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Challenges and solutions for designing a Covid-19 vaccination hub: a simulation approach

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Abstract

It is the intent of the work to support experts in the organization process of Covid-19 vaccination hubs. An approach based on Modelling & Simulation (M&S) is proposed and in particular, a simulation model of a real vaccination hub, located in South of Italy, has been developed. The simulation model recreates, with satisfactory accuracy, the evolution over the time of the real system and it has been used to analyze the system behavior under several operative scenarios. The generation of the alternative operative scenarios comes from the variation of multiple design parameters that affect multiple performance measures. The quantitative evaluation of the effects of the multiple design parameters on the multiple performance measures can be used as starting point to improve processes as well as to plan effectively available resources within vaccination hubs.

Keywords: Covid-19 pandemic, vaccination hub organization, Modeling & Simulation, process design, resources planning

1. Introduction

From the beginning of the COVID-19 pandemic, more than 265 million confirmed cases and more than 5.2 million deaths were documented by the World Health Organization (WHO). A range of several measures have been presented and implemented by governments in response to the Covid-19 pandemic. The discovery and the development of a vaccine was indeed among the best scientific achievements (Graham, 2020; Lurie et al., 2020), however it represents only the beginning of a long path towards a final solution (Bertsimas et al. 2022). Vaccines production, distribution and delivery at large scale are the next important challenges to be faced (Bertsimas et al. 2022) in order to deal with the pandemic emergency and proceed with an effective vaccination campaign. Nowadays 67.7% of the world population has received at least one dose of a COVID-19 vaccine, 57.3% is fully vaccinated, and 12.59 billion doses have been administered globally (further information can be found at https://ourworldindata.org/covid-vaccinations).

The mass vaccination is still an on-going process and the number of vaccinated people must be brought as close as possible to the totality of the world population. In this context, it is important to underline that maximization of the vaccination campaign is also achieved through appropriate resources planning and process design of vaccination hub (Asgary et al. 2021). The process of organizing a vaccination hub needs to be structured by taking into considerations stringent storage and handling requirements on Covid-19 vaccines temperature, venue, and other conditions (Zhang et al. 2022) as well as by planning sufficient staff and space for screening, registration, vaccination and observation (Carrico, 2002). Obviously, everything must be aimed, from one side, at maximizing the number of vaccinations considering the available resources while making sure that the throughput time is kept to a minimum and, from the other side, at reducing vaccines storage and transportation time and costs (Georgiadis et al., 2021). In this challenging scenario, it is clear that the optimization of the performance measures of a vaccination hub is definitely affected by its process design and by an effective plan of the available resources.

This research work aims at supporting experts and decision makers in the organization process of a Covid-19 vaccination hub by studying and analyzing its behavior under different operative scenarios. An approach based on M&S is proposed and a simulation model of a real vaccination hub has been developed and used to evaluate the effects of multiple design parameters on multiple performance measures. The quantitative evaluation of those effects can be used as starting point to improve processes as well as to plan effectively available resources within vaccination hubs. The reminder of the paper is organized as follows: section 2 provides a description of the operational context as well as of the operative model and dynamics behind a vaccination hub; section 3 presents the development of the simulation model; section 4 describes the multiple design parameters, the multiple performance measure as well as the main results of the simulations. The last section reports the conclusions that summarizes the scientific and academic value of the work.

2. Context analysis and vaccination hub operative model

The vaccination hub considered in this research work is located in South of Italy (Calabria). The hub consists of two different vaccination lines: a drive-through line for cars and a vaccination line for pedestrians. Moreover, a home vaccination service is foreseen for those people which have difficulties to reach the hub and, whose average inoculation capacity is 7 vaccines per day. In the hub, vaccines are administered only by appointments so that the daily schedule is fixed and known. Every day, vaccines are delivered to the hub early in the morning by means of dedicated trucks, which are unloaded by using specific carts and stored in the hub warehouse, where several refrigeration cells are located. Within the hub, the vaccines are allocated to the vaccination lines by operators moving either by carts or by foot. The vaccines administration to people starts at 9 a.m. and ends at 5 p.m., 12 cars is the average hourly capacity for the drive-through vaccination line, while 8 patients can be hourly managed in the pedestrian line. As soon as the patients arrive to the hub, first, registrations activities, in dedicated areas, are carried out by medical staff, then it is proceeded with vaccines inoculation. Once this latter activity is completed, patients are requested to wait about 15 minutes in specific hub areas to monitor possible vaccine side effects, for which a first aid may be needed. At the end of the vaccination cycle, operators put all the used equipment to inoculate vaccines into rubbish boxes, which are daily picked up from garbage trucks at 6 p.m.

3. Simulation model development

This section presents the simulation model being developed to recreate, with satisfactory accuracy, the evolution over the time of the vaccination hub. The simulation model has been developed by means of the discrete event simulation software *AnyLogic 8* (further information on *AnyLogic* can be found at https://www.anylogic.com/). Three different simulation frames have been developed to reproduce respectively:

1. the arrival of trucks which deliver, in the morning, the vaccines to the hub and the arrival of trucks which pick, in the afternoon, the garbage up from the hub.
2. the handling process of vaccines within the hub, from the storage in warehouse to the allocation to the vaccination's lines till the vaccine's inoculation to the patients.
3. the physical flow of all the patients which enter the hub either by cars or pedestrians, from their arrival till their departure after the vaccine administration.

Each simulation frame consists of (i) *source objects*, reproducing entities (i.e., trucks, cars, pedestrians, etc.) entering the vaccination hub, (ii) *resources pool*, reproducing all the entities (i.e., nurses, medical staff, etc.) directly operating within the hub, (iii) *moveTo objects*, recreating the movements of all the entities within the hub and finally (iv) *schedule objects* to reproduce the vaccination cycle processes. Moreover, *variables objects* have been used to store data and information related to the simulation models runs. Figure 1 shows an example of the simulation model flowchart related to the physical flow of all the patients entering the hub, while figure 2 and figure 3 depicts, respectively, 2D and 3D views of the simulation model.

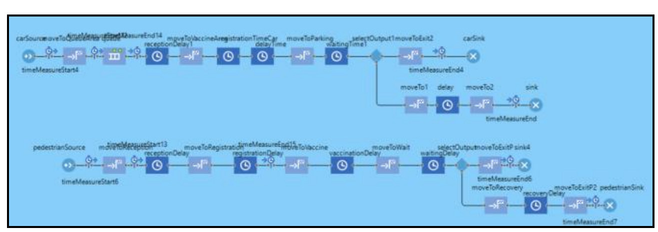

Figure 1. Physical flowchart of cars and pedestrians

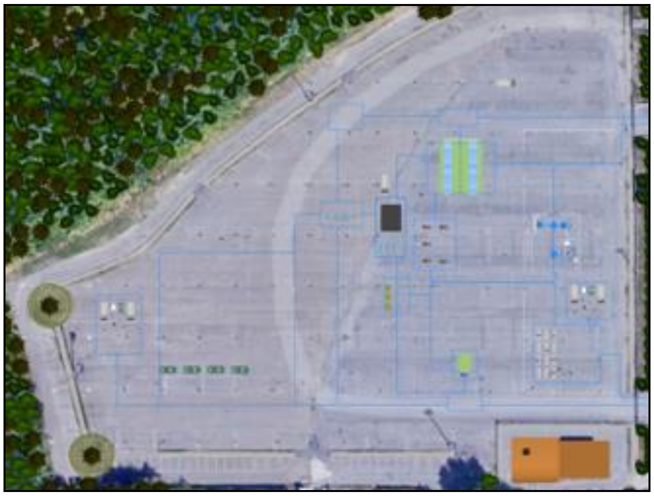

Figure 2. 2D view of the simulation model

Figure 3. 3D view of the simulation model

4. Design parameters, performance measures and simulation results

One of the main goals of the paper is to study and analyze vaccination hubs behavior under different operative scenarios. The generation of the alternative operative scenarios comes from the variation of multiple design parameters that affect multiple performance measures. In the sequel the authors present the design parameters (called also design factors), the performance measures as well as the simulation results. Section 4.1 presents the multiple design parameters, section 4.2 describes the performance measures, while section 4.3 reports a description of the simulation results.

4.1. Design parameters definition

At this stage, a preliminary analysis for detecting the design parameters (factors) that could have an impact to the vaccination hub performance measures has been carried out. The analysis shows that numbers of vaccination hub employees (i.e., nurses and operators), number of patients (i.e., pedestrians and cars) entering the hub per day as well as process times related to the vaccination cycles activities could be significant factors impacting the overall hub performances. 7 factors have been identified and 2 levels have been assigned to each of them, so generating 128 scenarios to be tested by using the simulation model. A brief description of each factor is reported below and table 1 shows the levels assigned to each of them.

- *avgNumberOfArrivalsCar*, it represents the average number of cars entering daily the vaccination hub.
- *avgNumberOfArrivalsPedestrian*, it represents the average number of pedestrians entering daily the vaccination hub.
- *receptionTime*, it represents the average time requested to each customer to fill registration forms in.
- *registrationTime*, it represents the average time needed to the operators to enter registration information for one patient within the vaccination hub IT system.
- *vaccinationTime*, it represents the average time needed to inoculate the vaccine to one patient.
- *numberOfVaccineCart*, it represents the number of operators that uses a cart to displace the vaccines to vaccination lines.
- *operatorsNumber*, it represents the number of operators that by foot displace the vaccines to vaccination lines.

Table 1. Design parameters.

FACTOR	MIN LEVEL	MAX LEVEL
avgNumberOfArrivalsCar	60	100
avgNumberOfArrivalsPedestrian	40	80
receptionTime	2 min	5 min
registrationTime	1 min	2 min
vaccinationTime	2 min	2,5 min
numberOfVaccineCart	2	3
operatorsNumber	2	3

4.2. Performance measures definition

The analysis of the vaccination hub behavior, under different operative scenarios, is carried out through the quantitative evaluation of the impact that the identified factors (see section 4.1) have to the multiple performance measures. The identified multiple performance measures are:

- *outputNC,* it represents the average utilization time of each nurse for each car in the drive-through vaccination line.
- *outputNP,* it represents the average utilization time of each nurse for each patient in the pedestrian vaccination line.

- *outputCartAndOperators1,* it represents the average working time per day of the operators which displace the vaccines by carts and by foot to the drive-through vaccination line.
- *outputCartAndOperators2,* it represents the average working time per day of the operators which displace the vaccines by carts and by foot to the pedestrian vaccination line.
- *outputAvgTimeForCarsLine,* it represents the average time that one patient, arriving by car, needs to complete a vaccination cycle, from its arrival to the hub to its departure after the vaccine administration.
- *outputAvgTimeForPedestriansLine*, it represents the average time that each pedestrian needs to complete a vaccination cycle, from its arrival to the hub to its departure after the vaccine administration.

Figure 4 depicts a windows view, being developed within the simulation model, to monitor and track the performance measures values.

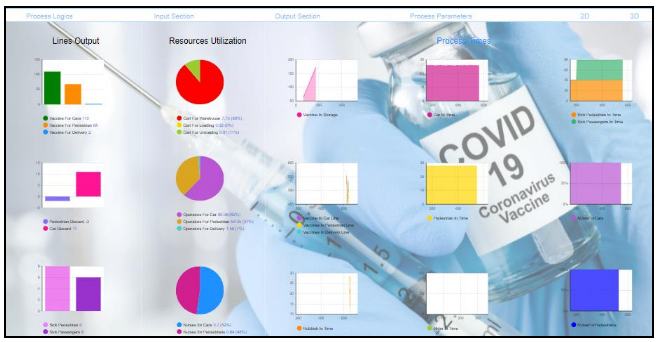

Figure 4. Performance measures output window

4.3. Simulation results

As stated before, the factor level combination of the design parameters has been used to generate several operative scenarios of the vaccination hub. Each scenario has been simulated and the simulation results have been assessed by using the Minitab software. Following the simulation results for each performance measure are described:

- *outputNC* and *outputNP:* the simulation results shows that the average utilization time of each nurse per car, in the drive-through vaccination line, as well as per patient, in the pedestrian's vaccination line, slightly and proportionally increases to the increase of reception, registration and vaccination times. Moreover, while an increase of the daily average number of cars leads also to a slight increase of the nurse's utilization time, an increase of the daily average number of patients in the pedestrian's vaccination line has almost no impact to the utilization time of the nurses. In fact, while the drive-through line is equipped to administrate vaccines in parallel and up to 2 cars simultaneously, in the pedestrian line only one patient per time can be vaccinated. An increase of pedestrian's number has therefore no impact to the nurse utilization time since the pedestrians just arrive 1 per time and as for the scheduled appointments. Finally, the simulation results shows that the average utilization rate of the nurses is 73% in the drive-through line and 76% in the pedestrian line. Figures 5 and figure 6 depicts numerically respectively the simulation results related to *outputNC* and *outputNP* performance measures.

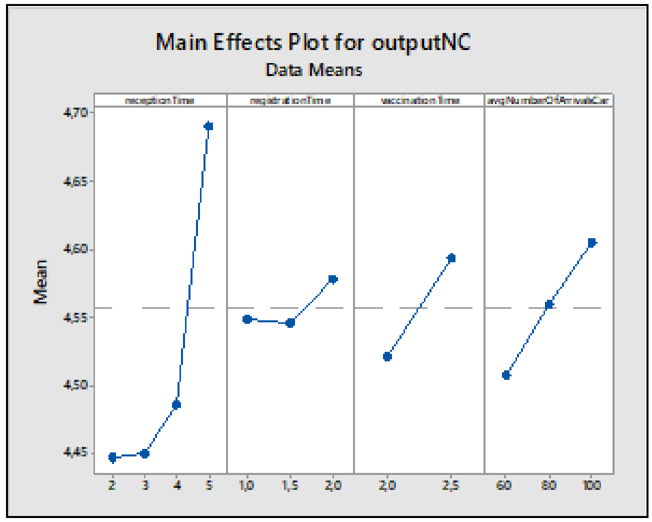

Figure 5. Main effects plot – outputNC

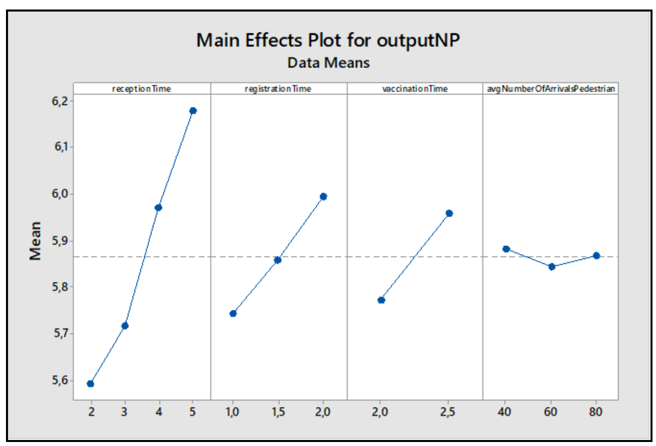

Figure 6. Main effects plot – outputNP

- *outputCartAndOperators1, outputCartAndOperators2*: the simulation results show that the average working daily times of the operators responsible to displace the vaccines, by carts and by foot, respectively to the drive-through and pedestrians vaccination lines are strongly affected by the number of operators hired to perform these activities. In fact, by employing even only one additional operator the average working times drop by 30%, and precisely from ca. 190 to 145 minutes per day.

- *outputAvgTimeForCarsLine,outputAvgTimeForPedestriansLine:* the average time for each patient to complete the vaccination cycle is definitely not affected by the number of patients being processed per day (factors *avgNumberOfArrivalsCar* and *avgNumberOfArrivalsPedestrian*). In fact, since the vaccination hub works only per appointments, each patient arrives at a scheduled time and immediately starts the vaccination process. Any changes to the number of patients leads only to an increase or to a reduction of the appointments being scheduled per day. On the contrary, the process times (reception, registration and vaccination times) strongly impact the time spent from the patients within the hub, from their arrival to their departure. Figure 7, for the drive-through line, and figure 8, for the pedestrian line, report the numerical impact of process time to the vaccination cycle.

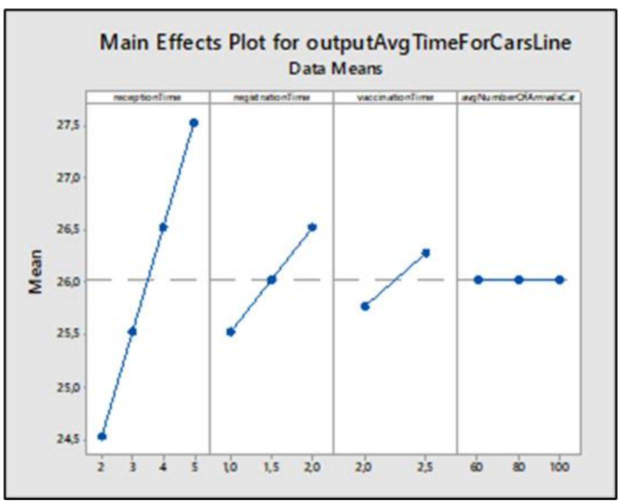

Figure 7. Main effects plot – outputAvgTimeForCarsLine

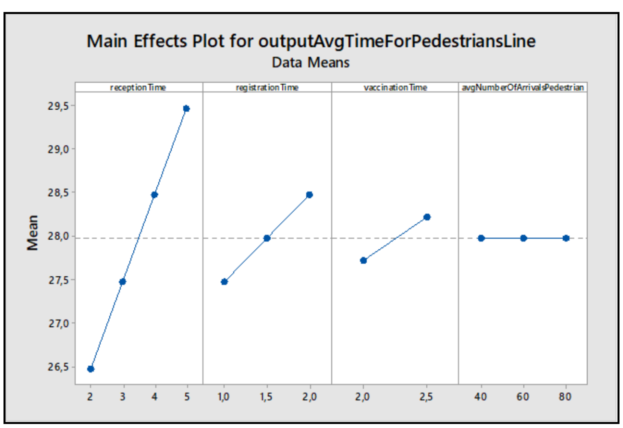

Figure 8. Main effects plot – outputAvgTimeForPedestriansLine

5. Conclusions

Covid-19 pandemic has changed humans' every-day life and in the last years a range of several measures have been presented and implemented by governments in response to it. Among the others, the discovery and the development of the vaccine represents one of the best scientific achievements. However, it is important to underline that maximization of the vaccination campaign is also achieved through appropriate resources planning and process design of vaccination hubs. In this context, this research work aims at supporting experts and decision makers in the organization process of a Covid-19 vaccination hub by studying and analyzing its behavior under different operative scenarios. An approach based on M&S is proposed and a simulation model of a real vaccination hub, located in South of Italy, has been developed. The simulation model has been used to evaluate the effects which multiple design parameters have on multiple performance measures. The factor level combination of the design parameters drives the generation of several operative scenarios of the vaccination hub. Each scenario has been simulated and the simulation results have been assessed by using the Minitab software. The simulation results show that vaccination cycle processes time (reception, registration and vaccination times) are among the most impactful parameters to the vaccination hub performance measures. Moreover, in case of vaccination hubs working only per scheduled appointments, an increase of the number of patients being processed per day has really low impact to operators' and nurses' average utilization times. Finally, an increase of the number operators responsible to move the vaccines from storage area to the vaccination lines drastically reduces the average working time per day of each of them, however additional costs vs. benefits analysis must be carried out before proceeding with new employments. Further researches are still on going to optimize the potentiality of the developed simulation model.

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