Assessing Registration and Screening Technologies for Efficient Mass Vaccination and Public Health Monitoring

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Abstract: Vaccine data collection during mass vaccination campaigns is a difficult task due to the lack of a unified system; yet, accurate and timely documentation is essential for monitoring efficacy and adverse effects. In this study, we evaluate five electronic registration and screening technologies to test for how quickly immunizations could be delivered and recorded given the different physical and cyber requirements of the different technologies. Using time–motion studies and service data analysis from influenza vaccination campaigns, we demonstrate operations and tracking efficiency with throughput improvements of 16% to 45%. Based on these findings, we propose a prototypical unified system for dispensing, monitoring, and assessment that is interoperable with existing immunization and electronic medical record systems. This paper highlights the potential of electronic technologies to significantly enhance processes in vaccine administration and data management. With the resource-constrained public health setting, the design emphasizes on minimally-enhanced technology requirements to achieve seamless data and process management and improved operations efficiencies. The system is flexible, scalable, and adaptable for different types of medical countermeasures.

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1 INTRODUCTION

During a pandemic or other vaccine-preventable disease outbreak, it is essential to vaccinate as many people as quickly as possible. Delaying vaccination can lead to widespread illness and loss of lives and serious burdens to healthcare systems (https://www.cdc.gov/globalimmunization/fast-facts/index.html; Lee, E. K., et al., 2015; Miller, M. A., et al., 2008; Tisoncik, J. R., et al. 2009; Wein, L. M., et al., 2003).

There has been active research in advancing operations and logistics to maximize vaccination and mass dispensing throughput under time and resource constraints (Cot, C., et al., 2021; Danzon, P. M., et al. 2005; Ferreira, L. S., et al., 2022; Hupert, N., et al., 2002; Lee, E. K., et al., 2006a; Lee, E. K., et al., 2006b; Prieto Curiel, R., et al., 2021; Wagner, C. E., et al., 2022; Washington, M. L., 2009). To establish real-time, locale-specific and scalable capabilities for public health decision-making, working with the Centers for Disease Control and Prevention (CDC), Lee et al. developed RealOpt©, a large-scale information decision support system that seamlessly integrates a disease modeling engine, a simulation module and optimization technology into a unified all-purpose response system. RealOpt allows real-time analysis to maximize operations efficiency, optimize staffing and resource allocation, analyze layout design, and mitigate disease spread (Lee, E. K., et al., 2010; Lee, E. K., et al., 2013; Lee, E. K., et al., 2017; Lee, E. K., et al., 2021; Kwong, J. C., et al., 2010).

The recent COVID-19 pandemic caused by the SARS-Cov-2 virus underscores the importance of the rapid development of effective medical countermeasures. Through Operation Warp Speed, a partnership between the Departments of Health and Human Services and Defense that aimed to help accelerate vaccine development, the first COVID-19 vaccine was distributed to the public by December

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2020. Still, the United States reported over 111 million cases, resulting in over 1.2 million deaths. Worldwide, over 7 million died from the disease.

Despite the vaccine development success, the initial rollout of COVID-19 vaccines in the U.S. was chaotic. There were supply shortages, distribution issues, confusion over eligibility and a serious lack of documentation. Many states struggled to set up efficient appointment systems. Each state had its own vaccine sign-up website, often run by the state health department or local county health offices. Some of these systems crashed due to high demand. Hospital and healthcare provider systems used their own patient portals for scheduling vaccine appointments, and major pharmacy chains set up scheduling systems too. With no centralized booking system, people had to check different sites — state portals, pharmacy chains, hospitals, and mass vaccination sites — hoping to find an available slot. Many people signed up on multiple websites, leading to wasted appointment slots. The high traffic overwhelmed and crashed scheduling systems, causing long wait times, and raised access issues for seniors and underserved communities. At the vaccination sites, clients were given a paper card with their name, the vaccination date and type, and a short note regarding where to report an adverse effect.

Currently, there is no unified or integrated system for effective vaccine data collection. Unless steps are taken, inefficiencies such as these could occur during a future emergency. Information regarding uptake is critical for monitoring adverse effects and vaccine efficacy. This is especially important when a newly developed vaccine is being dispensed or when multiple doses of vaccine are needed per person. These data can provide valuable information during an emergency and serve multiple purposes for public health planning and research (Kwong, J. C., et al. 2010).

In this paper, we describe and analyze five types of electronic technologies used for registration and screenings in vaccination clinics. We contrast their functionalities, usability and operations performance based on time-motion studies and service data collected during actual influenza vaccination campaigns ("Campbell mass dispensing flu clinic" CDC Report, n.d.; "Platte mass dispensing flu clinic" CDC Report, n.d.; "Denver public health closed POD for flu vaccination" CDC Report, n.d.; "Philadelphia department of public health Closed POD for flu Vaccination" CDC Report, n.d.; "CDC closed POD for flu vaccination" CDC Report, n.d.) (Section 3.1). We evaluate their dispensing performance under an optimal dispensing clinic design (Section 3.2). Our analysis shows that these electronic technologies can improve operations and tracking efficiency with 16% to 45% increase in overall throughput. Based on our assessment and analyses, we propose a unified prototypical registration and screening system with integrated information flow for vaccination that can be used for dispensing, monitoring and assessment (Section 3.3). The system is interoperable to the local Immunization Information system and electronic medical record systems. The design is flexible and adaptable for different types of medical countermeasures and can be used by a broad spectrum of regional public health departments.

2 METHODS AND DESIGN

This paper presents the first study using time-motion techniques to scrutinize point-of-dispensing operations by analyzing five different (inexpensive and practical) electronic technologies for data input and collection. RealOpt, an informatics-decision-support enterprise system used by over 14,000 public health emergency response users across 50 states, is used to simulate and optimize the dispensing operations to contrast the performance of each technology. Through hundreds of time-motion studies, it has proven that RealOpt is able to predict the performance of the actual system throughput well (within 95% to 105%). Hence, the analysis herein should offer useful foundations and insights into the potential improvement that can be achieved by the electronic data collection technologies. Figure 1 briefly layouts the schematic method and design of our study.

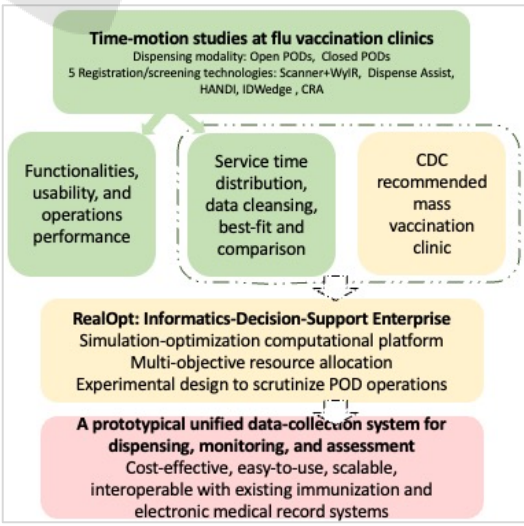

Figure 1: A schematic layout of the method and design.

2.1 Technologies for Registration and Screening

A variety of methods have been used for client registration and screening (Nanji, K. C., et al., 2009; Pereira, J. A., et al., 2012). Based on a catalogue of available electronic technologies developed by CDC (Oak Ridge Associated University, 2016) and several hundreds of time-motion studies on mass vaccination, five representative technologies were investigated, including barcode, mobile and magnetic stripe scanners and web-based software modules. They were chosen by public health leaders as candidates and were supported by comparison results (done independently) to be practical and cost-effective in actual settings.

At the point-of-dispensing sites, through time-motion study, we recorded the completion of each task by observing and documenting staff members performing their duties and interacting with clients. Using RealOpt (Lee, E. K., et al., 2010; Lee, E. K., et al., 2013; Lee, E. K., et al., 2017; Lee, E. K., et al., 2021; Kwong, J. C., et al., 2010), a CDC-recommended vaccination clinic is designed and used to analyze the vaccination throughput performance and contrast the strengths and limitations of each technology. Table 1 summarizes the five data collection technologies and its usage information.

Table 1: Summary of the five studied sites.

Gillette, Wyoming	Platte City, Missouri	Denver, Colorado	Philadelphia, PA	Atlanta, Georgia
Vaccination period				
7am–7pm	10am–2pm	12pm–4pm	8am–1pm	8:30am–3pm
POD location				
Public health facility	Middle school	Public health facility	Police building	State facility
Dispensing module				
Walk-in open POD for all residents	Drive-through and walk-in open POD for adult residents (18 years or older)	Closed POD for employees with valid badges	Closed POD for first responders and their family member	Closed POD for site employee
Data collection technology				
Barcode scanner and Wyoming's Immunization Registry (WyIR)	Dispense Assist	Handheld Automated Notification for Drugs and Immunizations (HANDI)	IDWedge & AutoFill	Countermeasure and Response Administration (CRA)

We briefly describe each technology below.

2.1.1 Barcode Scanner Linked to an Immunization Registry

Barcode scanner linked to an Immunization Registry was used at the Wyoming event. A Honeywell 4600G Barcode scanner was used to scan the linear and 2D barcodes on the Wyoming Drivers' licenses. The scanned information includes name, address, date of birth, and gender. This information is populated onto the Wyoming's Immunization Registry (WyIR). If the scanning is successful, the system searches for existing information linked to the driver's license. For those without valid licenses (new licenses or children) or if the scanning failed, the demographic information is input manually. Vaccine information is also entered manually into the registry.

The entire setup is rather straightforward. Scanning itself does not require an internet connection. The scanners can be connected to the computer via USB ports. A software program is used to sync the barcode scanner to WyIR, allowing the scanned data to be populated onto WyIR in real-time.

WyIR is an Immunization Information System (IIS) and within it there is a password-protected mass vaccination module, among other modules. Lot numbers and other vaccination data (vaccinators, manufacturers, clinic dates, etc.) can be input into WyIR prior to the POD operations. Internet connection is required to use the WyIR.

There are two levels of access within WyIR: entry access and full access. Vaccine administrators login via entry access to view data, conduct queries on clients, and perform data entry. Full access allows inventory management, and more complex tasks. Vaccine can also be ordered from WyIR.

The barcode scanner-WyIR setup allows direct import of client demographic information, reduces data entry of client information after the dispensing event, hence saving time and reducing potential errors. The state health department provides technical assistance for WyIR through email or telephone.

2.1.2 Dispense Assist

Dispense Assist is an online tool developed by the Johnson County Department of Health and Environment in Kansas (https://www.kshcc.com/ dispense-assist.html). It is used by multiple county health departments across the nation. Dispense Assist collects both client information (name, address, phone number, date of birth, and gender) and vaccine information (the vaccine type (CVX code), manufacturer (MVX code), expiration date, injection site, route of administration, provider and type and publication date).

Clients fill out the registration form either through a web browser or a mobile app. The questions cover demographic information and medical screenings. The medical screening determines which medication or treatment the client is eligible for. One family member can fill out forms for an entire family. The address input in the first form can be saved as a default address and pre-populated to subsequent forms. Multiple vouchers can be saved on one device.

Dispense Assist interfaces with barcode scanners (Motorola Symbol) and printers. The system generates QR codes that can be scanned directly from the mobile app. Vouchers can be printed or saved to a mobile device. Alternately, it can be sent to an email account set up by the clinic and printed when the client arrives at the POD. Scanning the QR code adds an entry to an Excel spreadsheet. This spreadsheet can later be exported to electronic medical records (EMRs) after being reformatted to fit the EMR's specifications.

Real time usage requires an Internet connection, a barcode scanner that can read QR codes ($80) and a USB connection between the scanner and a laptop. Once the QR code is scanned, the corresponding coded data will pop up on the laptop screen for POD staff to review. A server that can handle thousands of simultaneous hits is required. Dispense Assist can also be downloaded and used off-line. Staff can record vaccination information on the form and scan them into the database later. The system has Spanish translation capability through a web-link.

2.1.3 Handheld Automated Notification for Drugs and Immunizations (HANDI)

Handheld Automated Notification for Drugs and Immunizations (HANDI) is a mobile device application developed by Denver Public Health to improve data capture and efficiently administer immunizations for closed POD operations. The system consists of two parts: a backend database system and a front-end handheld device (iPod Touch and scanner). It uses a three-step process to collect data: (a) client pre-registration; (b) medical contraindication; and (c) vaccination information.

Clients register online through a website setup via HANDI. Once registered, the client’s employee ID is scanned using a scanner attached to the mobile device. The scanner reads the magnetic stripe on the ID. If the identification card is not readable or available, the information will be manually entered into the device. Otherwise, registered information of the client will be loaded for verification. Any additional information can be updated at this point. Once scanned into the system, it helps to monitor contraindications and track immunizations, and treatment plans administered during mass intervention events.

At the POD vaccination station, the nurses scan the information to identify the vaccinator, lot number, dosage and site name before administering the vaccine. The information on the mobile device is sent to the server after the POD is closed. The server bundles the data from each station and the complete data set is securely transferred to a designated database or registry (e.g., a state immunization registry). The application server stores the information in a SQL-server database and can export the data to other designated formats. For example, HANDI can convert the data to HL7 and send its records to any system that accepts HL7.

2.1.4 IDWedge & AutoFill IDWEdge

IDWedge & AutoFill IDWedge (Tokenworks) supports scanning of drivers’ licenses and military IDs from all U.S. states and all Canadian provinces. Used in conjunction with IDWedge, AutoFill is a Windows application that can be configured to automatically populate forms with information from scanned IDs. Prior to the clinic, a simple user defined formula is generated to specify the field order (first, last, etc.) and the keystrokes (tab, arrow up, enter) which are sent to a database.

At the dispensing site, staff swipe drivers’ licenses or state identification cards using IDWedge to collect client identification information. The data prefills into the customized Microsoft Access database in real time. The licenses scanned and their vaccination records are automatically updated. For children who do not have valid drivers’ licenses, their parents’ licenses are scanned, and the children’s personal information is input manually.

AutoFill is configured to automatically populate the Access form with the client data. The Access form also contains checkboxes for screening questions (manually entered by the data collectors) and vaccination information. The manufacturer, lot number, and date of administration are copied for all clients, while the injection site and provider are manually entered for each vaccination. After the event, the Access databases from each computer are downloaded, merged, and manually cleaned up, removing duplicates and populating missing fields. The final merged database is uploaded onto the IIS.

2.1.5 The Countermeasure and Response Administration (CRA)

The Countermeasure and Response Administration (CRA) is a web-based application developed by CDC contractors. Prior to the event, staff customize the form manually and select various fields to record. The only client ID collected is the employee ID number. Information including the vaccine type (CVX code), manufacturer (MVX code), dose number, expiration date, dose volume and unit, injection site, lot number, date of administration, and provider can be recorded. In addition, the VIS type and publication date are collected with the latter given to the client.

At the vaccination event reported herein, four fields were selected: employee ID number, date of administration, vaccine lot number, and injection site. The date of administration is pre-populated with the event date and the vaccine lot number is pre-populated with the lot number of the last vaccine scanned. During the event, when a new batch of vaccine is used, the staff scans the vaccine. The vaccinator only records manually two fields, the employee ID number and the injection site.

CRA can work as a stand-alone system to support jurisdictional operations if an Internet connection is not available. Aggregate data and reports can be produced for individual clinics and client populations. CRA can also create recall reminders for future doses that clients may need. These reminders can be sent to both providers and clients. After the event, all recorded information is exported to a single file and sent to the employer's electronic medical record.

2.2 Analyzing Operational Performance via a Common Vaccination Clinic Layout

To gauge the operational performance, we derive experiments to analyze the importance of each technological component with respect to POD operations and the overall performance. Figure 2 shows a medical dispensing clinic process flow recommended by CDC for mass medical countermeasure dispensing and commonly used by public health sites.

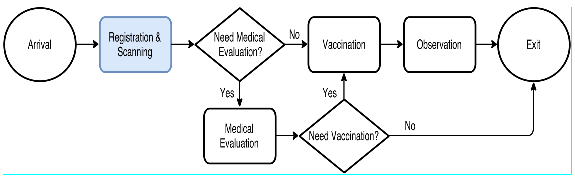

Figure 2: A medical dispensing clinic used for mass vaccination.

2.3 Simulation-Optimization Computational Platform and Multi-Objective Resource Allocation

2.3.1 The Simulation-Optimization Computational Platform

RealOpt is designed for responding to emergencies, including biological, chemical, radiological, nuclear incidents and natural disasters. Figure 3 shows an overview of RealOpt-POD for biological defense and the analytic methodologies that are embedded in it. In the frontend, users interact with the system through the multi-panel, cognitive-analytics interface. In the backend, the simulation-optimization module consists of the large-scale simulator and the rapid optimizer. The solution engine works by running optimization and simulation in an interlacing manner. The system has been used for mass vaccination (and diagnostic testing) events including seasonal flu, Ebola, Hepatitis, and COVID-19. It has been used for fire, flood and hurricane responses (for setting up shelters, food/medical/supply distribution sites, and command-control logistics etc.), Haiti earthquake emergency response relief, Japan Fukushima radiological response (rapid screening and decontamination, food/shelter, supplies distributions), hurricane Sandy response, optimizing Ebola treatment center operations, and predicting and containing Zika disease spread. The system has also been used by numerous hospitals/clinics for optimizing hospital workflow and operations efficiency (Lee, E. K., et al., 2015). The system allows management of multiple resource types simultaneously, for example, labor, equipment, beds, financial investment, medical supplies, and countermeasures (Lee, E. K., et al., 2010; Lee, E. K., et al., 2013; Lee, E. K., et al., 2017; Lee, E. K., et al., 2021; Lee, E. K., Li, Z. L., Liu, Y. K., & Leduc, J., 2021; de Mesquita PJB, et al., 2021).

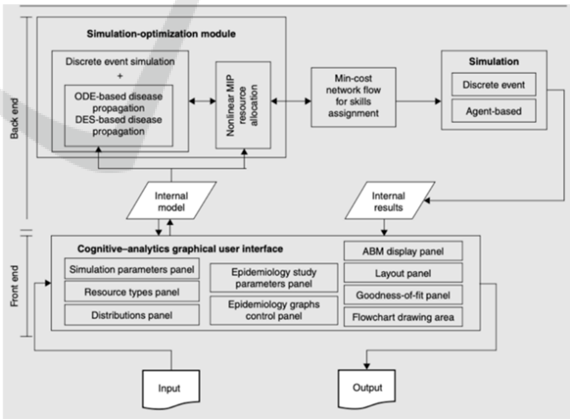

Figure 3: The architectural design of RealOpt-POD.

2.3.2 Nonlinear Mixed-Integer Program for Optimizing Resource Allocation and System Performance

Within RealOpt, system optimization can be performed to ensure the best operations and system performance (throughput, wait-time, queue length, utilization, etc). The resource allocation is modeled via a nonlinear mixed integer program (NMIP). Resources can include labor, equipment, computer, etc. Constraints in the model include: (a) maximum limits on wait time and queue length (which is dictated by the capacity of the waiting room in the facility and also the desire to maintain sufficient distancing to minimize potential infection); (b) range of utilization desired at each station; (c) assignability and availability for each resource group, and resource types at each station (i.e., the skill set and the numbers available); and (d) maximum limit on the cycle time of the individual. Mathematically, the model parameters are defined as follows:

- $\mathbf{R}$: the set of resource groups.
- $\mathbf{T}_r$: the set of resource types in resource group r, $r \in \mathbf{R}$.
- $\mathbf{S}$: the set of services in the process flow.
- $\mathbf{S}_{ir} \subseteq \mathbf{S}$: the set of services in which resource type i in resource group r can be assigned. This models the assignability of the resource (e.g., based on skills of workers).
- k_{ijr}: the cost of assigning a resource of type i in resource group r to station j. $r \in \mathbf{R}$, $i \in \mathbf{T}_r$, $j \in \mathbf{S}_{ir}$.
- $\overline{m_{ijr}}$ and $\underline{m_{ijr}}$: the maximum and minimum number of resources of type i in resource group r that may be assigned to station j. $r \in \mathbf{R}$, $i \in \mathbf{T}_r$, $j \in \mathbf{S}_{ir}$.
- n_{ir}: the number of available resources of type i in resource group r. $r \in \mathbf{R}$, $i \in \mathbf{T}_r$.
- w_j, q_j, and u_j: the average wait time, average queue length, and average utilization rate, respectively, at station j. $j \in \mathbf{S}$.
- c: the average cycle time (i.e., the length of time a customer spends in the system).
- θ: the average throughput (number of customers served in a specified period).

The decision variables for this problem are $x_{ijr} \in \mathbf{Z}_+$: the number of resources of type i in resource group r assigned to station j. $r \in \mathbf{R}$, $i \in \mathbf{T}_r$, $j \in \mathbf{S}_{ir}$.

We can represent the cost at each station j as $g_j\left(\sum_{(i,r)\in\mathbf{\Omega}_j} k_{ijr}x_{ijr}, w_j, q_j, u_j\right)$, $j \in \mathbf{S}$, where $\mathbf{\Omega}_j = \{(i,r) | r \in \mathbf{R}, i \in \mathbf{T}_r, j \in \mathbf{S}_{ir}\}$. The total system cost depends on the cost at each station, and on system performance variables, such as cycle time and throughput. Thus, we can represent the total cost as $f\left(\sum_{j\in\mathbf{S}} g_j, c, \theta\right)$. Here, g_j and f are functions that are not necessarily expressible in closed form. We can formulate a general representation of the multiple resources allocation problem as

Min	$z = f\left(\sum_{j\in\mathbf{S}} g_j, c, \theta\right)$	
s.t.	$\underline{m_{ijr}} \le x_{ijr} \le \overline{m_{ijr}}$	$\forall\, r \in \mathbf{R}, i \in \mathbf{T}_r, j \in \mathbf{S}_{ir}$ (1)
	$\sum_{j\in\mathbf{S}_{ir}} x_{ijr} \le n_{ir}$	$\forall\, r \in \mathbf{R}, i \in \mathbf{T}_r$ (2)
	$w(x)_j \le w_{max}$ $q(x)_j \le q_{max}$ $u_{min} \le u(x)_j \le u_{max}$	$\forall\, j \in \mathbf{S}$ (3)
	$\theta(x) \ge \theta_{min}$ $c(x) \le c_{max}$	(4)
	$x_{ijr} \in \mathbf{Z}_+ \;\; \forall\, r \in \mathbf{R}, i \in \mathbf{T}_r, j \in \mathbf{S}_{ir}$	(5)

Constraint sets (1) to (5) form a NMIP problem for cost minimization under the constraints of multiple resources allocation and stochastic system performance. Constraint sets (1) and (2) describe the resource availability for each service or decision. Constraint sets (3) and (4) ensure that services satisfy safety guidelines to minimize potential cross infection, e.g., individuals are not waiting for too long, the queues are of reasonable size, workers are not overwork, individuals do not spend excessive amount of time inside the dispensing facility, etc.

We note that Constraint sets (3)-(4) are system parameters in the simulation, and performance variables in the optimization. Since some of the functions in the objective and constraints are not necessarily expressible in closed form, the system optimizes the overall outcome performance using the cycle time as a surrogate measurement and the effect on different processes and the global return. The problem is proven intractable by commercial systems. RealOpt is designed to overcome such computational bottlenecks by interweaving rapid system simulation and optimization (Lee, E. K., et al., 2010; Lee, E. K., et al., 2013; Lee, E. K., et al., 2017; Lee, E. K., et al., 2021).

Given a clinical process configuration with various service distributions for each process and decision point and associated performance metrics, RealOpt simulates the entire clinical process to acquire the cycle time and the system performance under the configuration. The output simulation statistics are then input into the stochastic NMIP optimization model where performance and resources are optimized. The resulting optimization output is entered back into the simulation to obtain the next system performance metrics. The simulation-optimization iterates until no further improvement is achieved.

3 RESULTS

3.1 Time-Motion Study and Data Collection for Modeling

3.1.1 System Functionalities

Based on system functionalities and time-motion studies, we summarize key features and user experiences for each registration and data collection technology in Table 2.

Table 2: Comparison of the five registration technologies.

Scanner+ WyIR	Dispense Assist	HANDI	IDWedge & AutoFill	CRA
Pre-registration online				
No	Yes - via website or mobile app	Yes - via internal website	No	No
Onsite registration				
No	Yes - via website or mobile app	Yes - via internal website	No	No
Input mechanism: how client data are read into the system				
Barcode scanner	Barcode scanner	Magnetic stripe scanner	Magnetic stripe scanner	Manual input
Identification used as input for client data				
Driver's license	System generated QR code	Employee ID	Driver's license	Employee ID
Pediatric				
Manual input	QR code	Not supported	Manual input	Not supported
Data collected - Client data				
Name				
Yes	Yes	Yes	Yes	Yes
Address				
Yes	Yes	Yes	Yes	
Birthday				
Yes	Yes	Yes	Yes	
Insurance status				
	Yes			
ID type				
				Yes
Gender				
Yes	Yes		Yes	
Phone number				
	Yes			
Email				
		Yes		
Vaccine data				
Vaccination date				
Yes – manual input	Yes - manual input	Yes - scanned	Yes - manual input	Yes - manual input
Vaccine dose number				
		Yes - scanned		
Vaccine dose volume and unit				
		Yes - scanned		
Vaccine expiration date				
Yes - manual input	Yes - manual input	Yes - scanned		
Vaccine data				
Vaccine injection site				
Yes - manual input	Yes - manual input	Yes - scanned	Yes - manual input	Yes - manual input
Vaccine lot number				
Yes - manual input	Yes - manual input	Yes - scanned	Yes - manual input	Yes - manual input
Vaccine manufacturer (MVX code)				
Yes - manual input	Yes - manual input	Yes - scanned	Yes - manual input	Yes - manual input
Vaccine provider				
Yes - manual input	Yes - manual input	Yes - scanned	Yes - manual input	Yes - manual input
Vaccine route of administration				
	Yes - manual input	Yes - scanned		
Vaccine type (CVX code)				
Yes - manual input	Yes - manual input	Yes - scanned		Yes - manual input
VIS date given to client				
	Yes - manual input			Yes - manual input
VIS type & publication date				
				Yes - manual input
Organization of data during/after events				
Database type				
Interfaced directly with IIS	Generates a generic Excel form	Data stored in local SQL-server database	Data stored in local Access database	Data stored in the local database
Imports data electronically to database (merge automatically to the database)				
Yes - Interfaced directly with IIS	No - generate Excel files that needs manual operation	Yes - The server bundles the data from each station and the complete data set is securely transferred to a designated database or registry	Yes - data stored in Access database	Yes - data stored in local database
Transfer data to other formats (EMRs, etc.)				
No - data directly reported to IIS	No - data stored in local Excel files and needs manual operations to transfer to other formats	Yes - can transmit the data to other designated formats, convert to HL7 and send its records to any system that accepts HL7	No - data stored in local Access database and needs manual operations to transfer to other formats	Yes - data is exportable to other databases including the electronic medical records and CDC's occupationa l health database

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Table 2: Comparison of the five registration technologies (cont).

Organization of data during/after events				
Require internet connection during events				
Yes – for connecting to IIS during operations	Yes - for onsite registration (5/4G or LTE connections for mobile phones will also work)	Yes - for onsite registration; but essentially only Ethernet is needed as it is an internal tool for closed-POD	No – unless connecting to IIS is necessary	No – does not need connect to any database in real time; standalone deployment available; registration and vaccination are performed by the same nurse
Scalability for larger events				
Speed of data input				
Fast with scanner, slow with manual input	Fast with scanner, slow with manual input	Fast	Fast with scanner, slow with manual input	Slow
Need for reliable servers				
Yes	Yes	Yes	No	No
Observations during actual events				
Training				
Just-in-time training; workers performed well	Just-in-time training; workers performed well	Team has 5-year of experience	Just-in-time training; workers performed well	Difficult for vaccinators to use, more prone to entry errors
Pediatric				
children without driver's license take longer to process	Via QR code, same as adults	Not supported	children without drivers' license take longer to process	Not supported
Scanner				
Failed to scan some drivers' licenses	No scanner available on site. Pre-filled forms had to be emailed and printed on site		Occasionally failed to scan some drivers' licenses.	
Registration				
Automatic	Required clients to register online, many forgot	Only limited employees showed up; unclear if system is scalable for large events	Automatic	No mechanism to input client information automatically
Health information				
Not connected to EMR; Health information needs to be manually filled out by clients.	Not collected	Not collected	Not collected	Not collected

3.1.2 Service Time Distributions

Observations were recorded for all clients entering the vaccination site. Table 3 below shows the staffing and total throughput (number of observations collected) at each site.

Table 3: POD hours, staffing and throughput of the five sites.

Gillette, Wyoming	Platte City Missouri	Denver, Colorado	Philadelphia, PA	Atlanta, Georgia
Vaccination period				
7am–7pm	10am–2pm	12pm–4pm	8am–1pm	8:30am–3pm
POD type				
Open POD	Open POD	Closed POD	Closed POD	Closed POD
Total throughput				
650 adults 50 children	200	275	1,400	310
Staffing				
8 staff, 4 volunteers	10 staff, 4 volunteers	4	11	10
Nurses				
14	7	2	14	5

During time-motion studies, we observe several factors that influence the service time.

- *Technology familiarity:* For Scanner+WyIR, Dispense Assist, and IDWedge systems, POD workers received just-in-time training on the use of the technology. For HANDI, the staff have used it for multiple years and are quite proficient in its usage. For CRA, workers log in a few days prior to the vaccination event to learn of its usage and to pre-set the dispensing information.
- *Incomplete technology:* Scanning devices were not available for the QR codes generated from Dispense Assist to fully take advantage of its capability. If equipped with proper scanning devices to scan the generated QR codes (as the technology is designed for), the service times will be significantly shortened.
- *Human factor:* Staff served at varying rates depending on how busy the clinic was. Staff tended to operate faster when the queue was long, and slower when the clinic was not busy.

To address some of these factors, we perform three steps: (a) Within each observed time, we subtract from it the time spent on leisure chat between the worker and the client (which we also collected). (b) We remove outliers that are greater than the 90 percentiles. (c) We use only the service times reflecting staff performance when the demand is high.

Figure 4 shows the adjusted service time with the associated best-fit distribution (Chi-Square Goodness-of-Fit Test) for registration and scanning (data collection) for the five technologies and the current manual process. The boxplots in Figure 5 contrasts these service times for each technology. It shows that scanner-type technology shares comparable median time while computer input requires a longer time. The figure depicts clear time variance among users or types of clients.

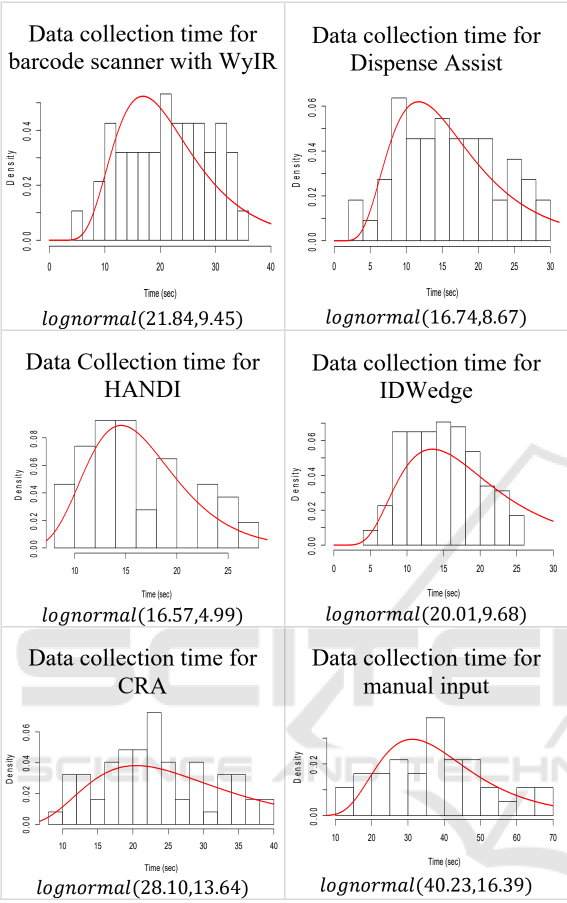

Figure 4: Service time distributions with the associated best-fit distribution for each technology after adjustment: using only service times reflecting performance of staff when demand is high. This excludes time spent on leisure chats and outliers.

We note that across the five sites, there is marginal difference in the service times for vaccination, medical evaluation, and post-vaccination observation respectively.

During the actual events, 90% of the clients in Gillette, Wyoming event had valid Drivers' licenses, 60% of the clients pre-registered at the Platte City Missouri site, 86% of the clients pre-registered for HANDI in Denver and 87% of the clients in Philadelphia had valid Drivers' licenses. We note that at the Wyoming site, the form-filling process by the clients themselves does not affect the performance of the technology nor the POD process.

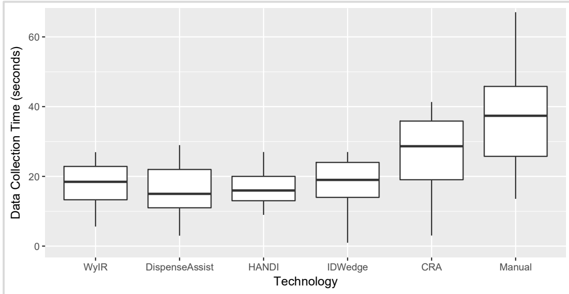

Figure 5: Boxplots contrasting the adjusted service times for each technology.

3.2 Operations and Performance Efficiency

Table 4 summarizes the associated service time distributions and decision probabilities that are collected from the time-motion studies. Using the vaccine clinic layout in Figure 2 and these service distributions, we simulate and perform systems, operations and resource allocation optimization using RealOpt for each of the technologies to obtain the best throughout under the same number of staff (30) and necessary equipment resource constraints. We report some comparison findings below.

Table 4: Service time distributions and probabilities at decision blocks obtained via time-motion studies of actual influenza vaccination events.

Service Station	Service Time Distribution (all units in seconds)
Registration & Scanning	Specific to each technology as shown in Figure 4
Best fit distribution obtained using combined data from all five sites	
Vaccination	$lognormal(32.20, 10.59)$
Medical Evaluation	$lognormal(61.03, 21.54)$
(Post-vaccination) Observation	$uniform$ (51.03,78.43)

Scanning Device versus Web Input Versus Manual Approach. Figure 6 compares closed-POD performance using magnetic strip scanners (HANDI, IDWedge) versus input via website (CRA) versus the manual approach. Magnetic strip scanners (HANDI and IDWedge) gather the demographic information of clients from their employee IDs or drivers' licenses, while CRA requires workers to manually input data onto the computer. When the pre-registration percentage (for HANDI) or the percentage of valid drivers' licenses (for IDWedge) are low, the resulting performance is similar to CRA. During the actual vaccination events, 86% of the

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clients pre-registered, and 87% had valid drivers' licenses. Thus, both HANDI and IDWedge produce higher throughput than when using CRA by 14%. However, we note that CRA results show that even with a simple web-based system, the gain in throughput can be significant (15% increase) when compared to the traditional manual process. ***This confirms that automatic scanning is essential for efficient closed-POD operations and should be incorporated into any data collection technology***

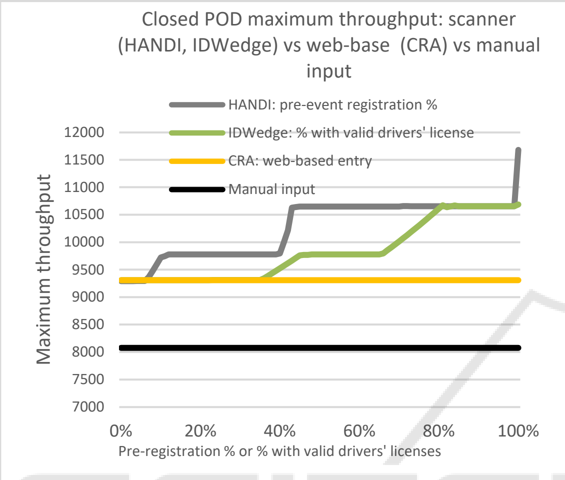

Figure 6: Maximum throughput achieved when using magnetic strip scanners, web-based input, and manual registration respectively, under varying pre-registered percentage or percentage with valid drivers' licenses.

QR-Code versus Drivers' ID. What is more efficient for registration, QR codes or drivers' licenses? Scanner+WyIR and IDWedge use drivers' licenses to populate client demographic data automatically onto the computer, while Dispense Assist generates a QR code for each client (family) during online/mobile registration for automatic population. Such registration can be done either pre-event, or with on-site kiosks or a mobile app. Figure 7 contrasts the maximum throughput achieved by scanners (Scanner+WyIR and IDWedge) versus QR-based (Dispense Assist). When pre-registration and valid drivers' licenses percentages are both below 15%, there is a marginal difference in the performance among these technologies. However, Dispense Assist shows a clear advantage as pre-registration picks up. During the actual vaccination events, 60% of clients pre-registered, while over 85% of clients have valid drivers' licenses. Uniformly, Dispense Assist processes 20% more clients under the same resource and time constraints. The IDWedge site performs better than the Scanner+WyIR site. This may reflect the fact that the former was a closed-POD operation, where staff have used the same technology for five years already; hence the POD operations ran more efficiently. The clients were very comfor with the environment. ***In general, QR code technology is very competitive in an open-POD environment for automatic registration. ID scanners are equally competitive in closed-POD operations when most clients have valid drivers' licenses.***

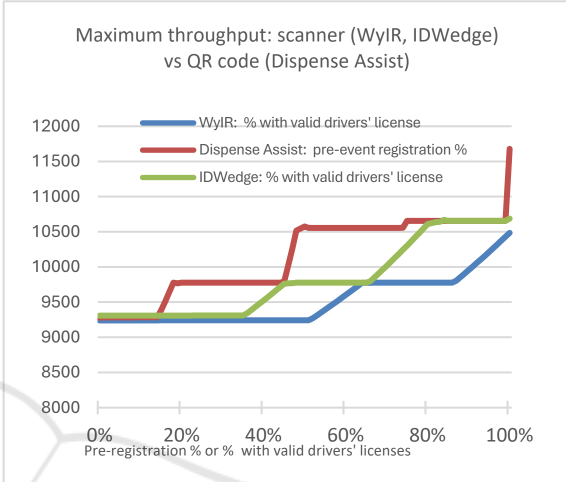

Figure 7: Maximum throughput achieved using QR codes versus ID scanners, under varying pre-registered or percentage with valid drivers' licenses. Note that WyIR uses onsite form-filling for medical screening while IDWedge staff conducts verbal medical screening.

Verbal Medical Screening versus Form-Filling Before Scanning. Both Scanner+WyIR and IDWedge scan the drivers' license to gather demographic data automatically. In addition, clients in Wyoming were asked to fill out a preliminary medical screening form (by themselves) prior to scanning, while Philadelphia IDWedge site conducted onsite medical screening verbally during scanning. Figure 7 (Blue versus Green) shows that the throughputs are similar when the percentage of valid drivers' licenses is below 35%. Beyond 35%, IDWedge is more competitive with slightly higher throughput (10.5%) than Scanner+WyIR. When every client has an ID, the difference in throughput is only 1.9% (203 clients). During the actual events, similar percentage of clients (90% vs 86%) had valid IDs. ***The results show that verbal medical screening (especially used in conjunction with the online EMR or personal health records) is more efficient***. The time spent by nurses to review each paper form is not negligible and may take up to a couple of minutes. In addition, extra physical space is needed to accommodate clients filling medical screening forms onsite, which can potentially create congestion.

During a pandemic, this may increase infection transmission within the dispensing facility; hence proper crowd control such as the use of multiple rooms or open space may be needed to facilitate distancing among clients while completing the form.

Pre-Registration Impact. Dispense Assist uses online pre-event registration and medical screening, whereas IDWedge performs the entire process within the POD (during scanning). We compare the performance of these two technologies to gauge their efficiency (Figure 7 Red versus Green). When less than 15% of the clients pre-register or have valid ID, performance of both technologies are similar. When the pre-registration rate or percentage of valid licenses range from 15% and 80%, Dispense Assist performs better than IDWedge, while the maximum difference in throughput is achieved at 49% with 10% throughput difference. At a 60% pre-registration rate for Dispense Assist and 87% valid ID for IDWedge, there is only a marginal difference in the throughput. We caution that Dispense Assist was used during an open POD event (serving a more diverse population). Hence its performance is remarkable when compared to the closed-POD IDWedge results. ***Public campaigns to encourage pre-registration during mass dispensing events can help with the overall efficiency and throughput***

Open POD versus Closed POD. Dispense Assist is used for general open POD events. The QR codes generated via an online/mobile pre-registration is scanned on-site. HANDI is used for closed POD events to scan employees' IDs. Both technologies require pre-registration. Employee ID is an efficient method for data input since every employee has one, and with the same and standard data fields. Figure 8 show the maximum throughput under different pre-registration rates. The two technologies have similar trends as the pre-registration rate increases. At a low pre-registration rate, HANDI has slight advantages in the throughput. ***The results show that when operating an open POD, QR codes are a good alternative for employee IDs.*** QR code technology is flexible in gathering information. Besides demographics, and premedical screening questions, additional information such as contact phone numbers, primary physician, etc. can also be encoded. This information can become crucial for health monitoring and follow-up, or second dose reminder. Although such information may also be recorded in some employee IDs/records, they may not be uniformed across different organizations.

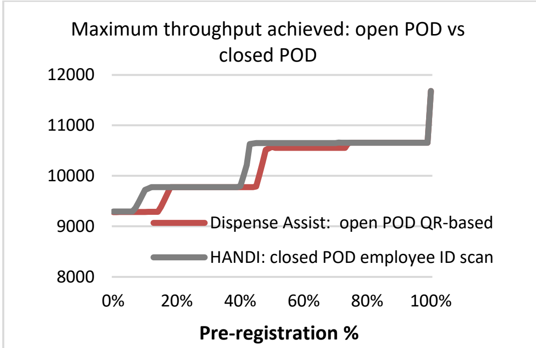

Figure 8: Maximum throughput achieved for QR-based technology (Dispense Assist) versus employee ID scanner closed POD (HANDI) under varying pre-registered percentage.

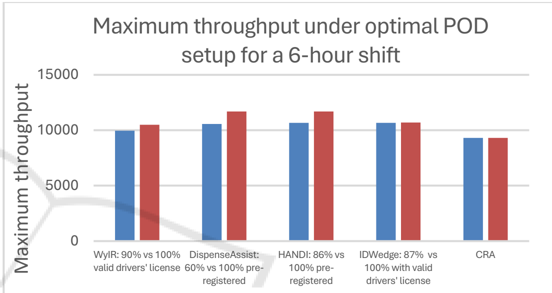

Figure 9a: Maximum throughput under an optimal POD setup for a 6-hour shift using the observed time-motion study data for each technology.

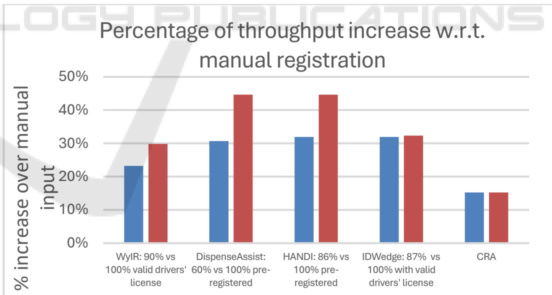

Figure 9b: Percentage throughput increases with respect to manual registration is calculated as (x-manual)/manual * 100%.

Optimal Throughput For a 6-Hour Shift. Figure 9a and 9b compare the maximum throughput of the five technologies under the medical POD setup (Figure 2) operating for a 6-hour shift. Each throughput is obtained using the observed (real) time-motion study data with the associated percentage of clients with valid IDs and pre-registered. We also contrast the results against the ideal scenario where all clients have valid IDs and pre-registered (orange bar). In contrast to the manual approach (Figure 9b), the CRA web-based approach increases the throughput by 16%. Scanning drivers' ID or using QR codes (even with just 60% of client pre-registration) can increase the throughput by 30%. If more people pre-register, the gain could be as high as 45%.

3.3 A Prototypical Electronic System for Data Collection During Mass Dispensing

Based on our findings, we design a computerized system for data input and collection during dispensing and post-event monitoring and assessment. Figure 10 shows the design structure and architecture of the system. The system includes four key modules:

The digital registration module facilitates online or on-site mobile registration. A QR code in generated which stores the client information (e.g., name, address, zip code, immunization history etc.) in standard format. QR codes are widely used in daily activities including information gathering, identification and mobile payment, air transportation security (e.g., boarding passes), attendee ID at conferences, and retails and sales. It is both reliable and scalable.

The scanning module with a scanner, the client information will pop up rapidly allowing staff to review and cross reference to prepare for vaccination. Scanning the barcode from vaccines saves time and reduces errors. The scanning module streamlines the POD operations, improves efficiencies and staff utilization.

The database and interoperable encrypted transfer module establishes a functional platform for data analytics and interoperable data transfer. The data collected is organized into various formats to support key functions. SQL-like data queries and management functionalities are employed to support data analysis. HL7 and EMR-standardized format are used to push data to immunization registries and local EMRs. This is important for IIS data transfer — IIS is critical for overall state level planning and management beyond the individual POD site. The system design is modulized with simple and extensible architecture. This allows for flexible expansion of system functions, ease of maintenance, and connectivity to an EMR for pre-event cross-reference on medical / vaccination history and post-event monitoring and assessment of the efficacy of the medical countermeasures.

The client-communication interface module is critical for monitoring adverse effects and determining vaccine efficacy. This is especially important when newly developed vaccines are being dispensed. Public health efficacy for the vaccines can only be obtained when clients report their response / health effect after vaccination. The communication interface module is essential also for sending out updates on vaccines, or reminders (to both providers and clients), when multiple doses of vaccine are needed per person. These features were sorely missed (and are still missing) during COVID-19 vaccination (Apartsin, K. A., et al., 2021; Chekol Abebe, E., et al., 2022; Riad, A., et al., 2021; Yadav, T., et al., 2023).

This system captures the best among the five technologies, it is practical, implementable, and scalable.

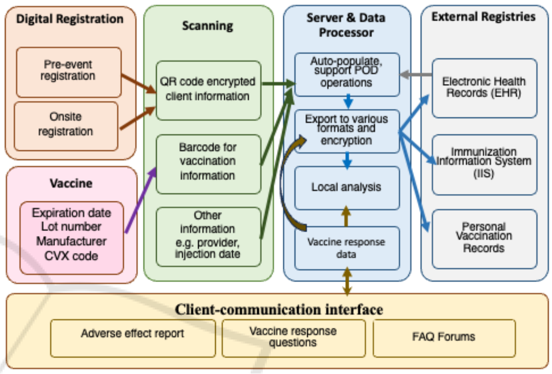

Figure 10: The design architecture of an electronic system for data collection during mass vaccination.

3.4 Contribution

Documenting clients, screening, and vaccinations administered is of particular importance during mass vaccination, since information regarding uptake is critical for monitoring adverse effects and vaccine efficacy. This is especially crucial when newly developed vaccines are being dispensed, or when multiple doses of vaccine are needed per person. Hence, it is important that vaccine providers document vaccinations administrated accurately and quickly and upload this information onto the local Immunization Information System. These data can provide valuable information during an emergency and serve multiple purposes for public health planning and research. Currently, there is no uniform or integrated system for effective vaccine data collection. In this paper, we describe and analyze five types of electronic technologies for registration and screening in vaccination clinics. We contrast their functionalities, usability, and operations performance based on time-motion studies and service data collected during actual influenza vaccination campaigns. We evaluate their dispensing performance under an optimal dispensing clinic design. Our analysis shows that these electronic technologies can improve operations and tracking efficiency with 16% to 45% increase in overall throughput. Based on our assessment and analyses, we design a prototypical registration and screening system with integrated information flow for vaccination that can be used for dispensing, monitoring, and assessment. The system connects to the local Immunization Information system and electronic medical record systems. The design is flexible and adap and can be used by a broad spectrum of regional public health departments.

4 CONCLUSIONS

This paper addresses the critical issue of efficient vaccine data collection during mass vaccination campaigns. Recognizing the importance of accurate, timely documentation for monitoring adverse effects and efficacy, we evaluate five electronic registration and screening technologies to test for how quickly immunizations could be delivered and recorded given the different physical and cyber requirements of the different technologies. Through time–motion studies and service data analysis from influenza vaccination campaigns, we demonstrate and throughput improvements of 16% to 45%. Based on these findings, we propose a prototypical integrated system designed for dispensing, monitoring, and assessment, emphasizing its flexibility and interoperability with existing immunization and medical record systems.

During a pandemic or other vaccine-preven disease outbreak health emergency, it is essential to vaccinate as many people and as quickly as possible. Documenting vaccines administered during the event is particularly important, and vaccination administration information (i.e., patient and vaccine information) will need to be reported to the jurisdiction's Immunization Information System quickly. Advanced technologies play an irreplaceable role in healthcare and vaccine dispensing and can be used to accelerate the processing rate of vaccination clinics.

Few studies have investigated the time staff spend registering clients and collecting data in a mass vaccination or other dispensing event. This paper presents the first study using time-motion techniques to scrutinize point-of-dispensing operations by analyzing five different (inexpensive and practical) electronic technologies for data input and collection. There are clear advantages of electronic input technologies compared to traditional manual input approaches. They automate or eliminate labor-intensive tasks such as searching and typing, and reduce manual-entry errors. These technologies can improve POD throughput, operations efficiency, and quantity and accuracy of collected data.

The five technologies analyzed herein offer different input mechanisms. Scanner+WyIR and IDWedge both scan Drivers' drivers' licenses to populate demographic information, while the vaccination information is input by staff members. Both systems can be linked in real-time to a jurisdiction's immunization information system. This assists during health screening of clients the determination of the type of vaccination/medication that should be used. CRA, on the other hand, allows scanning of the vaccination information but requires manual input of clients' demographic information. The two technologies that benefit from pre-registration (HANDI and Dispense Assist) also utilize scanning devices to facilitate input of information. Moreover, Dispense Assist is the most flexible by generating a QR code using data input by clients.

During observation, most on-site registrations are done by manual form filling, even though electronic form-filling options are available (the mobile app for Dispense Assist, and the on-site web-based registration for HANDI). This creates additional workloads for both clients and staff: clients have to spend extra time in the POD filling out the forms, and staff need to spend extra time and pay attention to reading the handwritings when inputting these hand-filled forms to a computer system. Although implemented not very efficiently at the influenza vaccination clinic, Dispense Assist does provide a very promising solution to overcome this issue. The gain in throughput is remarkable.

A mobile app or website for registering clients and disseminating knowledge regarding the type of medical countermeasures to be dispensed is practical and useful to the public. These sites can be accessed easily via web browsers on clients' mobile devices and generate barcodes or QR codes that can later be used for scanning. This setup can significantly reduce the workload for POD staff and the time clients spend inside PODs. It also improves accuracy in the data collected.

RealOpt is a live evolving informatics decision-support enterprise system and has over 14,000 public health emergency response users across 50 states. Among the hundreds of time-motion studies conducted for real dispensing events, the results from RealOpt simulation analysis predict the performance of the actual system well (within 95% to 105%). Hence, the analysis present herein provides useful foundations and insights into the potential improvement that can be achieved by the electronic data collection technologies.

Our analysis shows that electronic technologies for registering and screening can improve 16% to 45% in overall throughput. Moreover, it is not necessary for a health department to seek the most advanced, most cutting-edge electronic data collection technologies. Our findings show that simple technlogy increment (e.g. a scanner) can already provide improved operations efficiency and data accuracy. Health departments should carefully analyze their demand and environment and choose the technology that best suits their needs. Simple-to-use is key for just-in-time easy training. Automation reduces input errors. These are all key elements to consider during selection. Health departments should incorporate these devices into their routine vaccination process. This ensures staff confidence in using the devices and that proper device maintenance is performed.

We propose a prototypical integrated system designed for dispensing, monitoring, and assessment, emphasizing its flexibility and interoperability with existing immunization and medical record systems. The prototypical electronic system for data collection during mass dispensing (a) transfers most of the time-consuming tasks to clients before their arrivals to improve efficiency; (b) enables fast and computerized onsite registration through the online / mobile registration tool; (c) improves data / process flow and efficiency and reduces errors by automating the vaccine data collection using scanning devices; (d) connects clients to vaccine reminders, and the vaccine effect registry where clients can report their response and also receive vaccine update information; (e) is easy to use and maintain; and (f) is flexibility and scalability. In our design, we propose a synthesis of the various techniques that would prove more efficient than the least efficient methods while requiring a minimally-enhanced technology and methods. This is critical for the resource strapped public health organizations. The system can easily accommodate new devices to reflect the rapid advances in electronic devices, systems, and software.

At the time of this writing, our recommendation has been adopted by CRA. CRA has incorporated the scanner for registration and screening, affording 45% throughput improvement over the manual input.

This work highlights the potential of electronic technologies to significantly enhance vaccine administration and data management. The design is flexible and adaptable for different types of medical countermeasures and dispensing purposes. For example, it can be used for prophylactic medical countermeasure dispensing against biological attack, or decontamination and health registration for radiological incidents. The online registration can be adapted based on the nature and purpose of the event.

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