Using DES to Improve the Efficiency of a Covid-19 Vaccination Centre

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Abstract. Many research and development teams around the world have developed and continue to improve Covid-19 vaccines. As vaccines are produced, preparedness and planning for mass vaccination and immunization has become an important aspect of the pandemic management. Mass vaccination has been used by public health agencies in the past and is a viable option for Covid-19 immunization. To be able to rapidly and safely immunize a large number of people against Covid-19, mass vaccination centres are accessible in the UK. Careful planning of these centres is a difficult and important job. Two key considerations are the capacity of each centre (measured as the number of patients served per hour) and the time (in minutes) spent by patients in the centre. This paper discusses a simulation study done to support this planning effort. In this paper, we explore the operations of a vaccination centre and use a simulation tool to enhance patient flow. The discrete event simulation (DES) tool outputs visually and numerically show the average and maximum patient flow times and the number of people that can be served (throughput values) under different number of patient arrivals (hourly). With some experimentation, the results show that marginally reducing the hourly arrival rate, patient congestion reduces enabling good patient service levels to be achieved.

Keywords: mass vaccination centre; Covid-19 vaccination; discrete event simulation, capacity planning

1 Introduction

In the early phase of the year 2020, a novel virus outbreak led to a worldwide pandemic with millions of confirmed cases (1) that caused large proportions of the world population to be in temporary lockdown. With non-essential travel discouraged and everyone but key workers staying at home the world economy came to a sudden pause (2). The containment of the virus, a novel coronavirus named Covid-19, required quick resource re-allocation on a large scale and was prioritised on every level of healthcare delivery, first identified in East Asia. As the outbreak continued the epicentre shifted to Europe and the Middle East, and eventually affected the Americas (3). It led to restrictions on public life previously unimaginable during times of peace (4). Schools were closed,

work from home was strongly encouraged, and non-essential travel was forbidden; some regions, and even countries, were entirely locked down for weeks or months (5).

The UK Covid-19 vaccines delivery plan (6) published on Monday 11 January 2021 to coincide with the opening of seven new regional vaccination centres, said England would have capacity to vaccinate at least two million people per week by the end of January. This will be delivered across 206 hospital sites, 50 vaccination centres, and 1200 local vaccination sites run by primary and community care teams, it says.

The expansion of capacity means that everyone will live within 10 miles of a vaccination centre, or, in the case of a small number of highly rural areas, have access to a mobile unit delivering vaccinations. In this paper, we utilise DES to improve the operational efficiency of a typical vaccination centre. The vaccination centre was located in a sports/community facility that provides spacious accommodation to support high patient flow for advance-booked individuals. In the UK, the population is vaccinated in order of priority group, based mainly on age but also accounting for underlying health conditions and employment as a health or care worker (7).

2 Methodology

Witness Horizon software was used to demonstrate the value of DES computer modelling in supporting operational planning of Covid-19 vaccination centre. This study followed a standard simulation study methodology, consisting of the following steps: vaccination centre operations (scope of study), data collection, analyse data, model building, model testing, results/experimentation, discussion, and conclusion.

The scope of the simulation study was limited to the vaccination centre operations and the key performance measures of capacity and time-in-system. Arrival of patients to the centre is assumed to be by car or walk-ins on the basis of 60:40. Data collection relied upon observational data of a vaccination centre and secondary data from related literature. At the time of the study, the Pfizer-BioNtech(PZ) vaccine was being administered.

3 Vaccination Centre Operations

Vaccination centres require careful planning and implementation and are governed by National Health Service (NHS) England guidelines (8). The correct number of staff must be assigned to roles when the centre operates. Two key considerations are the capacity of the centre (measured as the number of patients served per hour) and the time (in minutes) spent by patients in the centre (this is known as the flow time or throughput time). Centre capacity affects the number of centres that must be opened, and the total time needed to vaccinate the population. The flow time affects the number of patients

who are inside the centre. More patients require more space as they wait to receive treatment. If throughput is too high then unsustainable queues will form, compromising social distancing and impairing patient experience (important for ensuring a repeat visit for any additional dose). On the other hand, if throughput were too low, then this would lead to an uneconomic use of available resources. The balance between centre capacity and flow time is very subjective in mass vaccination and regularly tweaked to meet operational targets. Additional considerations relate to the optimal allocation of activity-level resources to ensure balanced server utilisation and the incorporation of sufficient 'slack' in pathway capacity to ensure any 'shocks' can be readily absorbed (such as staff sickness or a number of patients arriving all at once).

There is, however, very little information and learned experience to guide managers through these considerations. Events of such magnitude have simply not occurred in recent times and so, beyond the limited number of national and regional level emergency preparedness roles, there is little existing knowledge and expertise within the local frontline entities tasked with setting up the vaccination centres. Most previous studies on pandemics and vaccination centres use the discrete-event approach to stochastic simulation, given its capacity of capturing the modelling requirements of service systems with individual entities (such as patients) which flow through a care pathway, competing for resources such as appointment slots (9).

vaccination centre operates on a pre-booked appointment basis. This means that slots are available on-line for patients to book. The centre receives patients as walk-ins or by car. Either case the patients enters the site via a car park. Cars are directed onto the car park in a controlled manner by marshals (volunteers) who limit car arrivals on to site. Once parked the patient walks to the building and usually join a patients queue that forms at the entrance. Walk-in patients also join the same entrance queue. The entrance queue moves slowly enabling patients to enter the building containing the centre. Upon building entry patients have a temperature check done whilst in a moving queue. Patients follow an orderly queue which meanders along the entrance corridor to enter the main hall. Within the main hall, the patients first stop is Registration that involves confirming basic personal details and collecting a personal data sheet. After Registration, the patient's second stop is Clinical Assessment where the patients' medical condition is evaluated. The patient then follows the snake like queue and is directed to the next available Vaccination cubicle. Within the Vaccination cubicle, the personal data sheet is collected, information is given, and the vaccine administered. The patient is then directed to take a seat in the Observation area. Volunteers manage the Observation area and allow patients to exit after a 15-minute stay. Patients leave the building through a separate exit and walk through the car park and either drive through or walk through the site gates. A simple flowchart representing the drive-in patient is shown in Fig 1.

For the vast majority of patients, the procedure described earlier reflects their experience. However, some patients are likely to leave the centre with or without vaccination because they have been un-successful at any of the stations. These patients have

not been considered in this study because observational evidence suggests the failures are negligible.

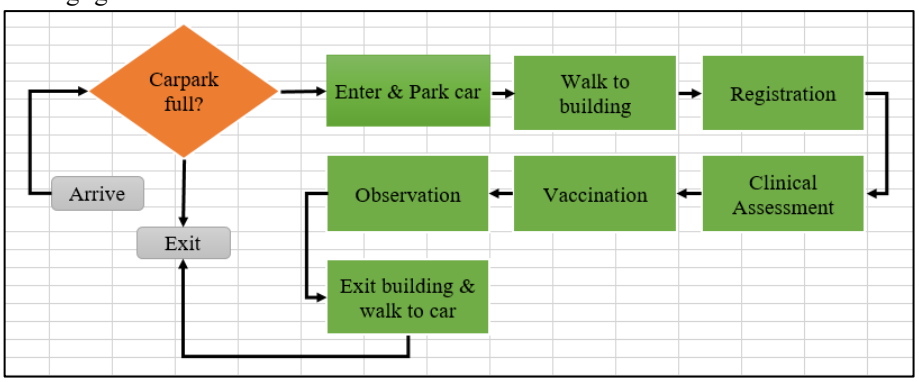

Fig 1. Patient flow for a drive-in patient

4 Data Collection

Operations of the vaccination centre were observed by following the patient flow through the various stations in addition to secondary data (10). The observations included patient arrivals and mode, queue lengths, walking speeds, distance and capacity of stations, staffing levels, and service times. The various stages involved:

- Arrival either by car or walk-in through the car park
- Walking to the building entrance, essentially joining a patient queue to enter the centre
- Registration
- Clinical Assessment
- Vaccination cubicle
- Observation area
- Exit via the car park

Although the data collection was carefully planned, the data collected was not complete and may have included some inaccuracies due, in part, to the limited number of people, time, and equipment available to conduct the time study. Missing data was estimated from secondary data (11,12). Computer simulation was used to model vaccination centre operations. An analytical solution was not attempted due to limitations on variability. The data was sufficient for constructing a valid simulation model.

5 Data Analysis

Raw data was collected from the centre, mostly by observations and some by estimates. Ultimately the data was collated and manipulated to determine how long a patient spent at each station and ultimately the total time in the centre.

Table 1. Operational Parameters

Operational Parameters	
Patient Arrivals	
Number of arrivals expected per hour	100
Operational hours per day	12
New cars allowed on car park at any one time	5
Ratio of car arrivals to walk-ins	60%
Resources	
Registration staff	3
Clinical Assessment staff	8
Vaccinators	6
Observation spaces	25
Queue Capacity	
From Entrance to Registration	100
From Registration to Clinical Assessment	10
From Clinical Assessement to Vaccination	10
From Vaccination to Observation	2
Car park capacity	100

Table 2. Activity Timings (in minutes)

Activity Timing Distributions (mins)	
1. Registration	
Minimum	0.5
Mode	1
Maximum	1.5
2. Clinical Assessment	
Minimum	4
Mode	5
Maximum	6
3. Administer Vaccine	
Minimum	2
Mode	3
Maximum	4
4. Observation	
Minimum	15
Mode	15
Maximum	15

It was determined to separate the conveyance timings from activity timings. This enabled value-added data to be independent of non-value-added data. It was deemed appropriate to use a triangular distribution for conveyance and service times due to the limited data and wide variability. Tables 1, 2 and 3 depicts key parameters and operational timings of the centre.

Table 3. Conveyance Timings (in minutes)

Conveyance Timing Distributions (mins)							
1. To Park a Car		2. Walk: Entrance to Registration		3. Walk: Registration to Clinical		4. Walk: Clinical to Vaccination	
Minimum	1	Minimum	0.5	Minimum	0.5	Minimum	0.5
Mode	2	Mode	1	Mode	0.5	Mode	0.5
Maximum	4	Maximum	2	Maximum	0.5	Maximum	0.5
5. Walk: Vaccination to Observation		6. Walk: Observation to exit building		7. Walk: to Car/Site exit		8. Car to Site exit	
Minimum	0.5	Minimum	1	Minimum	1	Minimum	1
Mode	0.5	Mode	2	Mode	1.5	Mode	1.5
Maximum	0.5	Maximum	3	Maximum	3	Maximum	3

6 Simulation Model

Discrete event simulation (DES) is a method of simulating the behaviour and performance of a real-life process, facility or system. DES is being used increasingly in health-care services (12) and the increasing speed and memory of computers has allowed the technique to be applied to problems of increasing size and complexity.

DES models the operation of a system as a (discrete) sequence of events in time. Each event occurs at a particular instant in time and marks a change of state in the system. DES assumes no change in the system between events. DES is used to characterize and analyse queuing processes and networks of queues where there is an emphasis on use of resources. The core elements are:

- Entities: objects that flow through the processes and have work done on them e.g. patients
- Resources: objects that are used in the workflow to process entities e.g. health care services
- Events: important and specific moments in the system's lifetime e.g. vaccination
- Queues: waiting lines.

DES is particularly suitable for models of systems of patient care where the constraints on resource availability are important. This type of study allow patients to have individual attributes and to interact with resource provision. Due to the superior balance of functionality and ease of use, Witness Horizon software was used to develop a model of the vaccination centre. A table of operational parameters were developed, based on a combination of observation data and discussions with management of a vaccination centre. The operational parameters and their values are depicted in table 1.
A mapping activity produced table 4, enabling the real world elements to be mapped to Witness Horizon elements.

Table 4. Element mapping

Mapping to Witness Elements	
Description	Witness Element
Patient	Entity
Park car	Activity
Walk to: Registration/Clinical Assessment/Vaccination	Queue
Registration/Clinical Assessment/Walk to Observation	Activity
Observation area	Queue
Drive/walk off site	Activity
Patient ID / mode of arrival	Attribute
KPI display	Variable array

A DES model was developed and iteratively refined to credibly represent the operations at the target vaccination centre. Fig 3 displays the vaccination centre after one day (12 hours) of simulation. Some of the key drivers was to establish performance and patient service levels. National guidance in the UK is that a single vaccination station should deliver 260 vaccinations per 12-hour operating period. Secondly, locally agreed patient service level was defined by two criteria:

- Avg patient flow time around 40 mins
- Max patient flow time not to exceed 50 mins

To ensure variability and realism, the patient arrival rate (hourly) was implemented using an exponential inter-arrival time.

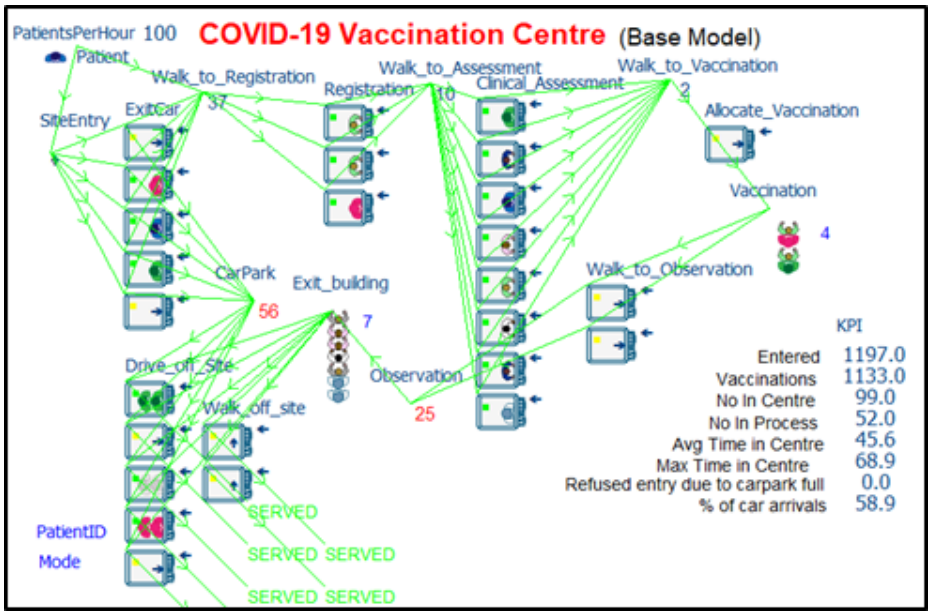

Fig 3. Base Simulation Model @ 12 hours

7 Model Testing

To be useful, the model must logically represent the process flow observed in the vaccination centre, known as verification. This was accomplished by techniques such as a structured walkthrough of the model code, test runs and checking of the animation display.

Before the model results were recorded, model behaviour was checked to ensure the model is providing valid results. Validation is about ensuring that model behaviour is close enough to the real-world system for the purposes of the simulation study. The model validation process consisted of comparing simulation results with actual statistics to determine the correctness was a critical step before performing what-if analysis. To our initial surprise, in many cases, our simulated results did not closely replicate the performance of the vaccination centre. This was largely due to the absence of some data to model accurately the operations. The model was then fine-tuned to adjust some of the model parameters to match closer with the performance of the vaccination centre (10).

Finally, demonstration of the model between interested parties provided a forum for communication of model behaviour and helped identify any anomalies. The credibility of any model is dependent on reliable data, which are not always readily available in the British Health Service.

Once the model had been validated, it was run over a set time period and results collected. At this stage, the model is simply reproducing the behaviour of the current

process. This “as-is” model provided a visual representation of the whole process, which was important to provide a consensus that the model provides a convincing representation of the process.

8 Results and Experimentation

An arbitrary single simulation run of 12 hours of operations is displayed in Fig 3. However due to the use of random sampling of statistical distributions, a single replication is not representative and some experimentation was necessary.

Full results were obtained by performing multiple replications (500) of the simulation, each with a different random number seed used to generate the timing of patient arrivals, service times, and conveyancing time. In accounting for realistic conditions at the beginning of the operating period, each simulation starts empty and with no warm-up period. Table 5, illustrates the simulated results for the base model.

Table 5. Base model results (Time in minutes).

	Scenario Name		No of Vaccination	Avg Flow Time	Max Flow Time
1	Base Model		1128.074	48.129	70.682

The key performance indicators (KPIs) in table 5 show that desired throughput and service levels were not achieved by the configuration of the base model. This finding can actually be derived without modelling – 1560 daily vaccinations are not achievable with a patient arrival rate of 100 per hour.

Recognising that the current configuration of the vaccination centre is not achieving the desirable outputs then changes need to be considered. However, the present configuration is operational and works safely. Ultimately, the aim of the project is to maximise throughput, but this must be done under Covid-19 safety rules. If throughput is too high then unsustainable queues will form, compromising social distancing and affecting patient experience. The base model configuration is showing a very stable behaviour across the operating period.

To explore alternative configurations, permissible operational changes were reviewed with management. The outcome was to increase the patient arrival rate (hourly) and resources. However, the service times and conveyancing times could not be changed and hence maintained. The changes transpired as: (1) increase the patient arrival to 130 patient/hr; (2) The staffing levels for the activity levels were Registration (3-5), Clinical Assessment (8 – 12), Vaccination (6 – 10); Observation seating (25 – 40).

An improved simulation model was explored using Witness Horizon’s Experimenter and appropriate permissible changes. Initially as a result of the changes, 1200 scenarios

were generated. This was subsequently revised. With careful planning of the step size we reduced the optimisation problem to 180 scenarios. Each scenario was run for 50 iterations with a focus on meeting the desired KPIs. An extract of the results obtained are shown in figure 4. Analysis of the results enabled an optimum configuration to be selected. The selection criteria was to maximise throughput, reduce the patient flow time and minimise staffing levels. An adaptive simulated annealing algorithm was used for the optimisation.

Scenario	No of Vaccinations	Registration .Quantity	Clinical_Assessment .Quantity	Vaccination .Capacity	Observation .Capacity	Avg Flow Time (mins)	Max Flow Time (mins)
40	1398.000	3	11	6	40	61.907	92.156
41	1180.750	3	11	8	25	84.699	117.554
42	1414.000	3	11	8	30	58.794	88.862
43	1528.100	3	11	8	35	37.605	47.910
44	1528.100	3	11	8	40	37.603	47.949
45	1180.750	3	11	10	25	85.141	118.020
46	1414.000	3	11	10	30	58.800	89.116
47	1528.250	3	11	10	35	37.558	47.822
48	1528.250	3	11	10	40	37.558	47.915

Fig. 4. Experimentation results

From the results shown in Fig 4, scenario 43 is seen as the best configuration as it meets the desired patient service levels and maximises the patient output. The pinch points of the configuration were the Clinical Assessment capacity and the seating capacity of the Observation area. The latter change is seen an easy fix with little financial implications as the spacious venue could easily accommodate the change. The selected configuration was developed as the improved model as shown in Fig 5.

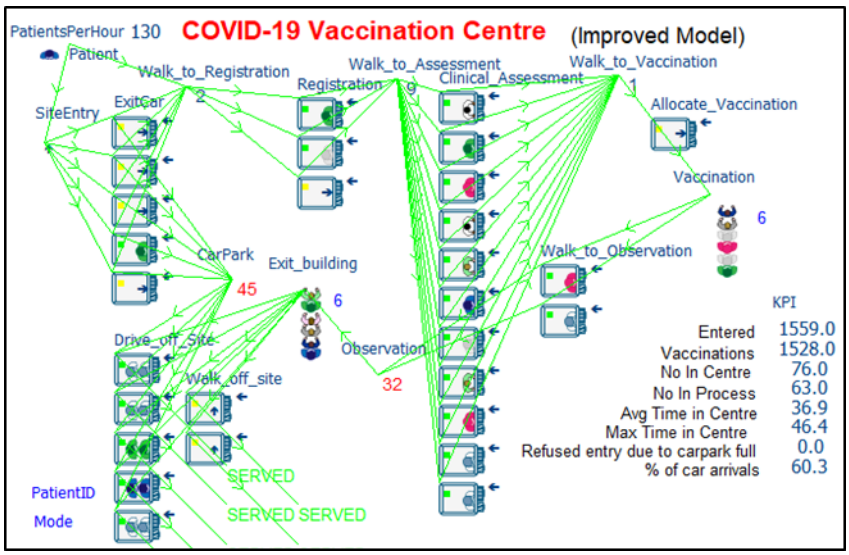

Fig. 5. Improved simulation model @12 hours.

The improved model was further experimented upon to understand its behaviour. A comparison of the two models for the number of patients in service and in queue was undertaken. The simulated results are shown in table 6. A noticeable marked decrease in queue size at Registration and Clinical Assessment are predicted using 95% confidence interval. The impressive vaccination output of an additional 400 patients has serious performance impact on the mass vaccination programme for that community.

Table 6. Simulation results of improved model after 12 hrs.

	Vaccination Output (per day)	Mean Number (95% CI) of Patients in Queue			
		Registration	Clinical Assessment	Vaccination	Assessment
Baseline Model	1128	20.516 (19.661 - 21.371)	9.225 (9.161 - 9.289)	0.805 (0.803 - 0.808)	0.782 (0.782 - 0.783)
Improved Model	1528	4.149 (3.977 - 4.321)	6.268 (6.092 - 6.445)	1.091 (1.089 -1.094)	1.060 (1.059 - 1.061)

9 Discussion

We have introduced a simulation tool for evaluating a Covid-19 vaccination centre. Such tools can help with enhancing the service level and operational performance of such facilities. We used Witness Horizon simulation software to develop the model as it provides opportunities for more effective functionality and visualization (2D and 3D) capability over other available tools.

The results presented in Fig 3 were generated by one realization of the simulation for demonstration purposes. The parameters here have been set using observation data from the vaccination centre in the as-is state. The results of our single simulation were rather different to those observed due to stochastic elements. This was rectified through experimentation. Our goal was to explore operational changes that could improve patient throughput to 1560 daily vaccinations and also meet patient service levels. Improvements were conducted using Witness Horizon Experimenter enabling good confidence levels to be achieved through hundreds of replications. A 30% increase in patient arrivals (hourly) was instigated coupled with minimal increase in resources. The best configuration was determined using adaptive simulated annealing algorithm. The results shown in Fig 4 indicate that capacity at Clinical Assessment and that of the Observation area are very critical. Utilising this configuration enabled the improved model to be developed. Experimentation with the improved model demonstrated a daily vaccination output of 1528 patients. Whilst the target of 1560 vaccination is not achieved, the simulated output of 1528 is certainly a substantial improvement to the current operations.

Modelling has influenced the decision to increase staffing levels by +3 at Clinical Assessment and +2 at Vaccination as the productivity gains far outweigh the financial implications. The required increase of Observational capacity by +10 has no financial implications but interestingly very critical in the patient flow characteristics. Resource management is like a dynamic commodity and very challenging, whilst additional resources could have been utilised the optimisation algorithm has not shown to have an adverse performance impact (Fig 4).

Simulation results suggest that the improved configuration will noticeably reduce the patient queues at Registration and Clinical Assessment stations (table 6). Management are certainly very supportive of trialling these changes and achieving a good balance of high throughput, queue reduction whilst maintaining site safety.

10 Conclusion

This study and the simulation models can provide some insights regarding different vaccination centre parameters in terms of patient arrival rate (hourly), staff levels, queue capacities, vaccination cubicles, car park capacity. It is not possible to sensitively validate site performance since real-life operations involve intermittent shutting down of and re-opening of various service channels. This variance in many ways is not fully appreciated by the model.

An important point is that the patient arrival rates impacts the results significantly (13). In the improved model, we used a fixed arrival rate of 130 patients per hour. However, the arrival rate does not have to be fixed and can vary during the day depending on demographic and environmental factors. The arrival rate has significant impacts on the number of people being vaccinated. It has been assumed that pre-registration has been done and all patients have pre-booked appoint slots. According to previous studies, the registration stage contributes most to the formation of bottleneck in mass vaccination systems. The project has provided some insight in just some of the ways in which modelling and simulation can improve vaccination centre operations.

Public health agencies can use our simulation model to examine how many people can be vaccinated for a given number of days, shifts, and working hours per shift. Moreover, the model can help decision makers to have an estimate of how many vaccination centres would be needed to achieve a certain number of immunizations in a specific time period.

As with any type of modelling study, the various assumptions and simplifications can easily contribute to a number of limitations. The service times used in our model have come from observation data and published data (8). One limitation of this simulation that demands further work is consideration for additional behavioural and user needs, such as the ability of the simulation to allow people who change their mind after they enter the vaccination line to leave, people who need further recovery time and might even need to be taken care of in a caregiving area, patients need for washrooms, etc.

Although this study is based on observational data, measuring the actual impact of proposed interventions on patient arrival rates and patient flow times requires a real-world implementation. Such efforts, however, require financial support. As such, this is another limitation of the current study.

Given that, Covid-19 is unlikely to completely disappear; mass vaccination centres are probably going to become more common, therefore, there are many opportunities for future work in this problem area. In this study we assumed service times were not alterable, however combining Clinical Assessment and Vaccination into a single station is an approach worthy of consideration. We also have not considered the impact of shocks in the system and how readily they can be absorbed such as staff sickness or a number of patients arriving all at once. Seasonal variations have not been considered, extra layer of clothing worn during winter as compared to summer clothes. Magnitude and effects of "no shows" has not been considered.

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