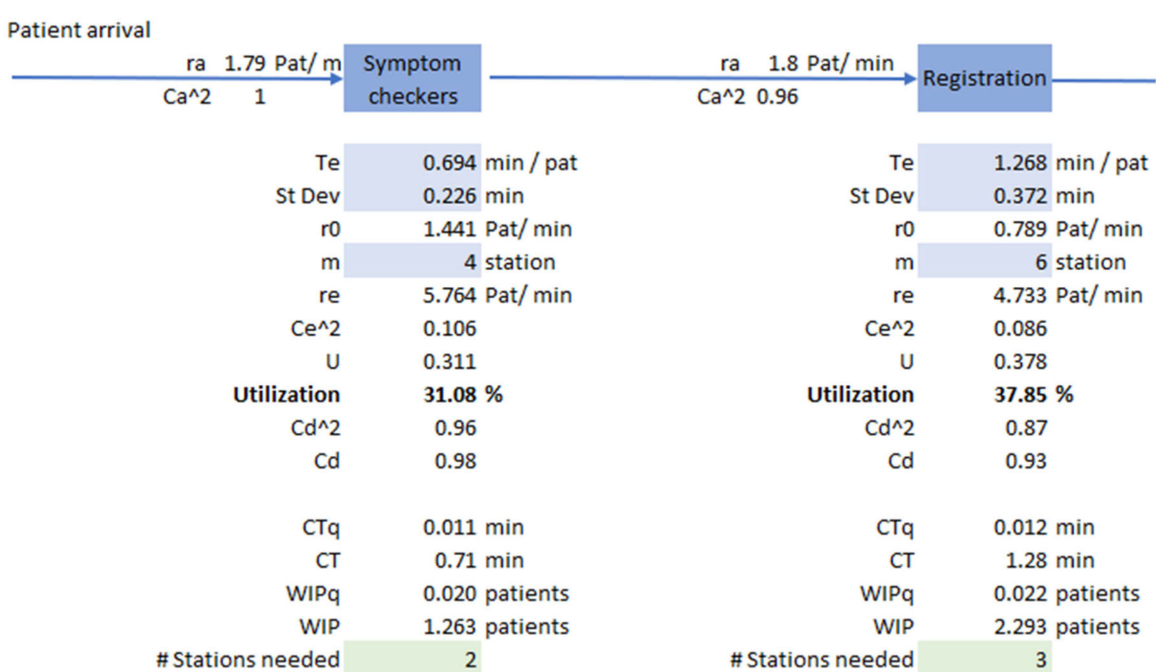


Figure 6. A – First clinic vaccine preparation process layout. B, C, D – Proposed layouts.



	Symptom checkers			Registration	
Te	0.694	min / pat	Te	1.268	min / pat
St Dev	0.226	min	St Dev	0.372	min
r0	1.441	Pat/ min	r0	0.789	Pat/ min
m	4	station	m	6	station
re	5.764	Pat/ min	re	4.733	Pat/ min
Ce^2	0.106		Ce^2	0.086	
U	0.311		U	0.378	
Utilization	**31.08**	**%**	**Utilization**	**37.85**	**%**
Cd^2	0.96		Cd^2	0.87	
Cd	0.98		Cd	0.93	
CTq	0.011	min	CTq	0.012	min
CT	0.71	min	CT	1.28	min
WIPq	0.020	patients	WIPq	0.022	patients
WIP	1.263	patients	WIP	2.293	patients
# Stations needed	2		# Stations needed	3	

Figure 7. A portion of the QT spreadsheet.

created 42% utilization for the dilution process and 72% for the dose preparation process. The following subsection compares the performance metrics between the clinics.

4.3. Comparison between both vaccination clinics

Table 4 presents the observed process cycle times (CT) and standard deviations (St dev) of the two clinics. Processing times decreased for all processes in the second clinic. For example, vaccination CT decreased by 17% and dilution CT decreased by 11%. Several factors may explain the reduction in processing time, including an improved layout that promoted better organization and supervision of every process. Additionally, because patients at the second clinic had already been through the process at the first clinic, the amount of time for education and paperwork was reduced due to patient

Table 2. Queuing theory (QT) variables description.

Process variable	Description
Te	Mean effective process time
St Dev	Standard deviation of the mean effective process time
r0	Natural processing rate for a station (patients/minute)
m	Number of stations in a process
re	Arrival rate of patients to a station (patients/ minute)
Ce	Coefficient of variation
U	Station Utilization - the fraction of time a station is not idle for lack of patients
Utilization	Station Utilization in percentage
Cd	Coefficient of Variation of departures (departure variability)
Cd○2	Squared Coefficient of Variation of departures (departure variability)
CT	Cycle time - the expected time spent at the workstation (waiting time plus process time)
CTq	The expected time spent waiting in the queue
WIP	The expected Work in Process (WIP) in the workstation. In other words, patients serviced in a workstation at a given moment
WIPq	The expected WIP level (patients) waiting in the queue
# Stations needed	Number of stations needed to service the rate if patients getting in the workstation

Table 3. Number of stations required for each scenario.

	1st clinic	Utilization < 85%	CTq < 20 seconds	2nd clinic
Patients	806	810	810	810
Total time (hours)	7.5	4.5	4.5	4.5
Arrival rate (Patient / min)	2	3	3	3
Dilution (stations)	3	3	3	3
Dose prep (stations)	3	5	4	4
Symptom checkers	6	3	3	4
Registration (stations)	6	5	5	6
Paperwork (stations)	15	18	18	24
Vaccination (stations)	22	19	19	22
Observation (stations)	80	71	67	84

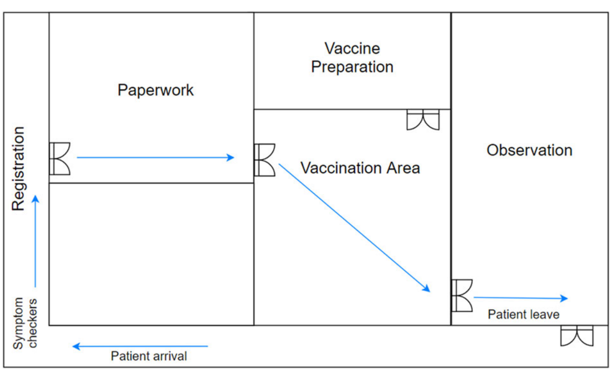


Figure 8. Second clinic layout.

Table 4. The first and the second clinic observed process parameters.

	First clinic		Second clinic		
Process	Average	SD	Average	SD	Units
Inter-arrival	Not observed		2.95	0.37	patient/min
Symptom checking	0.69	0.23	0.37	0.16	min/patient
Registration	1.27	0.37	0.82	0.59	min/patient
Paperwork	4.92	1.47	3.65	0.85	min/patient
Vaccination	5.37	1.87	4.45	1.84	min/patient
Dilution	4.21	1.50	3.31	1.73	min/patient
Dose preparation	7.21	1.36	6.86	1.52	min/patient
Observation	Not observed		47.68	6.71	patients/observation

familiarity. Moreover, many of the staff and students worked in both clinics, reducing the learning curve. At the same time, owing to increased patient throughput, utilizations generally increased, as shown in Table 5. For example, vaccination utilization increased 13 percentage points and dilution utilization increased 10 percentage points even with the same number of stations. However, some areas experienced decreased utilization owing to shorter cycle times. It is important to note that both clinics were staffed by volunteers, and there was a wide variety of performances among each participant. For example, one nurse in dilution had a consistent CT that was half of the other two nurses' CTs.

Table 5 also presents a proposed scenario in which patient throughput is increased to attain an 80% utilization of the observation area. This study estimates the maximum arrival rate at just over four patients per minute. The required number of the stations for the other processes was calculated assuming this arrival rate and an 80% utilization. The proposed scenario can increase the average utilization to 74% with a capacity of 245 patients/hour versus 210 patients/hour of the second clinic. This scenario is proposed to increase the efficiency of future clinics.

The following subsection proposes further opportunities for improvement and suggestions for future clinics.

5. Proposed changes for future clinics

To reduce potential disorder and confusion of many different patients moving in different directions, this study recommends that the symptom checkers inform/ask the patients to have their ID and vaccination card ready. It is also recommended to change the entrance layout to limit the patient access to one direction and mark the floor where the line starts and the safety separation from person to person. Patient entry should be controlled by the symptom checkers based on Registration availability such that Registration sets the pace of patient access.

Figure 9(a) shows the layout used during the second clinic in the registration area. The blue lines represent the different entrances from where a patient can arrive. Figure 9(b) depicts the demarcation that can be used to limit the

Table 5. The first clinic, the second clinic, and the proposed scenario (Observation area at 80% utilization) number of stations and utilization.

	First clinic		Second clinic		Observation 80%	
Process	# Stations	Utilization	# Stations	Utilization	# Stations	Utilization
Symptom Checking	4	31%	4	27%	2	76%
Registration	6	38%	6	39%	5	67%
Paperwork	15	59%	24	44%	24	62%
Vaccination	22	44%	22	58%	22	83%
Dilution	3	42%	3	53%	3	75%
Dose Prep	3	72%	4	82%	6	78%
Observation	80	37%	84	56%	84	80%
Installed capacity	150 Patients/hour		210 Patients/hour		245 Patients/hour	

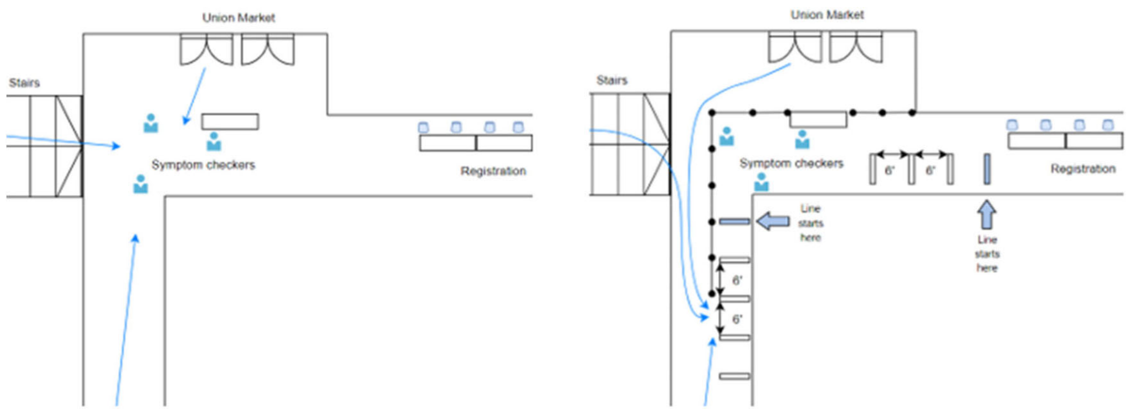


Figure 9. Registration layout second clinic (a). Registration layout proposed (b).

Figure 10. Vaccination Area for the Second Clinic.

Figure 11. Vaccination Stations for the Second Clinic.

access to the clinic and marks that can be placed on the floor to show the start of the line and the distance between patients. During both clinics, staff and volunteers were entering from this area. This situation generated confusion on registration, symptom checkers, and patients waiting to access. It was recommended for future clinics to provide separate access for the staff and volunteers.

It was observed that most of the patients removed their coats when the nurse was ready to administrate the vaccine, no matter how long they had been in the vaccination station. For future events, the staff in the paperwork area should inform/ask the patients to remove their coats before or when they sit in the vaccination area to accelerate the process.

The visibility of the stations in the vaccination area could be improved. Figures 10 and 11 show the Vaccination Area and the Vaccination Stations created for the second clinic.

It was observed that some stations received more patients since they were more visible to patients and the staff at the entrance. This study proposes that future clinics change the vaccination station's layout to promote better visualization of all the stations (Figure 12a). This could make it easier to identify the empty stations and direct a patient to a given one. In addition, the vaccination station numbers were too big and blocked the visual of the rest of the stations. Also, the number on the sign is located at the same height as the vaccinator's head and can be hard to see. This study recommends making the signs transparent, containing only the station number to improve the visualization of the stations on the back, and the number must be located above the head of the vaccinators.

Every vaccination station had two signals. One red indicated that the station ran out of vaccines, and a green one indicated the availability of the vaccination station (they can be seen in Figure 11). It was observed that the red signal

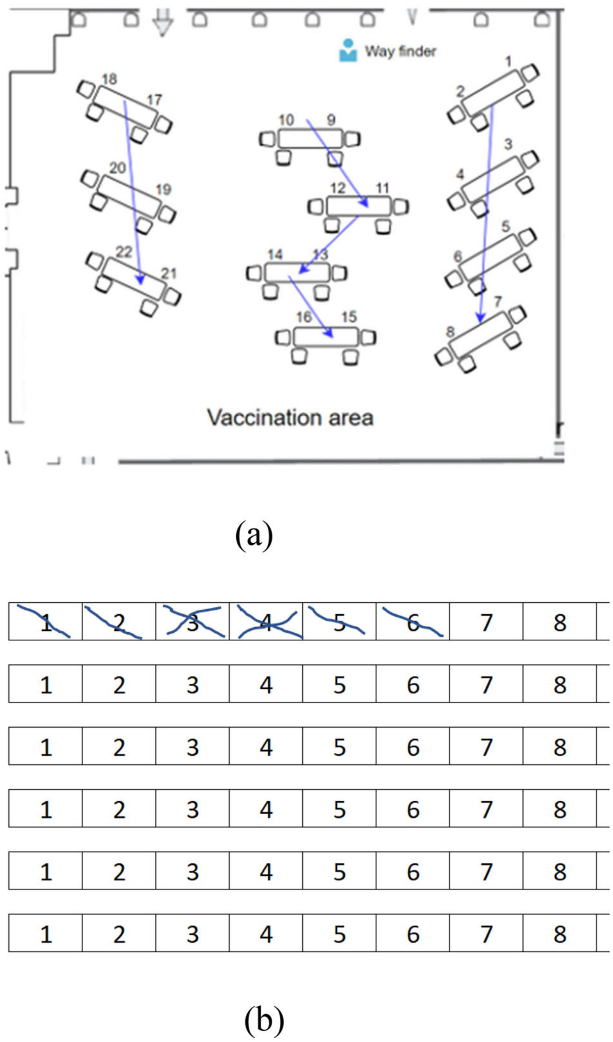


Figure 12. Vaccination stations proposed layout (a). Sheet for the recording of the vaccination station assignment (b).

was effective and used properly. Nevertheless, the green signal was not as effective; more training to the vaccinators can promote the use of this signal. This study also noticed two nurses would stand up when cleaning the station and sit down when they were ready for the next patient. This study recommends using this visual technique as an alternative to the green sign.

In addition, for future clinics, this study recommends implementing a cyclical assignation method for the vaccination stations. A sheet can be provided to the way-finders to keep track of the stations being assigned (Figure 12b). Therefore, the workload of the vaccination stations can be evenly distributed among the stations. On the right side of Figure 12(a), the blue lines indicate how would be the flow of the assignation of stations. This pattern can generate a pace at which the process would flow, and it will distribute the workload more evenly.

It is important to highlight that the area that generated more concern for the healthcare staff was the observation area. They had the perception that the area's capacity was not big enough and that they would run out of space at any given moment. Nevertheless, it was estimated that the utilization on the first clinic was around 37%, and the observations of the second clinic showed utilization of 56% (During the first clinic, the observation area received less than two patients/minute and the during the second clinic, less than three patients/minute).

Another recommendation is to collect patient data such as previous vaccines, allergies, and other eligibility data when a patient schedules an appointment (Virginia Department of Health V, 2021). While patients at the clinics received education on the vaccines and potential side effects during the registration paperwork process, future vaccination clinics may not require such detailed patient education. Therefore, this study recommends that future clinics capture this information through a pre-registration process that can be done in an online registration portal (Asgary et al., 2020). This will also reduce the need to manually enter data from paper records.

Observations made on the second clinic vaccination process included: the cleaning process in the vaccination station was irregular. Some vaccinators completed the vaccination and then put the syringe on the table while others discarded the syringe immediately after administration. Training can help standardize these processes and guarantee that safety standards are met. The tray used in the vaccination stations seems to be too large for how it was used and reduced the space available for the vaccinator to do the paperwork. This study recommends the use of alcohol dispensing bottles instead of alcohol prep pads to reduce waste and service time. In addition, as there were two stations at each table, this study recommends using one vaccine trash in the middle of both stations to reduce clutter in the stations. Table 6 presents the top recommendations proposed for future vaccination clinics.

6. Discussion

This study presents observations and analyses of two mass vaccination clinics at a university campus. The analyses resulted in improved efficiency and decreased patient waiting times when comparing the first and the second clinic. Using an interdisciplinary approach, this study demonstrates the value of industrial engineering tools in the planning and implementation of a large-scale vaccination effort.

Due to the need to quickly administer large numbers of vaccinations, many cities design drive-through clinics where patients remain in their cars throughout the vaccination process. Asgary, Najafabadi (Asgary et al., 2020) explained that drive-through mass vaccination has several advantages and disadvantages. Some of the advantages are low disease transmission risk (people with the virus have fewer opportunities to pass on the virus to others), low exposure to the virus (compared to closed settings), and large throughput. Some of the difficulties of a drive-through clinic are weather conditions, the need for considerable logistical planning, the need for large and suitable space, negative environmental impact from idling vehicle emissions, and accessibility issues for those without cars.

Drive-through clinics can vaccinate more people in a shorter time while keeping the transmission risk low

Table 6. Top ten recommendations.

1	Assign appointments for 5-minute blocks to reduce patient arrival variability.
2	Establish a patient point of pull at the beginning of the process so that Registration pulls the next patient; patients then follow a continuous flow from there until the end.
3	Ask patients to have all their information readily available.
4	Ask patients to remove jackets or coats before entering the vaccination area.
5	Assign stations in a cyclic fashion so that the server utilizations are evenly distributed and all volunteers get the same amount of practice.
6	Organize the vaccination tables in a way that maximizes visibility.
7	Use see-through signboards with only the station number written on them.
8	Ask patients to arrive no earlier or later than 5 minutes from their appointment time.
9	Ask volunteers to stand up when cleaning the stations and sit down once they are ready for the next patient (a visual way to show when they are ready).
10	Implement a FIFO lane system for vaccine preparation.

(Asgary et al., 2020). According to van de Kracht and Heragu (2021), patients prefer the convenience of waiting in their cars over walk-in clinics. They observed that people preferred to wait in a car line than to go to a walk-in clinic with an almost zero-minute waiting time. However, the type and scale of the space needed, the more demanding logistics, and the weather limitation make the drive-through clinics unsuitable for every location (Asgary et al., 2020). In this condition, a traditional clinic must find procedures to reduce the risk of infection while providing high throughput. Though, to lower the risk of transmission, more precautions and procedures are necessary, with more resources needed and more waste compared to a drive-through clinic (Kim, 2020).

These benefits and difficulties were considered during the clinic planning of the vaccine clinics this study presents here. Weather conditions are a key factor in Montana and both clinics happened in winter when conditions can be harsh. This study was able to take advantage of the relatively closed university community where most patients live on or near campus. This study also did not have a suitable space for a drive-through clinic. All these factors played an important role in choosing a walk-through clinic instead of a drive-through. Several measures were implemented to decrease the transmission risk, among those were: temperature checking before the admission to the clinic, the use of face masks throughout the clinic, requiring patients to replace their face mask with a new one when they get to the check-in process, sanitization of every surface after each patient was serviced, the use of eye protection for staff (face covering or glasses), and social distancing.

It is relevant to highlight that in both of the clinics this study implemented, no patients waited in a queue through most of the clinic, as opposed to other clinics where there was a queue before registration and throughout the vaccination clinics. Asgary et al. (2020) ran several drive-through clinics simulations with different scenarios changing arrival rates and number of staff. They found that an increase on the arrival rate will increases the number of patients being services and the average waiting time. The vaccination clinic observed by van de Kracht and Heragu (2021) did not have a scheduling system. They noticed cars wating for the vaccination clinic three hours before the clinic's opening. The lack of a scheduling system and staffing bellow their recommendation cloud contribute to the observation of queues in this vaccination clinic. In addition, Asgary et al. (2020) and van de Kracht and Heragu (2021) simulations evaluated different scenarios that were trying to obtain the biggest possible throughput. Then, the absence of queue in both of the clinics observed in this study could be explained by the number of patients scheduled per hour. The arrival rate promoted an average utilization close to 50% in both clinics observed in this study. It is important to consider all these scenarios since the value of mass vaccination increases immunity and decreases morbidity (Kim, 2020), therefore the need to increase the efficiency of this type of clinic to vaccinate the greatest quantity of patients in each one while keeping the waiting time to the minimum. To this end, the main objectives to be considered when planning a vaccination clinic could be to minimize staff numbers, maximize throughput, and minimize patients' waiting time.

While many people get their vaccines at their primary care provider's offices, the COVID-19 vaccine presents unique challenges to this approach. First, the specifications of the vaccine preparation and storage make it difficult for providers to maintain doses at the required temperatures. Second, many people in the United States lack a primary care provider or health insurance, creating the potential for a large number of persons to lack access to the vaccine. Third, many primary care providers' offices do not have the additional personnel or space capacity required to administer the COVID-19 vaccine (Goralnick et al., 2021). Therefore, mass vaccination clinics that are offered at a convenient place and location to patients while optimizing the efficiency of distribution are necessary for control of the pandemic.

The first clinic was designed according to interviews with nursing volunteers and staff. Engineering students and faculty collected performance measures of the first clinic and used Queuing Theory (QT) to improve the second clinic. The second clinic resulted in significant efficiency improvement over the first one.

The clinics' success was due to three main factors. The first factor was the team's interprofessional nature, which incorporated nurses and engineers aligned for one common objective: to vaccinate as many patients as possible with the least amount of waiting time for patients. Indeed, clinics that rely on the expertise of professionals outside of the healthcare field tend to have higher levels of success (Goralnick et al., 2021). The second factor was the clinics' technical design using queuing theory and lean principles. These principles allowed us to implement quality improvement recommendations based on data, which were well-received by the clinic planners, directors, and volunteers. Finally, the team adopted a continuous improvement mindset that was spread through all those who worked at the clinic. This provided opportunities for improvement between the first and second clinics and provides the potential for improvement at subsequent clinics.

7. Conclusions

This article presents the design and improvement process of a COVID-19 Vaccination clinic. Using a multidisciplinary approach, this study was successful in fully vaccinating 776 university staff, students, and faculty in a few hours. This study shares a success story of an interprofessional effort between nurses and engineers to design a patient-centered vaccination clinic with quality improvement measures implemented by engineering.

Innovative approaches designed to increase vaccination rates are essential in controlling the pandemic caused by the SARS-CoV-2 virus. Mass vaccination clinics that leverage existing resources, combine the expertise of multiple disciplines, and use available tools for quality improvement relieve some of the pressure on local health departments who are unable to keep up with the demand for vaccines. Lessons presented in this article can help others implement similar efforts to control this pandemic and to plan for future potential situations requiring the swift and efficient vaccination of many people.

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Consent and approval

This study was exempt from the IRB review as it falls under the category of: "Research involving the use of educational tests (cognitive, diagnostic, aptitude, achievement), survey procedures, interview procedures, or observation of public behavior unless: (i) information obtained is recorded in such a manner that human subjects can be identified, directly or through identifiers linked to the subjects; and (ii) any disclosure of the human subjects' responses outside the research could reasonably place the subjects at risk of criminal or civil liability or be damaging to the subjects' financial standing, employability, or reputation." The investigators only observed and recorded time data; no personal identifiers or other data types were recorded.

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