Simulation of Mass Vaccination Programs: Centralized versus Mobile Vaccination

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Abstract **- Vaccines of different types and purposes are crucial for preventing the spread of deadly infectious diseases. However, deploying vaccines in highly populated areas proves to be a great challenge that must be evaluated and planned thoroughly before relying on any possible mass vaccination program. First, this paper highlights the significant differences between centralized and mobile mass vaccination programs. Then, it proposes workflows for these two programs. These workflows are used as a foundation for model building using Petri Nets. Finally, the models are implemented in the GPenSIM tool. This paper also presents a case study using the population in the municipality of Stavanger, showing the results of the simulations.**

Keywords - Vaccination program; Centralized Vaccination; Mobile Vaccination; Petri Nets; Modular Petri Nets; GPenSIM.

I. INTRODUCTION

Vaccination has long been a powerful tool in providing immunity against infectious diseases, which have otherwise been far more deadly without the mass production and distribution of effective vaccines to provide immunity against such deadly diseases.

Fig.1 shows the fatality rate of major virus outbreaks worldwide in the last 50 years as of January 2020 provided by "statista.com" [1], an apparent decrease of the fatality rate from 80% of the Marburg disease in 1967 to 9.6% of the SARS virus disease in 2002 highlights the importance and benefits of vaccination in the fight against new viruses and infections.

This paper describes a practical project that aims to measure the effectiveness of a traditional centralized mass vaccination program compared to a more mobile mass vaccination program. The main goal of this paper is to develop Petri Net models for these two types of programs and implement the models with the GPenSIM simulation tool for simulation and analysis.

In this paper: Sections II and III present some information on vaccination programs. Section IV presents formal definitions of Petri Nets. Sections V and VI present the Petri Net models of the vaccination programs. Some model implementation details are given in section VII, and section VIII presents simulation results.

II. VACCINATION PROGRAMS

The vaccination experiences have proven their effectiveness in protecting human and animal populations against various diseases since its introduction in 900 CE [2]. However, most of the research has been focusing on developing the right vaccine against new outbreaks of diseases, with little effort to investigate how to distribute the developed vaccines across societies in an efficient and agile approach. The speed and effectiveness in distributing vaccine doses to society members are essential in limiting and preventing disease outbreaks across the population - this is especially true in tight urban environments where individuals are dependent on daily physical contact to keep society functioning as desired.

This paper takes on the challenge of comparing the two main types of mass vaccination programs, namely, centralized program (asking residents to visit a vaccination center) and decentralized (mobile) program (health crew visit residents at their residence address).

Each vaccination program has its combination of advantages and disadvantages in terms of speed, quality, and environmental cost, along with some other factors:

- Centralized vaccination: easy to set up and manage; the disadvantage is the potential for spreading infectious diseases as people rush to the vaccination centers and wait in long queues to receive the vaccine.
- Mobile vaccination: Physical contacts can be minimized when a trained health crew visits residents to their homes to provide the vaccine. However, this mobile vaccination program comes with more management and coordination of the operations during the vaccination process.

III. CENTRALIZED VERSUS MOBILE VACCINATION PROGRAMS

The process that each vaccine receiver must go through is described as the workflow of the vaccination program; these workflows can vary in size and can become too massive for the modeling purpose. Therefore, this paper proposes two simplified workflows for centralized and mobile vaccination programs.

A. Short Literature Review

Smith & Smith [3] describes multiple considerations, challenges, and strategies associated with mass vaccination programs and their impact on the operation flow of vaccine deployment. This work focuses on studying the cycle time of various processes during the progress of vaccination programs.

Plotkin [4] presents a deeper insight into mass vaccination. This book addresses the importance of intelligent management of mass vaccination programs and highlights some of the benefits of having the right strategy behind mass vaccination operations.

B. Workflow for Centralized Vaccination Program

Starting with the centralized vaccination program, we assume visitors arrive at the vaccination center after booking an appointment. Also, the arrival rate is known to us (e.g., one visitor per minute). Upon arrival, the visitor should be registered at a registration desk before queueing up to receive the vaccine from trained health personnel. Then, the visitor stays in another queue to occupy a waiting room for observation for any unexpected side effects and reactions that might show within half an hour after receiving the vaccine. The process of registering a new visitor is estimated to take 5 minutes on average and requires the help of one staff member at duty. The vaccination process is expected to take 10 minutes on average and needs the help of one trained health personnel to inject the vaccine into the receiver's body in a safe way. At last, vaccine receivers are required to wait for 30 minutes in isolated observation rooms available at the vaccination center before leaving. This workflow is visualized below on the left side of fig.2.

C. Workflow for Mobile Vaccination Program

The previously proposed workflow of a centralized vaccination program is visitor-oriented flow, as visitors move from one stage to another through the vaccination center. This workflow is different for a mobile vaccination program as health personnel is dispatched from one street to another to visit residents at their homes and provide the vaccine, making the workflow more oriented to health personnel than the vaccine receivers.

The simplified mobile workflow is also shown in fig.2. It starts by dispatching a vaccination bus with one driver and one health personnel from one street to another, taking 15 minutes on average. After arriving at the target street, the vaccination process can start by visiting residents at their homes on this street or by letting the residents of the street queue up to receive their dose in the vaccination bus. Either way, it is estimated to take 10 minutes to provide one dose of vaccine (same as in a centralized vaccination program). After vaccinating the residents of the targeted street, the vaccination bus needs a turnaround time that is expected to take 1 minute before starting to drive to the next target street.

To focus on the primary operations of vaccine distribution, we assume that there exists a response team with sufficient capacity to respond to any side effects experienced by any vaccine receivers. For this reason, we will not include the details of the intervention from this response team in the main workflows of this research.

IV. PETRI NETS

The targeted mathematical models of the vaccination programs are Petri Nets. Hence, this section presents a brief introduction to Petri Nets. First, this section presents a formal definition of P/T Petri nets. And then, on Modular Petri Nets.

A. P/T Petri Nets

Petri net formalism consists of many classes of Petri nets. The simplest and original one is the P/T (Place-Transition) Petri nets. Fig.3 presents the formal definition of P/T Petri Nets [5].

B. Modular Petri Nets

Modular Petri Nets supports the development of models of large discrete systems by allowing independent development of modules and putting these modules together to make the overall model. Refs. [6] and [7] propose the newest modular Petri Nets. The modular Petri nets proposed in these two works are implemented in the General-purpose Petri Net Simulator (GPenSIM) [8], [9]. Hence, real-life systems can be modeled, simulated, and analyzed with GPenSIM as modular Petri Net models.

Due to space limitations, the formal definitions of Modular Petri Nets, Petri Modules, and Inter-Modular Connector are not shown in this paper. The interested reader is referred to [6] and [7].

V. PETRI NET MODEL OF CENTRALIZED VACCINATION PROGRAM

Centralized vaccination takes place in a fixed location where residents arrive at the vaccination center to receive a dose of the available vaccine. The process of receiving a dose of this vaccine is built around the idea of moving visitors from one stage to another and maintaining several intermediate places or queues between each stage.

A. The Stages of the Process

According to the proposed workflow on the left side of fig.2, centralized vaccination can be divided into three stages based on the purpose of each stage:

- **Registration**: This stage aims to verify and register a visitor upon arriving at the vaccination center. This stage is expected to take 5 minutes per visitor on average, and one staff member performs it.
- **Vaccination**: After registration, a visitor moves on to receive a dose of the vaccine from one trained health worker, which is a process that is estimated to take 10 minutes per visitor on average.
- **Waiting after vaccination**: Vaccines can cause severe allergic reactions and other side effects that can harm the person receiving the vaccine. A team of paramedics is available on the premises if anyone suffers from the side effects of vaccination. Therefore, it is essential to wait for at least 30 minutes before leaving the vaccination center. The waiting should also happen in isolated rooms to avoid infections between visitors because the receiver's body still hasn't gained the required level of immunity against the targeted disease.

It is vital to control the lengths of the queues involved in switching between the three stages as the longer the queue a visitor is more vulnerable to contract the disease from others. The length of these queues can be controlled by requiring the visitors to book an online appointment in advance before attending to receive the vaccine.

B. Petri Net Model

Fig.4 shows the Petri Net model of a centralized vaccination program. In this Petri Net, we have four types of transitions; these transition types are "tVISITOR", "tREGISTRATION", "tVACCINATION", and "tWAITING" each representing the processes of appointment booking, registration, vaccination, and waiting, respectively.

The Petri net model shown in fig.4 uses four places. Place "P1" denote visitors that have arrived at the vaccination center but still has not been registered yet, while tokens in "P2" denote registered visitors waiting to be vaccinated, and tokens at "P3" denote vaccinated visitors trying to access a waiting room and wait for 30 minutes before leaving the premises. Monitoring the number of tokens at "P4" allows us to track how many visitors the system was able to process at each time of the simulation.

C. Resources

Staff members and health personnel are active "elements" (in the Petri Nets terminology). However, it is troublesome to represent these active elements as transitions as the number of staff members and health personnel varies with time. In a Petri Net model, the number of transitions cannot vary; hence, GPenSIM provides "resource" as a mechanism to represent the varying number of staff members and health personnel (also, the capacity of waiting room). It won't be easy to develop a Petri Net model for a centralized vaccination program without using GPenSIM resources [10]. In fig.4, staff members (non-medical professionals), health personnel, and waiting rooms are represented by resources.

VI. PETRI NET MODEL OF MOBILE VACCINATION PROGRAM

Mobile vaccination offers residents the opportunity to receive a dose of the distributed vaccine at their residence without visiting a vaccination center as in centralized vaccination. The idea behind mobile vaccination is to divide the available team of trained health workers into different batches and equip them with a vehicle or what is also known as a vaccination bus. These busses are then dispatched to each street in the targeted residence area. Health workers either move on foot to vaccinate people at their homes or offer the vaccine to the residents of a specific street onboard the vaccination bus.

According to the workflow shown in fig.2, mobile vaccination can be divided into three stages:

- **Dispatch**: The operation of mobile vaccination starts with dispatching each health worker to a targeted street using a vaccination bus with its driver. Driving this vaccination bus to a new street address is expected to take 15 minutes on average from one street to another.
- **Vaccination**: After arriving at a new street, the health worker starts vaccinating street residents one by one. This process is estimated to take 10 minutes on average to vaccinate each resident.
- **Completion**: This is the turnaround stage performed after all residents of the currently visited street have been vaccinated. The bus can again get dispatched to a new street. The turnaround time is assumed to be 1 minute for this simulation project.

It is apparent that in a mobile vaccination program, residents do not have to stand in long queues to receive a dose of the vaccine. Minimizing the number of people who meet for vaccination helps contain infections.

A. Petri Net Model

Fig.5 shows the Petri Net model of a mobile vaccination program. This Petri net possesses three types of transitions, namely "tDISPATCH-*", "tVACCINATION-*" and "tCOMPLETION-*", each representing the processes of dispatching, vaccination, and turnaround completion, respectively. In this Petri Net, for simplicity, two bus drivers and two health workers are chosen (two dispatches).

VII. MODEL IMPLEMENTATION

Now that the Petri net models are in place (fig.4 and fig.5), it is time to start implementing the models for computer simulation using the GPenSIM tool. This paper is not giving implementation details due to space limitations. The interested reader is encouraged to check ref.[11] for implementation details. Some basic information on implementation is given below.

Petri net model implementation using GPenSIM results usually in four M-files:

I. Petri net Definition File (PDF).
II. Common Pre-processor File.
III. Common Post-processor File.
IV. Main Simulation File (MSF).

In addition to these four files, two particular files are known as "construct.m" (dynamic configuration files) that keep program-specific (centralized or mobile) details.

VIII. SIMULATION RESULTS

This section presents the simulation results to evaluate the differences in performance between centralized and mobile mass vaccination. The medium-sized municipality of Stavanger (in Norway) is chosen as the case study. Stavanger is selected because of its moderate density of human population and its geographic spread across various environments such as mountains and islands and areas of farming and residence. Table-I shows the assumed resources for simulation.

TABLE I. AVIALABLE RESOURCES.

Resources	Centralized Vaccination	Mobile Vaccination
Staff members	7	(not needed)
Health personnel	14	14
Waiting rooms	42	(not needed)
Busses with drivers	(not needed)	14

According to the central bureau of statistics in Norway, 144 515 residents live in Stavanger's municipality by the 3rd quarter of 2021 [12]. Also, 2021 streets are in Stavanger [13]. The average number of residents per street is calculated from these data, which results in 73 residents per street. These values (residents, streets, and average residents per street) are used as the arc weights of corresponding arcs.

Table-II summarizes the simulation results.

TABLE II. SIMULATION RESULTS.

Results	Centralized Vaccination	Mobile Vaccination
Total number of residents in Stavanger	144 515	144 515
Vaccinated residents in one simulated working day	602	629
Working days needed to vaccinate all residents in Stavanger	(144515 ÷ 602) = 241	(144515 ÷ 629) = 229

IX. CONCLUSION

This paper compares the two different approaches of mass vaccination programs, namely centralized versus mobile vaccination. Petri Net models based on the simplified workflows of the vaccination programs were used for the computer simulations using the GPenSIM tool.

The simulations for one working day reveal that the mobile vaccination program was able to finish vaccinating 27 more residents and still use fewer resources. This means the municipality of Stavanger (with its 144 515 residents and 2021 streets), mobile vaccination could finish vaccinating all its residents 12 working days earlier than traditional centralized vaccination.

It is important to note that no delays were assumed during the modeling phase. However, in reality, many factors can impact the progress of vaccination programs, like shortage of vaccine doses, sickness between personnel, less operational vaccination busses, or vaccination centers due to mechanical and logistical issues. Therefore, a model that includes these uncertainties is proposed as further work. Also, these models do not consider the costs involved. The costs are considered out of the scope of this paper.

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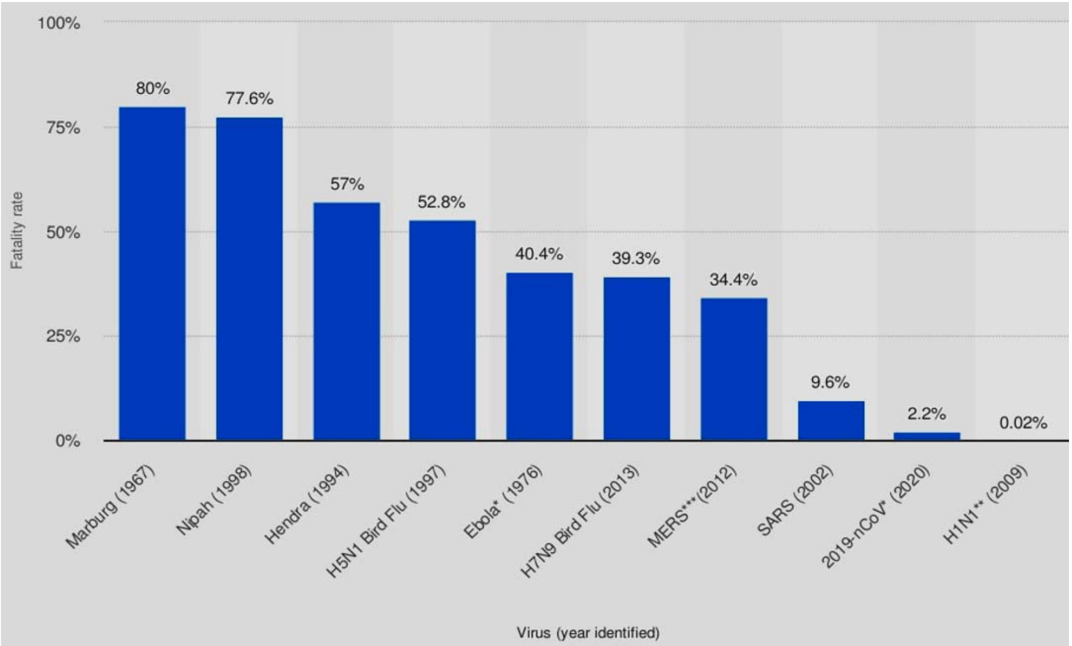

Figure 1. Fatality rate of some major virus outbreaks since 1976 [1].

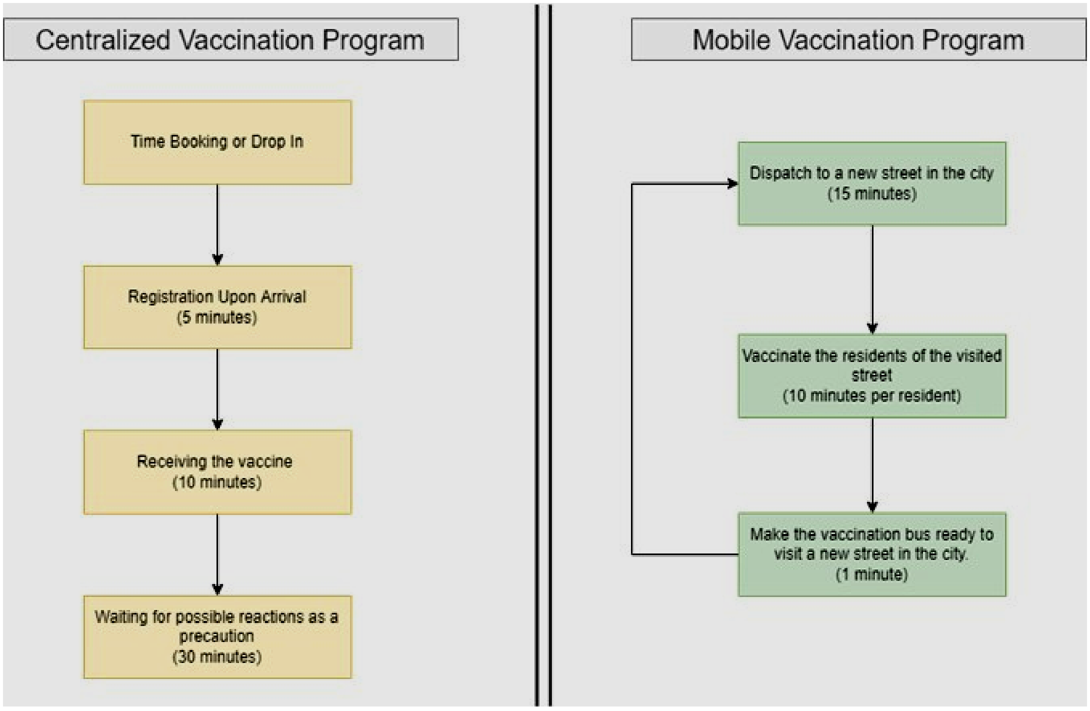

Figure 2. Simplified workflows of both centralized (left) and mobile (right) vaccination programs..

DOI 10.5013/IJSSST.a.23.01.06 ISSN: 1473-804x online, 1473-8031 print

The P/T Petri Net is defined as a four-tuple:

$$PTN = (P, T, A, M_0),$$

where:

P is a finite set of places, $P = \{p_1, p_2, \ldots, p_{n_p}\}$.

T is a finite set of transitions, $T = \{t_1, t_2, \ldots, t_{n_t}\}$.

$P \cap T = \emptyset$.

A is the set of arcs (from places to transitions and from transitions to places).

$A \subseteq (P \times T) \cup (T \times P)$.

The default arc weight W of a_{ij} ($a_{ij} \in A$, an arc going from p_i to t_j or from t_i to p_j) is one, unless noted otherwise.

M is the row vector of markings (tokens) on the set of places.

$M = \left[M(p_1), M(p_2), \ldots, M(p_{n_p})\right] \in N^{n_p}$,

M_0 is the initial marking.

Due to the markings, a $PTN = (P, T, A, M)$, is also called **a marked P/T Petri Net**.

Figure 3. Formal definition of P-T Petri Nets [5].

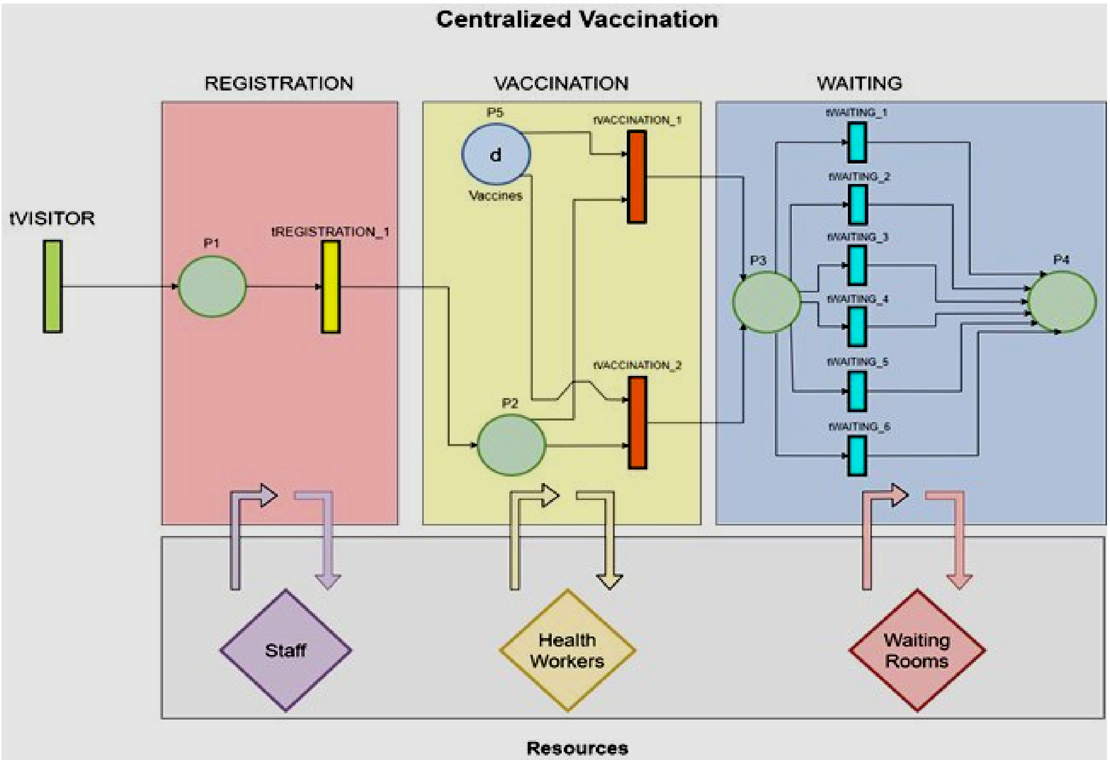

Figure 4. Petri Net model of centralized vaccination program.

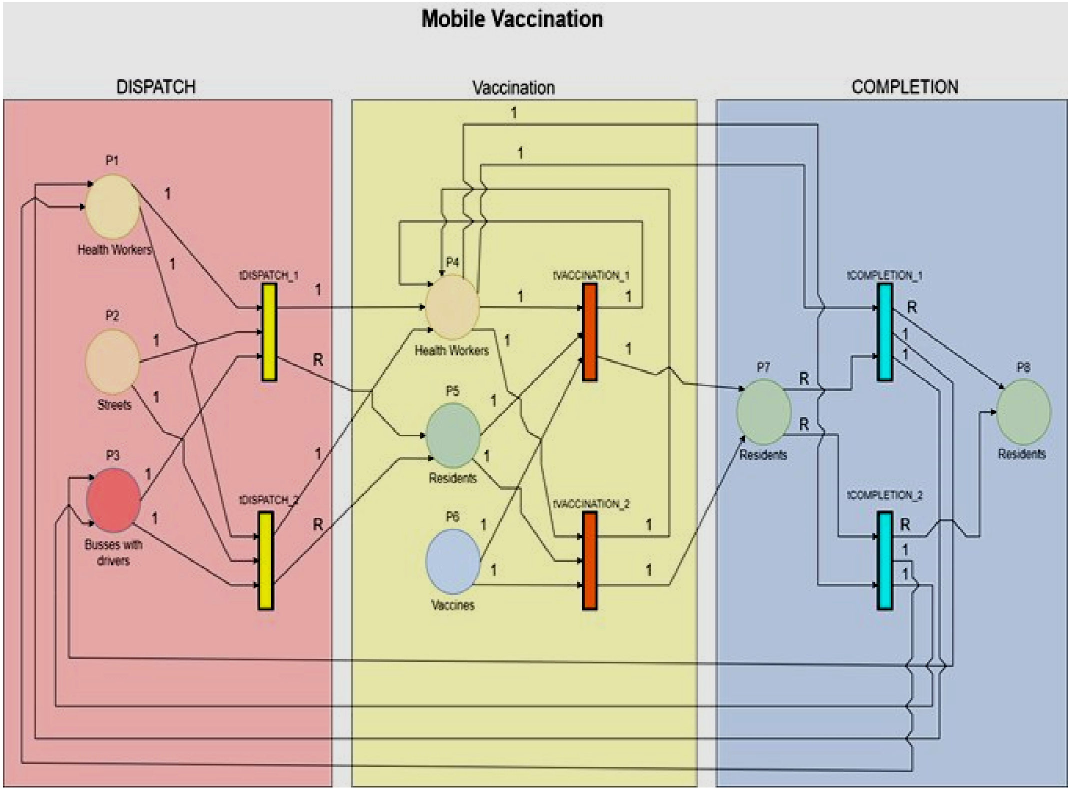

Figure 5. Petri Net model of mobile vaccination program.