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A decision support system for scheduling a vaccination campaign during a pandemic emergency: The COVID-19 case

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**Title**

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# A decision support system for scheduling a vaccination campaign during a pandemic emergency: the COVID-19 case

**Abstract**

This paper considers the organization and scheduling of a vaccination campaign during a pandemic emergency. We describe the decision process and introduce an optimization model, which showed a powerful multi-scenario tool for scheduling a campaign in detail within a dynamic and uncertain context. The solution of the model gave the decision maker the possibility to test different settings and have a configurable solution within few seconds, compared with the man-days of effort that would have required a manual schedule. Analysis of a real case study on COVID-19 vaccination campaign in northern Italy showed that the use of such optimized solution allowed to cover the target population within a much shorter time interval, compared to a manual approach.
*Keywords:* COVID-19, vaccination campaign, mathematical model, healthcare, scheduling

## 1. Introduction

Scheduling a vaccination campaign during a pandemic emergency is a hard organizational task. We have a limited amount of vaccine shots and a forecast of availability in the next weeks, which is extremely uncertain. As in the case of the COVID-19, vaccines can be of several types, each one with its own prescribed delay between consecutive shots, and prescribed target population based on age or clinical status. Hence, among the several groups of individuals which are candidate to receive the vaccine, one has to decide which individuals and when inoculate the vaccine, and has to organize and schedule the associated operations.

The COVID-19 vaccination campaign has been a task of great complexity for national and Local Health Authorities (LHAs) since December 2020. As for the Italian context, decisions relative to the planning and implementation of the COVID-19 vaccination campaign are taken at three main decision levels: the national board, composed by the Ministry of Health and the COVID commissioner; the regional coordination center; and the Local Coordination Center (LCC). The national board was a reference point for regional representatives in charge of monitoring the progress of procurement, vaccination and surveillance and responsible for strategic decision in terms of:

- volume of COVID-19 vaccines purchased from pharmaceutical companies (e.g. Comirnaty, Spikevax, Vaxzevria, Janssen);

- delivery schedule of purchased doses;
- guidelines for the vaccination campaign, including target age groups to be vaccinated, potential starting date for each age group or target population campaign (e.g. extremely vulnerable people), compatibility between age group or target population campaign and COVID-19 vaccines (e.g. Vaxzevria incompatible for extremely vulnerable people);
- schedule and case mix of supplies distributed among the twenty regional health authorities;
- weekly and daily target vaccination volumes for each regional health authority.

The regional coordination centers were the reference entity for the regional vaccination points in charge of monitoring the progress of procurement, vaccination and surveillance within the region. The regional center operated as an organizational bridge between national instructions and guidelines and local operational implementation. At this level decisions were taken in terms of:

- regional starting date for each age group campaign according to national guidelines;
- weekly and daily target vaccination volumes for each LHA;
- booking system to be used for each age group or target population campaign.

LCCs were in charge of the operational coordination in terms of work teams, ordering and making vaccines and other necessary products available, and highlighting any operational problems. LHA oversaw the operational implementation of COVID-19 vaccination campaign. At this level decisions were taken in terms of:

- number of vaccination points to be opened and geographical distribution in order to maximize the coverage of each catchment area;
- characterization of vaccination facilities per vaccination campaign (e.g. mass vaccination facilities for younger people, hospital clinics for extremely vulnerable people, proximity clinics for elderly people);
- maximum volume of daily vaccinations planned for each clinic based on layout capacity, workforce availability (medical, nursing and administrative staff) and stock availability of COVID-19 vaccines;
- configuration of booking diaries for each vaccination campaign;
- implementation of proactive invitation campaigns for extremely vulnerable people.

This paper focus in particular on the decisions taken at the third level, for which a decision support tool based on a Mixed-Integer Linear Programming (MILP) model is developed.

## 2. Literature Review

The development of vaccines was the most effective tool for controlling the COVID-19 pandemic emergency. However, efficiently exploiting this opportunity created new management challenges, calling for quantitative approaches.

The first challenge faced by the scientific community concerned the prioritization of people to access vaccination. This decision is important in particular at the beginning of a campaign with a new vaccine, due to the low-capacity production. A review of modeling methods to optimize the allocation strategies based on different utility measures has been conducted by Liu and Lou (2022). A relevant attempt has been performed by Shim (2021) who proposed a model that aims to obtain the best vaccine allocation in order to optimize three alternatives objectives such as infections, deaths and life expectation. A data-driven model of COVID-19 transmission to deal with the vaccination prioritization problem has been proposed for the Chinese context by Han et al. (2021). The problems of choosing the best candidates for the vaccination not only on the basis of age has been considered by Książek et al. (2022), who propose two MILPs , one focusing on the social groups and the second one on territorial units.

Another relevant topic involved the vaccine supply chain (VSC). Georgiadis and Georgiadis (2021) consider the problem of minimizing the total cost of VSC trough a MILP, by simultaneously addressing the planning of vaccine supply chains, and the planning of daily vaccinations in the available vaccination centers. Ibrahim et al. (2022) introduced a multi-product MILP vaccine supply chain model for supporting planning, distribution, and administration of different vaccines, having different conservation and distribution requirements. Tavana et al. (2021) developed a mathematical programming approach for fair distribution in developing countries, taking into account the different vaccine storage conditions. A specific item of VSC is the facility location problem. Soria-Arguello et al. (2021) focused on the cross-dock warehouse selection in Mexico in order to minimize costs, while Tang et al. (2022) realized a bi-objective MILP to choose vaccination point, while considering both the economic and service quality criteria.

Bertsimas et al. (2021) proposed an integrated method that considers both prioritization and supply chain through a novel data-driven approach.

Moving to operational issues, Zhang et al. (2022) addressed an overall optimization of the appointments organization, while considering four different objectives: fixed costs for opening a vaccination site, total travel distance of vaccine recipients, total appointment rejection cost, and total tardiness cost. Small instances were addressed through a MILP, while a matheuristics algorithm was used for larger ones.

To the best of the authors knowledge, in this manuscript we present the first MILP model for scheduling a vaccination campaign, while minimizing the vaccination delay, that has been applied in a real setting and for which a solution optimized through a mathematical programming approach has been implemented in a large campaign.

## 3. COVID-19 vaccination campaign for the Local Health Authority of Bologna

In the following sections we describe a MILP model used to support the operational programming of the COVID-19 vaccination campaign for the population of Bologna LHA. This LHA is responsible of health management and health services provision in Bologna, a major city in northern Italy. This is one of the largest health agencies in Italy by size, its territory includes 46 municipalities for a population of over 870,000 inhabitants, and it is divided into 6 territorial districts, each one headed by a director, including the urban area of the city, a plain exurban area, and a mountainous area.

The activities of the coordination center of the Bologna LHA for the COVID-19 vaccination campaign were structured according to a planning approach based on the sequential activation of vaccination sub-campaigns. Each sub-campaign was characterized by a priority grade and the definition of target population (age group or pathology-related) decided at a nation level. The sub-campaigns were based on a appointment scheduling and booking paradigm where appointment slots for vaccination were made available to the population for self booking through multiple channels (online, telephone, de-visu at booking desks or pharmacies). In addition, a compatibility matrix was given for each campaign, defining the kind of vaccines that could be used for the target population. A summary of sub-campaign data for Bologna LHA is reported in Table 1.

| Sub-campaign | Population | Comirnaty | Vaxzevria | Spikevax | Janssen |
|---|---|---|---|---|---|
| OVER 80 | 63714 | X | | | |
| 75-79 | 35278 | X | X | | |
| OVER 70 + VULN. | 69126 | X | X | | |
| OVER 60 | 34962 | X | X | | X |
| OVER 65 | 24548 | X | X | | X |
| FRAGILE | 15752 | X | | | |
| OVER 55 | 39306 | X | | X | |
| OVER 50 | 30426 | X | | X | |
| OVER 40 | 68756 | X | | X | |
| OVER 18 | 78586 | X | | X | |
| OVER 12 | 127506 | X | | | |

Table 1: Compatibility matrix for each population group and vaccines.

From an operational point of view, the LCC had therefore the responsibility to define the best distribution of the openings on the agenda for each sub-campaign, while taking into consideration the territorial proximity of the vaccination centers to the population, so as to vaccinate the largest possible number of citizens in the shortest time. In defining the appointment slots to be made available, it was necessary to take into account a series of operational constraints: (i) availability of vaccine doses in stock, (ii) maximum capacity of available vaccination sites and (iii) availability of medical, assistance and administrative staff for the management of the vaccination points.

The programming flow of the vaccination sub-campaigns was structured as follows. The regional coordination center, following the input of the national board, outlined the guidelines of the sub-campaign (population group, starting date and booking channels), and communicated them to the LCC that was responsible for operational implementation. The operational implementation of campaign programming for LHA of Bologna can be distinguished in two phases, an initial one (phase 1) in which no support tool was available, and a second one (phase 2) in which a mathematical programming model acted as a pivot in the decision-making process.

The phase 1 decision-making process was essentially based on the definition of the weekly vaccine doses budget available for each of the 6 territorial districts. The vaccine doses budget available was defined by the LHA of Bologna Operations Research team based on the forecasts of deliveries. The task of each District Director was then to identify and verify the availability of the territorial vaccination centers and coordinate the representatives of the other involved departments to check the availability of staff for shifts coverage. Once a proposal was formulated, each District Director communicated to the Operations Research team the appointment time slots to be opened which were checked to assess the consistency with respect to the stock availability. The validated appointment slots plan was then sent in configuration to guarantee bookability through the indicated booking channels. The duration of this decision-making process could take from 3 to 5 days with a time requirement of at least 6 hours for the development of a proposal of appointment slots to be opened being consistent with the availability of the vaccination centers for the second doses. A summary of the phase 1 decision-making process is describe in Figure 1.

The phase 2 decision-making process was activated with the "OVER 70 + vulnerable people" vaccination sub-campaign, and envisaged a substantial revolution thanks to the availability of a decision support tool based on a MILP model. The tool allowed the decision maker to schedule a vaccination campaign in few minutes. The campaign specifications were translated into quantitative parameters by the Operations Research team that was responsible for feeding the optimization model with data of the demand to be met (in terms of vaccination coverage), the available vaccination sites, their maximum vaccination capacity per shift, the plan of first and second doses already foreseen by previous sub-campaigns and the forecast of the weekly delivery volumes of vaccine. The hypothesis of vaccination sub-campaign schedule of each district, as computed by the model, was sent to each District Director who was therefore relieved from the tasks of elaborating a proposal and verifying compatibility. This way, the entire process of planning and configuring appointment slots could be completed in two days with a substantial risk error reduction. A summary of the phase 2 decision-making process is describe in Figure 2. The MILP model described in the next section was defined and used to support this planning activity.

## 4. Problem formulation and MILP model

A MILP model was developed in order to support the COVID-19 vaccination campaign, by identifying the calendar of opening agendas in line with stock availability and forecast, type of vaccine that can be used by target age group, sub-district demand, divided according to proximity to vaccination hubs and desired coverage rate. The objec-

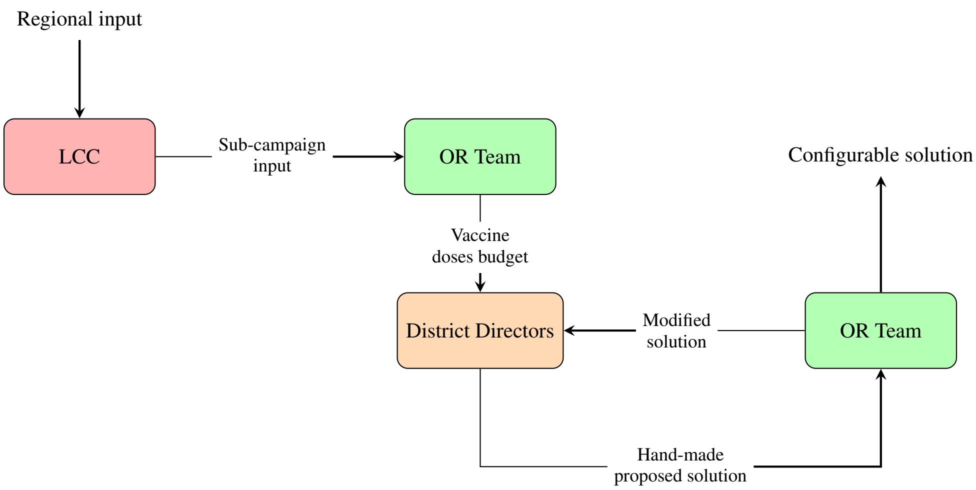


Figure 1: Decision flowchart phase 1

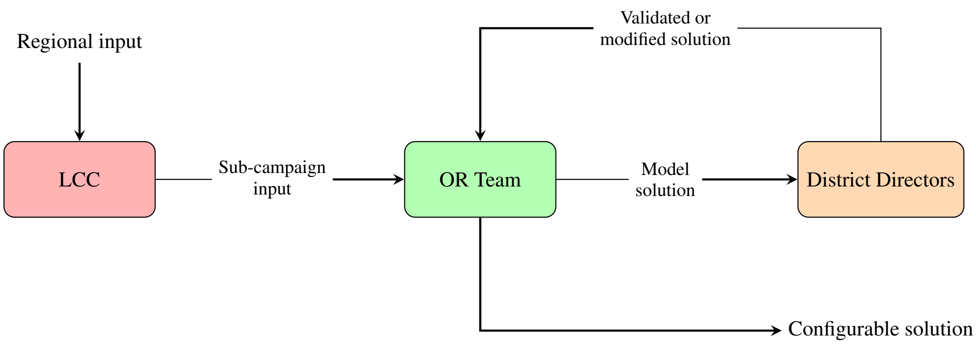


Figure 2: Decision flowchart phase 2

tive of the model is to cover the whole demand in the shortest time, by minimizing a suited function of delay. More in detail, we are given a set $S$ of facilities where the vaccine can be administered, a set $T$ of possible time slots, a set of districts $D$, each one with an associated demand $Q_d$, a set $V$ of vaccines and a set $Z$ defining the possible vaccine mix to be offered at a slot. We plan over a set $G = 1, \ldots, n$ of days; for each slot $t \in T$, we denote by $g_t$ the corresponding day; for each day $g$, we denote by $T_g \subset T$ the time slots of day $g$.

*Parameters.* $C_{st} =$ capacity of facility $s$ at slot $t$

$Q_d =$ demand for district $d \in D$

$r_{vz}$ = share of vaccine $v$ in mix $z$

$arr_{vg}$ = delivery of vaccine $v$ for day $g$

$a_{v1} =$ initial stock of vaccine $v$

$\Delta_v$ = second shot delay for vaccine $v$

*Decision variables.*

$$y_{stz} = \begin{cases} 1 & \text{if slot } t \text{ at facility } s \text{ is activated with a vaccine mix } z \\ 0 & \text{otherwise} \end{cases}$$

$x_{stz} =$ number of first shots of vaccine mix $z$ allocated on facility $s$ at slot $t$

$a_{vg} =$ number of shots of vaccine $v$ available at day $g$

Let $f(g_t)$ be a generic non-decreasing function penalizing the delay associated with day $g_t$. A MILP model for scheduling the vaccine campaign reads

$$min \sum_{s\in S} \sum_{t\in T} \sum_{z\in Z} f(g_t) x_{stz} \tag{F.O}$$

s.t

$$\sum_{z\in Z} y_{stz} \leq 1 \quad \forall s \in S, \forall t \in T \tag{1}$$

$$y_{stz} + y_{s\tau\zeta} \leq 1 \tag{1 bis}$$

$$\forall s \in S, \forall((z,t),(\zeta,\tau)) \in E$$

$$x_{stz} \leq C_{st} y_{stz} \quad \forall s \in S, \forall z \in Z, \forall t \in T \tag{2}$$

$$\sum_{\zeta\in Z} \sum_{v\in\zeta} \sum_{\tau : g_\tau + \Delta_v = g_t} x_{s\tau\zeta} r_{v\zeta} \leq C_{st} - \sum_{z\in Z} x_{stz} \tag{2 bis}$$

$$\forall s \in S, \forall t \in T$$

$$\sum_{s\in S_d} \sum_{t\in T} \sum_{z\in Z} x_{stz} \geq D_d \quad \forall d \in D \tag{3}$$

$$a_{vg} + arr_{vg-1} + \tag{4}$$

$$- \sum_{s\in S} \sum_{t\in T_g} \sum_{z\in Z} x_{stz} r_{vz} - \sum_{s\in S} \sum_{t\in T_{(g-\Delta_v)}} \sum_{z\in Z} x_{stz} r_{vz} = a_{vg+1}$$

$$\forall g \in G \setminus \{1, n\}, \forall v \in V$$

$$x_{stz} \in \mathbf{Z}^+ \quad \forall s \in S, \forall g \in G, \forall t \in T, \forall z \in Z \tag{5}$$

$$y_{stz} \in \{0,1\} \quad \forall s \in S, \forall g \in G, \forall t \in T, \forall z \in Z \tag{6}$$

$$a_{vg} \in \mathbf{Z}^+ \quad \forall v \in V, \forall g \in G \tag{7}$$

The objective function minimizes the cumulative delay of first shots, weighted by the penalty function $f(g_t)$. Constraints (1) impose that each slot $t$ in a facility is assigned to no more than one vaccine-mix $z$, while constraints (1 bis) define incompatibility constraints among vaccine-mix and slots at the same facilities, where $E$ is the list of such incompatible pairs. These constraints are imposed for slots taking place in the same day, in order to avoid possible confusion. Inequalities (2) impose capacity constraints for the first shots and link the binary slot activation variables with the integer $x$ variables. Similarly, (2 bis) impose capacity constraints, taking into account that the capacity available at slot $t$ is reduced by the number of second shots for a vaccine $v$ for which first shots were dispensed $\Delta_v$ days in advance. Constraints (3) impose that the demand of each district $d$ is completely satisfied through slots allocated to facilities within the district. Constraints (4) define the stock of vaccine at the end of each day. In particular, the LHS of these constraints sums-up the current stock, the deliveries, and subtracts quantities related with first and second shots, which equals the stock at the next day, appearing in the RHS. Finally, (5), (6) and (7) define the domain of the variables.

## 5. Algorithm

The model presented in Section 4 was used to organize the vaccination campaign, starting from the "*OVER 70 + vulnerable people*" sub-campaign. Therefore, a basis for direct evaluation of the performance improvement compared with a manual solution is not available. Nevertheless, we have developed a simple heuristic algorithm that mimics the strategy adopted for designing the vaccination campaigns before the model was developed, and provides an alternative realistic scenario for the vaccination campaigns organization.

The algorithm considers the same parameters as the MILP model, and computes a feasible solution, by following an iterative approach similar to the one used by experts. The objective is the same as for the MILP model, i.e., assigning all the demand in the shortest time while satisfying the constraints described in the previous section.

The pseudo-code in Algorithm 1 describes the optimization process. Starting from the district with largest (yet unsatisfied) demand, the algorithm tries to assign a specific number of vaccine shots (the remaining demand or a multiple of the facility capacity) in the first available time slot. This requires to check the facility capacity and the dose availability at the slot and at the time for the second shot. When an assignment is performed, the demand, and capacities are updated and a new district is considered. The algorithm iterates until the demand of all districts is satisfied.

### 5.1. Use of the MILP model and heuristic algorithm

In order to allow a fair comparison between the MILP model, which was used in practice to schedule the campaigns in Bologna, and the algorithm that mimics a manual solution, the latter was run on the same data and by following the

**Algorithm 1**

Input: demands $D_d$, $\forall d \in D$; ordered sets: facilities $S$, time slots $T$, vaccine-mix $Z$;
**while** $\exists d \in D : D_d > 0$ **do**
  pick district $d$ with largest demand $D_d$
  $PACK \leftarrow []$
  **if** $D_d \leq 100$ **then**
    $PACK \leftarrow Dd$
  **else**
    $PACK \leftarrow [100, 80, 60, 50]$ ▷ facilities opening multiples
  **for** $t \in T$ **do**
    **for** $pack \in PACK$ **do**
      **for** $s \in S_d$ **do**
        **for** $z \in Z$ **do**
          try to allocate $pack$ shots of $z$ on facility $s$ at slots $t$ and $t + \Delta t_z$
          **if** feasible **then**
            update $D_d$
            update capacity of $s$ at $t$ and $t + \Delta t_z$
            **Break**

same procedure.

We run each method (MILP or algorithm) starting from the first day of the first campaign, with the real stock availability. For each subsequent campaign which started before the previous one was concluded, the actual availability of vaccine doses and the actual capacity at vaccination centers was computed by deducting the resources allocated to the previous campaign. In this respect, the output of each campaign was used as an input of the following ones. In addition, since some campaigns were performed before those scheduled through the MILP model, and other campaigns were performed in parallel with those considered in this study (e.g., rest homes residents), we removed the corresponding doses from the warehouse availability.

## 6. Results

We implemented the MILP model in the Julia language (Bezanson et al., 2017) with the JuMP package (Dunning et al., 2017), a domain-specific modeling language for mathematical optimization embedded in Julia. JuMP uses a generic solver-independent interface provided by the MathOptInterface package, making it easy to change between a number of open-source and commercial solvers. The resulting model was solved with the GuRoBi MILP solver on a server with an Intel Xeon Gold 6230 processor, 16GB RAM under the CentOS Linux operating system. As already mentioned, our goal is to vaccinate the largest number of people in the shortest time.

During the period between 09/04 and 08/07 a constant evaluation of LHAs efficiency was performed by both the Regional Coordination Center and the National board. Comparing the progress of the LHA of Bologna vaccination campaign with respect to the regional one (Source Open data Commissioner Structure), the vaccinations performed by the LHA covered a share of 20.5%. The number of vaccinations performed by the LHA of Bologna was slightly higher than the supply provided (equal to 19.8% according to the regional distribution criterion of vaccine supplies). The resulting overproduction of 3.5% in the given evaluation horizon can be considered as an efficiency indicator with respect to other regional LHAs. During the same period the National and Regional Coordination Centers provided weekly production targets for each LHA that were, for LHA of Bologna, equal to 606668 vaccinations to be performed. The total number of vaccinations performed by the LHA of Bologna in the given period has been equal to 613568 exceeding the production by 1.1%, also in this case, the vaccination campaign supported by the MILP model proved to be efficient.

Table 2 shows detailed information for each considered campaign, comparing the timings obtained with the MILP model and the greedy heuristic algorithm. The table reports the population size, the campaign starting date, the date when the last individual was vaccinated and the mean waiting time. We see that at the beginning the two solutions have a similar mean waiting time but then we have a divergent trend [1].

| **DATA** | | | **MILP** | | **ALGORITHM** | |
|---|---|---|---|---|---|---|
| Campaign | Population | Start date | End date | M.W.T. | End date | M.W.T. |
| OVER 70 + VULN. | 69126 | 11/04/2021 | 15/05/2021 | 18 | 21/05/2021 | 17.8 |
| OVER 60 | 34962 | 29/04/2021 | 27/06/2021 | 18.4 | 03/06/2021 | 18.7 |
| OVER 65 | 24548 | 13/05/2021 | 30/05/2021 | 7 | 14/06/2021 | 15.4 |
| FRAGILE | 15752 | 14/05/2021 | 06/06/2021 | 12.3 | 23/06/2021 | 20.6 |
| OVER 55 | 39306 | 01/06/2021 | 15/06/2021 | 4.3 | 14/07/2021 | 10.6 |
| OVER 50 | 30426 | 08/06/2021 | 27/06/2021 | 6.7 | 22/07/2021 | 8.8 |
| OVER 40 | 68756 | 13/06/2021 | 20/07/2021 | 13.7 | 25/08/2021 | 42.3 |
| OVER 18 | 78586 | 01/07/2021 | 20/08/2021 | 23.6 | 02/11/2021 | 67.1 |

Table 2: Solution comparison for each campaign.

The performance degradation of the algorithm is due to a domino effect that leads to an accumulation of delay, in particular in presence of second shots and limited vaccine supplies. In the dynamic context of a vaccination campaign, greedy choices, which can look good in the short time, have a negative impact on future opportunities.

Over the whole considered population of 361462 individuals, the average waiting time (in days) for the MILP solution is 60.4 days, while this figure is almost 17 days larger for the algorithm, with an average waiting time of 77.0 days.

Figure 3 show how the number of vaccine shots evolves over time. The algorithm solution has higher peaks but it is less regular and has troubles in assigning the first shots for the month of July, mainly for lack of capacity in the vaccination facilities. The MILP solution, instead, is more regular and the whole campain has an earlier termination date.

[1] the OVER 60 campaign started before the OVER 65 campaign due to supply and policy changes.

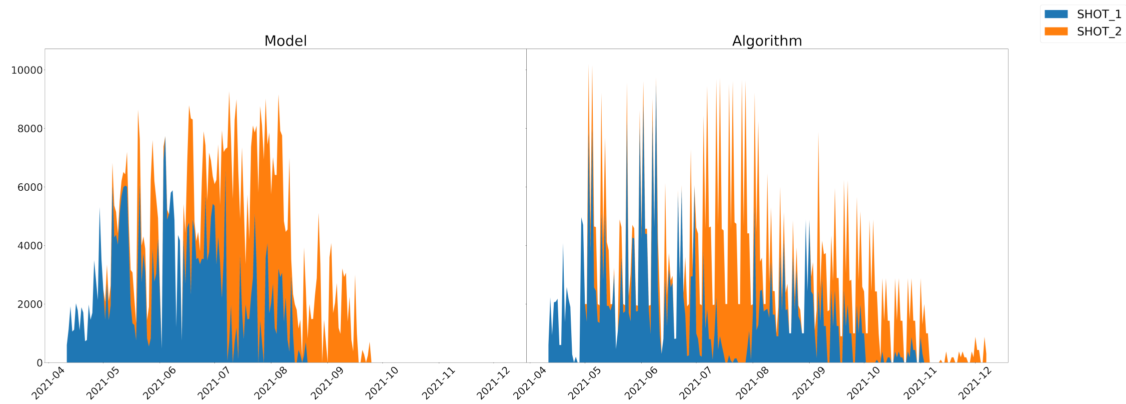


Figure 3: Vaccine shots trend

Figure 4 represents the stock evolution over time for each vaccine from 11/04/2021 to 30/06/2021, and it confirms that the algorithm performance deterioration is not due to stock availability.

The picture show that the consumption rate for Comirnaty is faster in the model solution as soon as there is a delivery. Moreover, Comirnaty trend consumption in the model solution is regular while in the algorithm solution a surplus stock is being accumulated. The stock of Vaxzevria follows a similar trend in both solutions, but in the algorithm solution there is long period of out-of-stock. Finally, Spikevax and Janssen have a limited impact on the vaccination campaign.

## 7. Conclusions

In this paper we have described the decisions that need to be taken for organizing a vaccination campaign during a pandemic, subject to strict constraints on availability of vaccine doses and limited capacity at vaccination centers. The design of the campaign is made even more difficult by the mix of different vaccines with diverse second dose delay and target population. In the specific case of the COVID19 pandemic, the effectiveness of the decision process was jeopardized by the extreme uncertainty concerning not only the forecast of the resources, but also the target population for each vaccine, which in some cases was changed from morning to night.

These difficulties made necessary to develop a fast multi-scenario tool to support the scheduling of campaigns. To this aim, we have introduced an optimization model which gave the decision maker the possibility to test different settings and have a configurable solution within a few seconds. A manual solution would have required about two working days with higher error probability, poor control of all the constraints and low flexibility, and also showed of lower quality in our analysis.

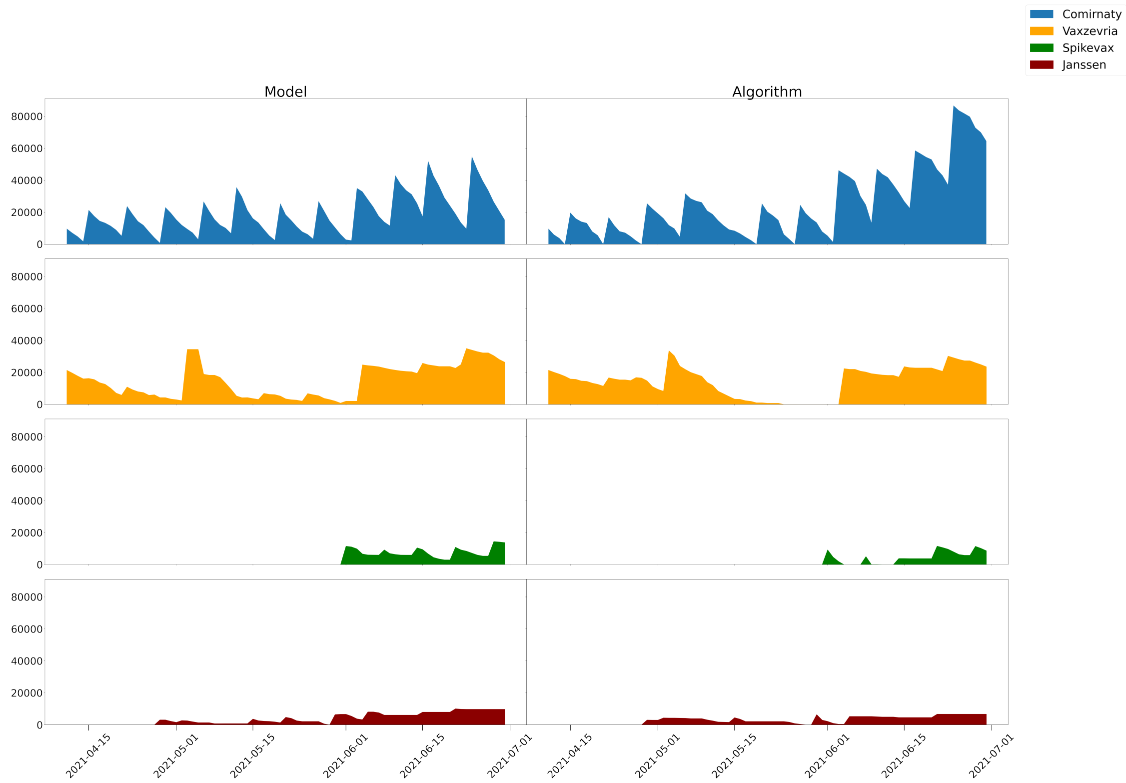


Figure 4: Stock trend for vaccine

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