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Applying Greenfield Analysis for Optimal Planning of COVID-19 Vaccination Outreach: A Case Study of Bali Province

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ABSTRACT

A key strategy to winning the war against the COVID-19 pandemic involves acquiring sufficient vaccination coverage of the population to attain herd immunity. Such a task is highly daunting for many countries, especially for those whose significant portions of the population have limited access to vaccination services. One way to overcome this challenge is by implementing an outreach program, which involves setting up new outreach sites in remote and sparsely populated areas to improve the vaccination access for people residing there. This paper presents a novel approach to the planning of such outreach sites systematically and optimally. Our approach comprises a two-step Greenfield Analysis (GFA) procedure implemented using supply chain design software. The first step involves the design of the vaccination network to find the number and location of outreach sites that maximize the vaccination coverage for people residing within a threshold distance from the outreach sites. This is followed by the design of the vaccine supply network between the health centers and the outreach sites to determine the required vaccine doses that need to be kept at the vaccination sites. The required number of vaccinators and their ancillary supply kits can also be determined accordingly based on the supply network. We have tested our approach on a case study involving the COVID-19 vaccination scheme for Bali Province in Indonesia. We obtained the optimal number and locations of outreach sites for each regency in Bali and the whole province.

Keywords: COVID-19 pandemic, outreach planning, vaccine allocation, cold chain management, center of gravity analysis

1. INTRODUCTION

The COVID-19 crisis has been declared the world's biggest challenge since the Second World War (Health Policy Watch, 2020). With more than two hundred and sixty-seven million registered cases and five million deaths and counting (Worldometers, 2021), this pandemic has become the most serious issue in virtually every part of the world, affecting not only the health and wellbeing of billions of people but also their livelihoods due to severe disruptions in the global supply chain caused by the country lockdowns (Pujawan and Bah, 2021). Thankfully, through unprecedented global cooperation, rapid sharing of research data and resources, and fast authorization from the regulators, several companies are able to successfully develop COVID-19 vaccines within less than a year.

One of the utmost important strategies to win the fight against this pandemic involves the rollout of the vaccine at various vaccination sites such as hospitals, clinics, and medical centers. The goal is to vaccinate a critical mass of people within the shortest possible time so as to break the chain of virus transmission. The sheer scale of such a task is daunting for many countries, especially for those whose significant portions of the population still have limited access to healthcare services—e.g. in remote areas with poor transport connections. One way to overcome the challenges for such regions is through vaccination outreach (Lim *et al*., 2016). Under this strategy, several outreach sites, known as mobile clinics, are set up at various locations near the target populations and the healthcare workers bring the vaccines from the storage locations such as hospitals and commute to the outreach sites to administer them on a regular basis. The benefit of such a strategy has been long documented in many studies. For example, a study by WHO reported an increase in the vaccination rate from 25% to 57% in one region in Kenya with low population density and an increase from 54% to 82% in a high population density area (WHO, 1977).

Given the positive impact of an outreach program in raising the vaccination coverage, it is thus essential for every country to incorporate such a plan as a part of their vaccine supply chain strategy. However, while a variety of mathematical techniques and modeling tools are widely available to support the design of vaccine supply chains, at present there are no standard approaches, quantitative models, and software tools that can assist countries in planning for optimal outreach strategies (Lim *et al*., 2016; Yang and Rajgopal, 2019).

In literature, studies on vaccination outreach planning have not received much attention until recently. Traditionally, vaccination outreach planning has been formulated as an optimization problem involving either population coverage or vaccination cost as the main objective. One of the early works on the subject was reported by Verter and Lappiere (2002), who extended a mathematical formulation, called maximal covering location model (MCLM) (Church and ReVelle, 1974), to find the optimal number and locations of outreach sites that maximize the population coverage—i.e. the number of people that resides within a threshold distance from the outreach sites. Later, Daskin and Dean (2004) evaluated the suitability of MCLM and two other facility location models, namely location set covering model and *p*-median model, on various outreach planning problems found in the literature. They categorized the characteristics of outreach planning problems into three classes and evaluated the suitability of the models to each problem class. In the same manner, El Mokrini *et al*. (2019) applied a location set covering model to determine the optimal number and locations of pharmaceutical warehouses that supply medicines to hospitals and various health centers in emerging markets. This location set covering model could also be potentially extended to vaccination outreach planning. Lim *et al*. (2016) proposed a mathematical formulation to maximize the number of people vaccinated at the outreach sites. They differentiated between the mobile clinics and the stationary healthcare clinics that serve as focal points for the mobile operations. Another optimal outreach planning approach was proposed by Carretti and Hashimoto (2020), who extended the approach of Lim *et al*. (2016) by incorporating additional factors such as the negative correlation of vaccination coverage and traveling distance, the capacity of the stationary clinics, and clinic operating costs.

Transport routing is one important factor that needs to be considered in the development of an effective outreach program, especially when multiple outreach sites are involved. In such a scenario, the vaccination team will need to visit multiple sites to render the services at each site before returning to the base point, which can be the hospital or the health center where the vaccines are kept. Some of the relevant work on this topic includes Hachicha *et al*. (2000), who introduced a location routing model to optimize the routes that must be taken by a vehicle to deliver the vaccines to various remote areas. Later, Doerner *et al*. (2007) extended the location routing model by introducing a multi-objective formulation involving three objective functions—i.e. the effective working time of the team, the average traveling distance of the population to the outreach sites, and the share of the population living outside the specified distances from the outreach sites—and solved it using metaheuristic algorithms. Building upon the work of Lim *et al*. (2016), Hasanzadeh Mofrad (2016) and Yang and Rajgopal (2019) proposed mathematical formulations by combining location set covering model and vehicle routing to minimize the vaccination costs. Liao *et al*. (2017) formulated a time-dependent vehicle routing model and solved it using the branch-and-price approach for efficient distribution of emergency healthcare supplies to hospitals and health centers.

While all the methodologies described above are valuable, they share several shortcomings. Except for the methodology proposed by Carretti and Hashimoto (2020), the rest are limited in their applications to optimizing vaccination coverage in regions with a relatively low population density or optimizing vaccine delivery to relatively small number of delivery nodes (i.e., hospital and medical centers). Outreach and delivery planning in dense population settings such as urban areas is much more challenging as it involves a large number of populations, hospitals, and medical facilities (Lim *et al*., 2016). The solution to such a large problem may necessitate the development of new formulations capable of finding optimal solutions within a reasonable computational time. Another inherent shortcoming of all of the abovementioned methodologies arises from the lack of GIS (Geographic Information System) support and functionality in their proposed mathematical models. For instance, in the reported work of Carretti and Hashimoto (2020), which can be considered as the most advanced approach to date, data grids covering the geographical area of interest need to be created first using a computer program—this is a very tedious procedure. Later, to avoid excessive computational burden during the optimization runs, the granularity of the data was reduced by decreasing the number of grids. Such simplification could lead to a lack of precision and hence compromise the accuracy of the optimal solutions.

Over the past year, studies about optimal design of vaccine supply chain and planning of COVID-19 vaccination outreach strategy have started to receive a lot of attention from researchers. To name a few, Sujaree and Samattapapong (2021) proposed a metaheuristic algorithm that was inspired by the chemical reaction theory to solve a vehicle routing problem of a COVID-19 vaccine supply chain network. Sun *et al*. (2021) proposed a transport simulation approach by combining vehicle routing and dynamic simulation to enhance the distribution of COVID-19 vaccines. Bertsimas *et al*. (2021) applied an epidemical model to capture the effects of vaccinations on the number of cases, hospitalizations, and deaths using US data. Next, they proposed a mathematical model to optimize the location of vaccination sites and the number of vaccines allocated to population age groups in one hundred most populous cities over a planning horizon. Xu *et al*. (2021) developed a mathematical optimization model for designing an optimal hub-and-spoke-based vaccine distribution network. Georgiadis and Georgiadis (2021) proposed a mathematical model for optimal planning of COVID-19 vaccine supply chains and the number of people vaccinated at vaccination centers. Our study contributes to the growing literature on COVID-19 vaccination strategy by proposing an outreach planning methodology for increasing the vaccination coverage of the population. Our approach is novel in the sense that we will customize a readily available supply chain design software to determine the optimal number and locations of outreach sites to maximize the population coverage. To the best of our knowledge, ours is the first study that applies commercial software to solve such a planning problem. Compared to other outreach planning methodologies proposed in the literature, which are quite complex and require advanced and specialized skills to develop the mathematical optimization models, the key advantage of our technique is that ours is more convenient to implement even by a non-expert who is not trained in mathematical modeling and optimization techniques. Further, the sophisticated GIS-aided functionality of the supply chain software that we use not only makes data entry a straightforward procedure but also obviates the need for data simplification. This will make this approach considerably more practical and thus may help in regional vaccination planning with greater accuracy.

2. METHODS

2.1 Vaccination Outreach Planning Methodology

Our methodology for vaccination outreach planning applies the concept of Greenfield Analysis (GFA)—also known as a center of gravity analysis—in supply chain network design. GFA is a technique commonly used during the early stages of supply chain design to find the optimal number and locations of production facilities and/or distribution centers. The goal of GFA is to meet a network of customer demands in the most cost-effective way. We noticed a striking similarity between vaccination outreach planning and supply chain network design in that a fixed health center can be represented as a production plant; an outreach facility is analogous to a distribution center, and maximizing vaccination coverage is the equivalent of meeting customer demands maximally.

Consider, as an example, an outreach plan involving five population sites (e.g. villages) and a fixed health center. There are several ways to solve the outreach location problem in this scenario. The most straightforward solution would be to make the health center also function as an outreach facility that residents from the villages can visit for their vaccination needs (see **Figure 1a**). Alternatively, one of the villages can be selected as an outreach site, as shown in **Figure 1b**. This means that residents from the other villages would need to travel to this outreach village to get vaccinated. Finally, we can set up a new outreach site close to all the villages, as illustrated in **Figure 1c**. While more than one outreach strategy can be employed here, in the final analysis, there will be two key factors that limit the selection of the outreach location. The first one would be the traveling distance from the population sites to the outreach site. This is an extremely crucial consideration in the outreach decision as several studies have highlighted the negative impact of distance on people's willingness to travel for vaccination especially in rural and sparsely populated areas (Lim *et al*., 2016; Feikin *et al*., 2009; Leithäuser *et al*., 2019). The second consideration involves the distance between the fixed health center and the outreach site as this will directly affect the cost of vaccine delivery to the population.

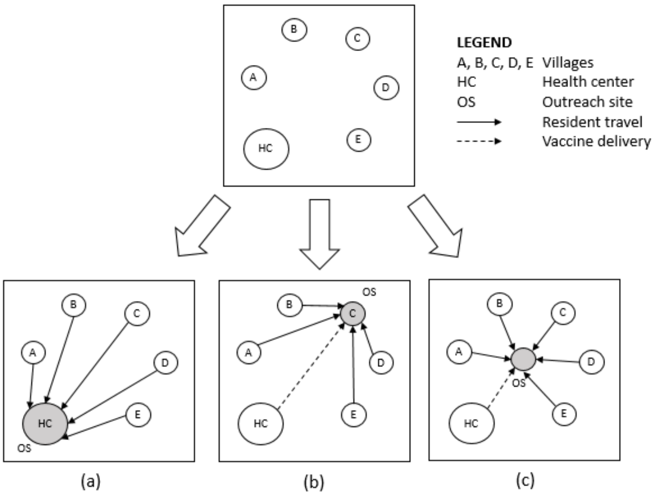


Figure 1 Vaccination outreach schemes

To address the important challenges of the outreach planning problem, we propose a two-step procedure as follows. First, we design the vaccination network by optimizing the number and locations of the outreach sites for the objective of maximizing the vaccination coverage of people residing within a specific distance from the outreach sites. Once the outreach sites have been set, we optimize the vaccine supply from the fixed health centers to the outreach sites. In both steps, we will apply a mathematical optimization that is based on GFA. This section describes the basic concept of the GFA formulation. The reader is referred to the work of Ivanov (2021) for more details.

Consider again the outreach siting problem illustrated in **Figure 1**. Each of the population sites i has a pair of coordinates (x_i, y_i) representing its location while the prospective outreach site p can be located at (x_p, y_p). The outreach site has an equivalent cost factor Z associated with its location and can be expressed using the following equation:

$$Z(x_p, y_p) = \sum_{i=1}^{N} D(x_i, y_i) \times d[(x_i, y_i); (x_p, y_p)] \quad (1)$$

where N is the total number of population sites; $D(x_i, y_i)$ is the vaccination demand from the people residing at population site i; and $d[(x_i, y_i); (x_p, y_p)]$ is the traveling distance from population site i to outreach site p, which can be represented in terms of Euclidean distance d_e as:

$$d_e = \sqrt{(x_p - x_i)^2 + (y_p - y_i)^2} \quad (2)$$

The goal of GFA, in the first step of our procedure, involves positioning the outreach site within a specific distance from the population sites to maximize the vaccination coverage with the minimum cost factor, i.e. min $Z(x_p, y_p)$. For this, following the WHO recommendation, we have specified a threshold of 5 km walking distance from population sites to outreach site (Lim *et al*., 2016). Assuming a detour index—i.e. the ratio of actual travel distance to straight-line distance—of 1.6 (Boscoe *et al*., 2012), we arrive at a straight-line Euclidean distance d_e of approximately 3 km. Accordingly, the following equations can be used to find the optimal coordinates of the outreach site (Ivanov, 2021):

$$x_p = \frac{\sum_{i=1}^{N} \frac{x_i \times D(x_i, y_i)}{\sqrt{(x_p - x_i)^2 + (y_p - y_i)^2}}}{\sum_{i=1}^{N} \frac{D(x_i, y_i)}{\sqrt{(x_p - x_i)^2 + (y_p - y_i)^2}}} \quad (3)$$

$$y_p = \frac{\sum_{i=1}^{N} \frac{y_i \times D(x_i, y_i)}{\sqrt{(x_p - x_i)^2 + (y_p - y_i)^2}}}{\sum_{i=1}^{N} \frac{D(x_i, y_i)}{\sqrt{(x_p - x_i)^2 + (y_p - y_i)^2}}} \quad (4)$$

Equations 1-4 can be applied accordingly to calculate the optimal coordinates pertinent to a single outreach site. For multiple outreach locations, as the calculations involved are much more complex, we have utilized a supply chain software, anyLogistix (The AnyLogic Company, 2021), to determine the number of outreach sites and their locations.

The second step of our procedure involves the optimization of the vaccine supply network. We apply the same GFA approach again to solve this problem. But this time each of the outreach sites is represented by coordinates (x_i, y_i) and each fixed health center by (x_p, y_p). The output from the vaccine supply optimization is a distribution network that specifies which health centers would supply each outreach site, the number of vaccine doses that need to be delivered, and the amount of storage capacity that needs to be made available at both the health centers and the outreach sites. **Figure 2** summarizes our proposed two-step vaccination outreach planning procedure. To demonstrate our approach, we have tested it by solving a case study involving one particular region in Indonesia: Bali province.

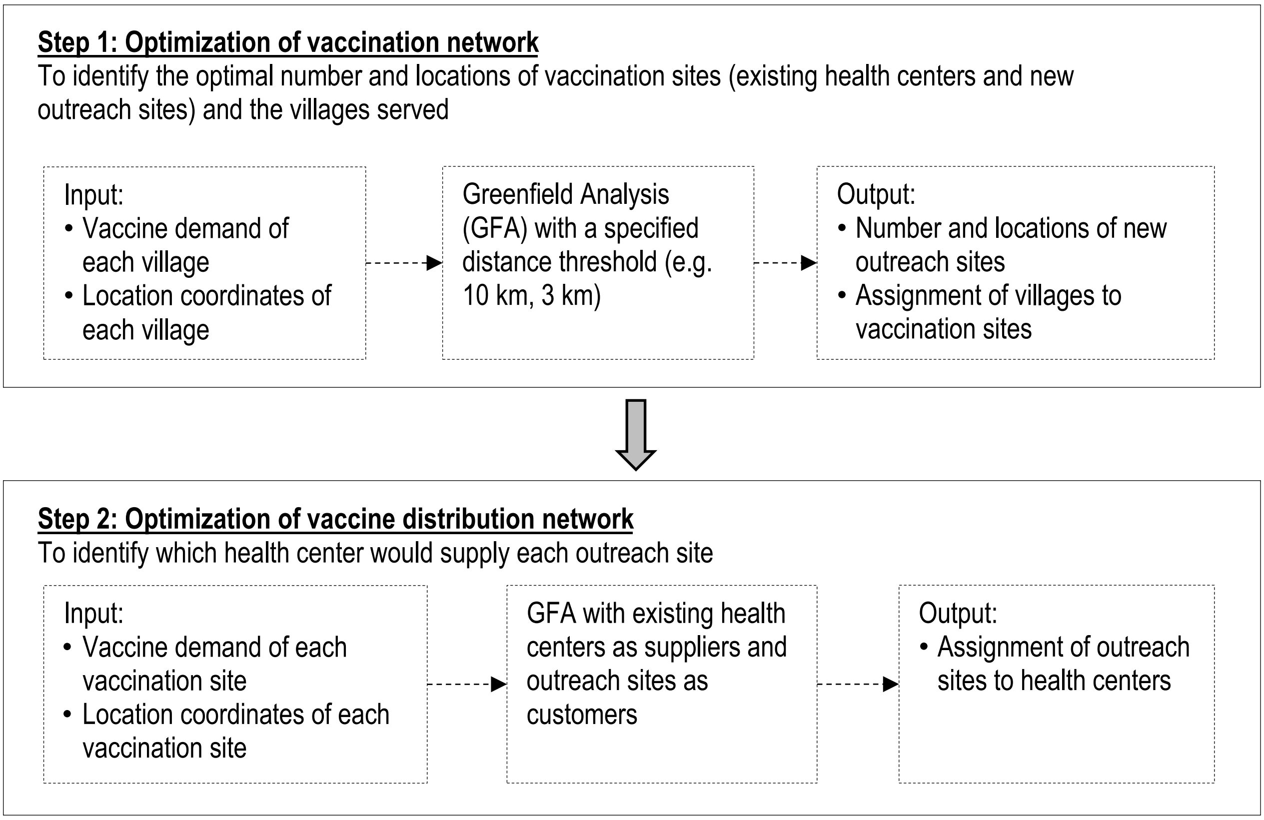


Figure 2 Two-step vaccination outreach planning procedure

2.2 *Case Study: Bali's Vaccination Plan*

Indonesia has been among the most affected countries in terms of the number of COVID-19 infection cases. As of December 8, 2021, Indonesia has registered a total of 4,258,340 cases with 4,109,068 recoveries and 143,909 deaths (Worldometers, 2021). As one of the world's most popular tourism destinations, Bali has become one of the hardest-hit provinces in Indonesia and thus one of the priorities in the country's vaccination program.

As shown in **Figure 3**, Bali province consists of nine regencies. The population profile together with the land size and the number of available hospitals and community health clinics (known as *Puskesmas*) are known to vary considerably in each of the regencies (**Table 1**). This signifies disparities in the access to healthcare services and consequently COVID-19 vaccination for the Balinese population. Therefore, a vaccination outreach program would most likely be useful for Bali. Due to the fact that mass vaccination at both the hospitals and the *Puskesmas* has played a vital role in the success of routine vaccination programs in Indonesia, in this paper, we propose incorporating outreach sites into the COVID-19 vaccination scheme for Bali. We will illustrate our outreach methodology by solving two scenarios: the Buleleng regency and the entire Bali province.

Figure 3 Bali province and its nine regencies

Table 1 Profile of the nine regencies in Bali province

Regencies	Area (km²)	Population Aged 18 and Above	Number of Villages	Number of Hospitals	Number of Community Health Center (Puskesmas)	Ratio of Health Center to Population Aged 18 and Above**
Badung	418.62	381,396	62	9	13	1:17,336
Bangli	490.71	197,296	72	2	12	1:14,093
Buleleng	1,365.73	653,000	148	7	6	1:50,231
Denpasar*	127.78	652,673	43	17	11	1:23,310
Gianyar	368.00	504,310	70	6	13	1:26,543
Jembrana	841.80	234,942	51	4	10	1:16,782
Karangasem	839.54	373,214	77	3	12	1:24,881
Klungkung	315.00	158,366	59	4	9	1:12,182
Tabanan	1013.88	364,244	133	9	20	1:12,560
Bali	5,780.06	3,519,441	715	61	106	1:21,074

**Formally, Denpasar is a city, which is at the same administrative level as a regency. For simplicity, in this paper Denpasar is considered also as a regency.*

***The number of health centers is the sum of the number of hospitals and the number of community health centers (Puskesmas).*

The following is the input data to our GFA model:

i. Population sites: all villages in each regency together with their location coordinates (Ministry of Home Affairs of the Republic of Indonesia, 2021).
ii. Vaccination target: assumed to be 80% of village residents aged 18 and above.
iii. Vaccine: assumed to be administered in two doses within a 14-day interval.
iv. Vaccination period: 365 days (based on the government's vaccination target).
v. Vaccination sites: health centers (i.e. hospitals and *Puskesmas*) and outreach sites (Ministry of Health of the Republic of Indonesia, 2019).
vi. Vaccine demand: calculated as (number of residents aged 18 and above) × 80% × 2 doses. For a vaccination period of one year, the daily demand can be expressed as vaccine demand divided by 365 days. Assuming that the supplies are replenished every 14 days, the vaccine demand per 14-day period is thus obtained as daily demand multiplied by 14. This 14-day demand indicates the required storage capacity at the health centers.

3. RESULTS AND DISCUSSION

Buleleng is located in the northern part of Bali Island. It is the largest regency in Bali province, both in terms of area size and population, and has the most number of villages, i.e. 148 (**Table 1**). However, it has the fewest number of hospitals and *Puskesmas* among the regencies in Bali: seven and six, respectively, for a total of 13 health centers. Furthermore, these health centers are not evenly spread out among the villages. In fact, for one of the villages, the straight-line distance to the nearest health center is 34.6 km (see **Figure 4**). Given these circumstances, it is expected that an outreach program would be beneficial for improving the vaccination coverage in this regency.

3.1 Buleleng Base Case Scenario: No Outreach Sites

First, we consider the base case scenario of using only the existing 13 health centers to serve as the vaccination sites. For this, each of the villages will be assigned to its nearest health center; the village residents will have to travel to the assigned health center for their vaccination. **Figure 4** shows the resulting vaccination network for this scenario. The villages are represented by yellow circles and the health centers by red crossed circles. The assignment of each village to its health center is represented by a line connecting the two circles.

The required number of vaccinators, vaccine doses, and ancillary supply kits such as syringes, needles, and alcohol swabs, as well as cold chain resources such as cold boxes, ice packs, and fridge storage capacity can be calculated accordingly based on this vaccination network. For example, consider Puskesmas Gerokgak I, which is the westernmost health center in the Buleleng regency that serves 11 neighboring villages (**Figure 4**). The number of the target population, vaccine demand, and straight-line distances to the corresponding health center of these 11 villages are listed in **Table 2**. The total number of vaccine doses to be supplied to Puskesmas Gerokgak I over one year period is found to be 194,647 doses. The daily demand can be calculated as 194,647/365 = 534 (rounded up) doses per day. Assuming that one vaccinator can administer around 30 doses per day, the number of vaccinators to be stationed at Puskesmas Gerokgak I is thus 534 / 30 = 18 (rounded up) vaccinators per day.

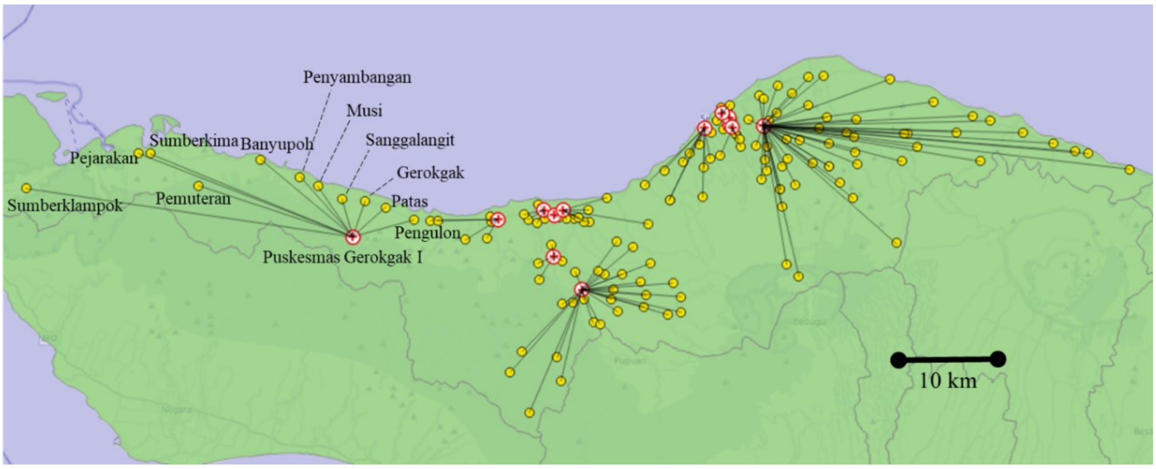


Figure 4 Vaccination network for Buleleng regency without outreach sites (red crossed circle: health center; yellow circle: village)

Table 2 Eleven villages served by Puskesmas Gerokgak I in the base case scenario

Village	Population Aged 18 and Above	Vaccine Demand* (doses)	Vaccine Demand per 14 Days (doses)	Straight-Line Distance to Health Center (km)
Banyupoh	3,707	5,931	227	11.2
Gerokgak	70,267	112,427	4,312	3.5
Musi	2,664	4,263	164	5.7
Patas	8,257	13,212	507	4.1
Pejarakan	8,197	13,115	503	21.5
Pemuteran	7,264	11,622	446	15.2
Pengulon	3,032	4,852	186	5.9
Penyambangan	4,628	7,404	284	7.5
Sanggalangit	4,245	6,792	261	3.7
Sumberkima	6,878	11,004	422	20.5
Sumberklampok	2,516	4,025	154	31.0
Total	121,655	194,647	7,466	-

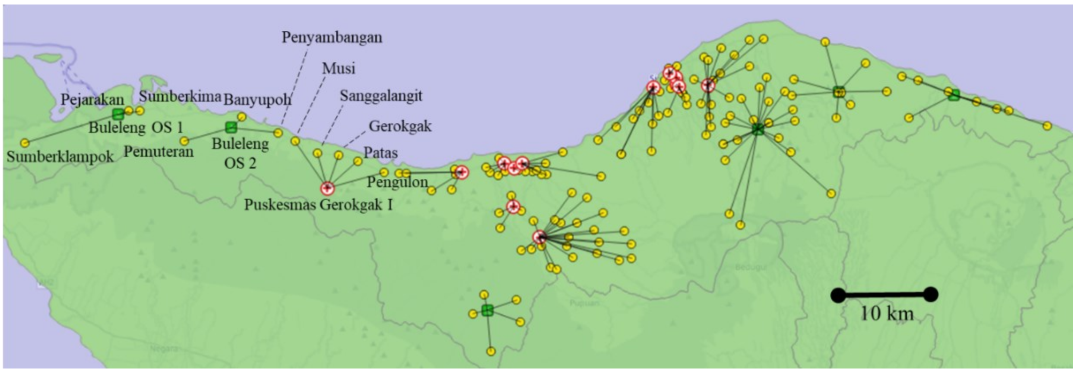
*In reality, the vaccine demand should be an even number, given that each person would receive two doses. However, in this study a simple approach of rounding to the nearest integer is taken.

Since we assume that the supplies are to be replenished in 14-day intervals, the total number of vaccine doses to be kept at Puskesmas Gerokgak I can be calculated from the daily demand and is found to be 7,466 doses (**Table 2**). Considering wastage and buffer stock of 20%, the amount of doses required becomes 120% × 7,466 = 8960 (rounded up) doses with the corresponding quantity of ancillary supply kits. This calculation procedure can be repeated for all other health centers in Buleleng, which would indicate the required storage capacity at each site. The total number of vaccinators required for all 13 health centers is found to be 101. The highest 14-day stock amount required at a health center is 17,669 vaccine sets (vaccine doses and ancillary supply kits).

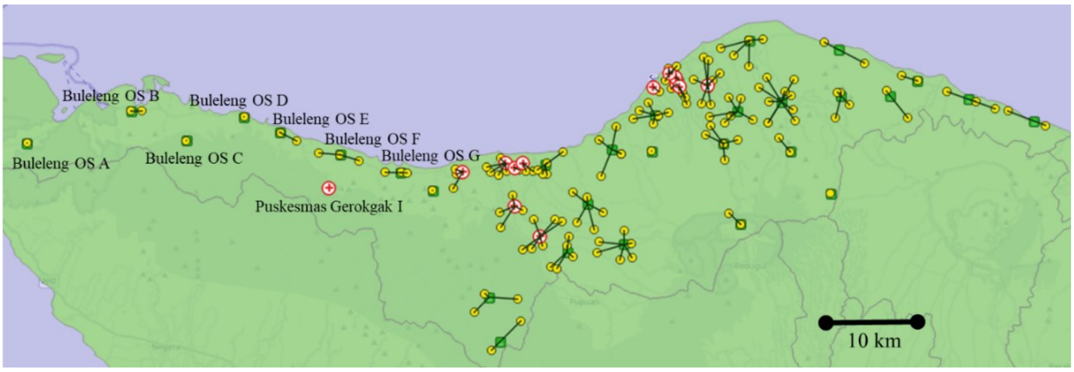
In this base case scenario, the maximum straight-line distance from the village to health center in Buleleng is 34.6 km while the average straight-line distance per person is 6.8 km. The 3-km coverage, i.e. the percentage of the target population that resides within the threshold of 3 km straight-line distance to its assigned health center, as calculated by the software, is 33.5%. Implicitly, we could infer that only 33.5% of the target population in Buleleng would have the willingness to travel to the health center for their vaccination. In the case of Puskesmas Gerokgak I, all the 11 villages assigned to this health center are located more than 3 km away (**Table 2**), with the farthest village (Sumberklampok) having a distance of 31 km.

3.2 Buleleng Outreach Scenario: with Outreach Sites

In this scenario, we perform GFA to find the optimal number of outreach sites and their locations for Buleleng using two different threshold distances: 10 km and 3 km. This means that every village must be located within 10 km and 3 km, respectively, from a health center or an outreach site. The resulting vaccination networks are shown in **Figure 5**. With a 10-km threshold distance, six outreach sites (represented as green squares) are added to the pool of 13 health centers to serve the population of Buleleng (**Figure 5a**). As shown in **Table 3a**, six of the 11 villages originally served by Puskesmas Gerokgak I in the base case scenario are now served by two outreach sites, namely, Buleleng OS1 and Buleleng OS2. Compared to the base case scenario, where five villages have a traveling distance of more than 10 km (see **Table 2**), all these 11 villages are located within 10 km from the health center or outreach site. Specifically for the residents of Sumberklampok, which is located 31 km away from Puskesmas Gerokgak I, they can now travel to the outreach site Buleleng OS 1 at a much reduced distance (9.9 km straight-line) to get their vaccination. With these six outreach sites, the 3-km coverage for Buleleng has also increased from 33.5% in the base case scenario to 45% in this 10-km outreach scenario.



(a)



(b)

Figure 5 Vaccination network in the Buleleng outreach scenario with (a) 10-km threshold distance, (b) 3-km threshold distance (red crossed circle: health center; yellow circle: village; green square: outreach site)

The vaccination network with a 3-km threshold distance identifies 30 outreach sites, as shown in **Figure 5b**. In this scenario, only 12 health centers are used for vaccination instead of all 13. Puskesmas Gerokgak I is not used as a vaccination site since there is no village located within its 3-km radius (**Figure 5b**). Six of the 11 villages originally served by Puskesmas Gerokgak I in the base case scenario are used as outreach site locations such that their distances are zero (**Table 3a**). With these 30 outreach sites, all 148 villages are now located within 3 km from a health center or outreach site; the 3-km coverage is therefore increased to 100%. The maximum straight-line distance from the village to the health center is further reduced from 34.6 km (base case) to 3 km. The average straight-line distance per person decreases significantly from 6.8 km (base case) to 3.4 km (10-km threshold) and 1.1 km (3-km threshold).

Table 3 Buleleng outreach scenario: (a) Health center/outreach site assignment for 11 villages, (b) Outreach sites supplied by Puskesmas Gerokgak I

Village	10-km Threshold		3-km Threshold	
	Assigned Health Center/Outreach Site	Straight-Line Distance to Health Center/Outreach Site (km)	Assigned Health Center/Outreach Site	Straight-Line Distance to Health Center/Outreach Site (km)
Banyupoh	Buleleng OS 2	1.6	Buleleng OS D	0
Gerokgak	Puskesmas Gerokgak I	3.5	Buleleng OS F	0
Musi	Puskesmas Gerokgak I	5.7	Buleleng OS E	1.9
Patas	Puskesmas Gerokgak I	4.1	Buleleng OS F	2.0
Pejarakan	Buleleng OS 1	1.2	Buleleng OS B	0
Pemuteran	Buleleng OS 2	4.9	Buleleng OS C	0
Pengulon	Puskesmas Gerokgak I	5.9	Buleleng OS G	1.6
Penyambangan	Buleleng OS 2	4.8	Buleleng OS E	0
Sanggalangit	Puskesmas Gerokgak I	3.7	Buleleng OS F	2.2
Sumberkima	Buleleng OS 1	1.3	Buleleng OS B	0.1
Sumberklampok	Buleleng OS 1	9.9	Buleleng OS A	0

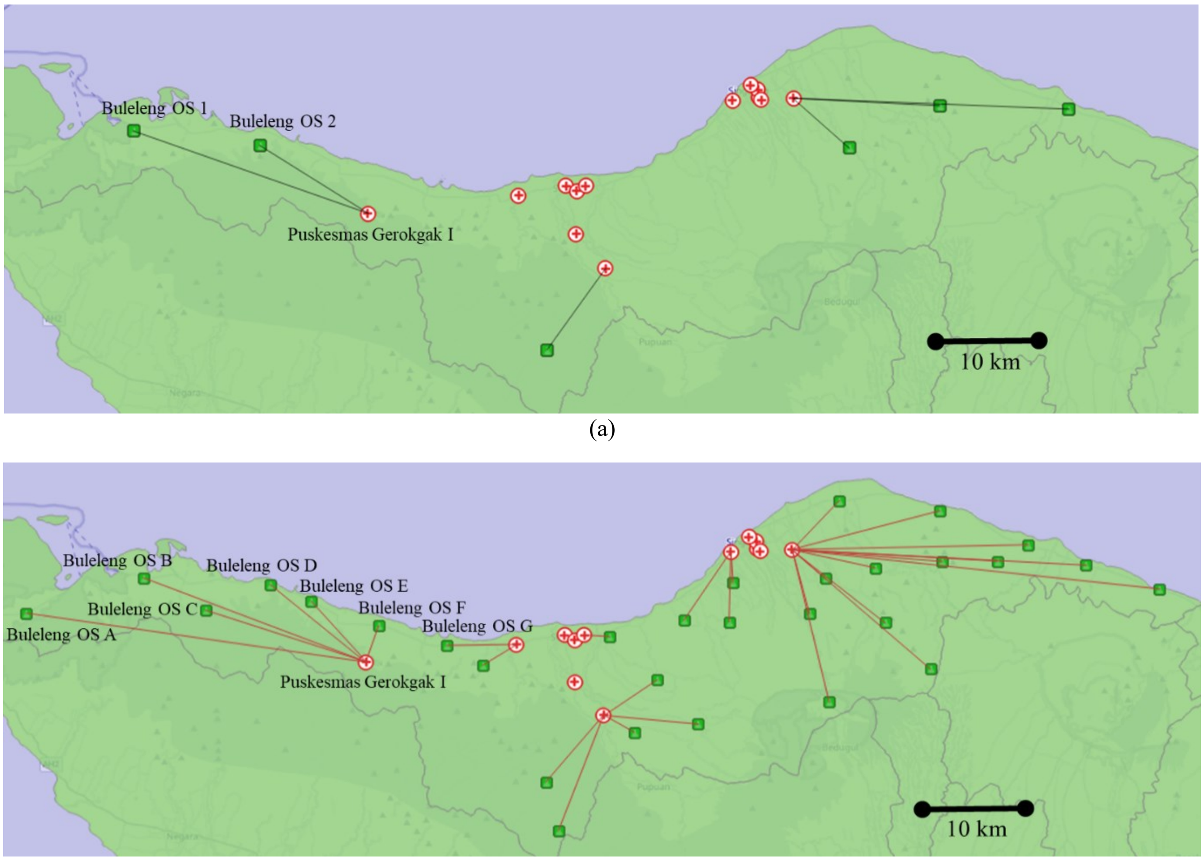
(a)

Table 3 Buleleng outreach scenario: (a) Health center/outreach site assignment for 11 villages, (b) Outreach sites supplied by Puskesmas Gerokgak I (Con't)

10-km Threshold			3-km Threshold		
Outreach Site/Health Center	**Vaccine Demand (doses)**	**Straight-Line Distance to Puskesmas Gerokgak I (km)**	**Outreach Site/Health Center**	**Vaccine Demand (doses)**	**Straight-Line Distance to Puskesmas Gerokgak I (km)**
Buleleng OS 1	28,131	22.5	Buleleng OS A	4,380	30.98
Buleleng OS 2	24,950	11.5	Buleleng OS B	25,185	21.54
Puskesmas Gerokgak I	141,566	0	Buleleng OS C	12,045	15.24
			Buleleng OS D	6,205	11.23
			Buleleng OS E	12,410	7.48
			Buleleng OS F	137,240	3.53

(b)

Figure 6 compares the vaccine supply network from health centers to outreach sites for each of the outreach scenarios. In the 10-km threshold scenario, Buleleng OS 1 and Buleleng OS 2 are located at 22.5 km and 11.5 km, respectively, from Puskesmas Gerokgak I (**Figure 6a**). These are the distances that need to be traveled by the vaccinators, most likely using land transport vehicles. The corresponding vaccine doses to be supplied from Puskesmas Gerokgak I to Buleleng OS 1 and OS 2 are 28,131 and 24,950 doses, respectively (**Table 3b**). In the 3-km threshold scenario, Puskesmas Gerokgak I is used as the supply source for six outreach sites (**Figure 6b**), with their vaccine demands and distances listed in **Table 3b**. The total number of vaccinators required is 104 (10-km threshold) and 118 (3-km threshold). The highest 14-day stock amount required for any health center is 17,682 sets (10-km threshold) and 17,780 sets (3-km threshold).



(a)

(b)

Figure 6 Vaccine distribution network in the Buleleng outreach scenario with (a) 10-km threshold distance, (b) 3-km threshold distance (red crossed circle: health center; green square: outreach site)

3.3 Bali Province

We have subsequently extended the above assessment for Buleleng to the other eight regencies in Bali, for both base case and outreach case scenarios. For this, we have applied the following precept: no village can be served by a health center or an outreach site outside its regency even when the distance from the other health center or outreach site in the neighboring regency is shorter. It is assumed that each regency has its local government in charge of the district budget and also planning and administering services to its residents.

Table 4 Base case scenario (BC) and outreach scenario with 3-km threshold (OC) for nine regencies in Bali province

Regency	Vaccine Demand (doses)	Number of Villages	Number of Vaccination Sites						Max Distance to Vaccination Site (km)		Average Distance per Person (km)		3-km Coverage (%)		Number of Vaccinators		Max 14-Day Stock at Health Center (sets)	
			Health Centers		Outreach Sites		Total											
			BC	OC	BC	OC	BC	OC	BC	OC	BC	OC	BC	OC	BC	OC	BC	OC
Badung	610,234	62	18	15	0	12	18	27	11.8	2.9	2.3	1.3	76.9	100	64	69	3,473	3,764
Bangli	315,673	72	13	13	0	12	13	25	8.3	2.9	2.9	1.5	65.5	100	36	41	2,640	2,093
Buleleng	1,044,800	148	13	12	0	30	13	42	34.6	3.0	6.8	1.1	33.5	100	101	118	17,669	17,780
Denpasar	1,044,277	43	22	22	0	1	22	23	3.6	2.3	0.9	0.9	99.4	100	109	109	6,279	6,295
Gianyar	806,896	70	18	18	0	5	18	23	6.9	3.0	1.9	1.5	90.7	100	74	86	3,988	4,429
Jembrana	375,907	51	13	11	0	10	13	21	9.8	2.9	3.5	1.3	49.2	100	43	45	3,046	3,926
Karangasem	597,142	77	15	15	0	14	15	29	9.5	3.0	2.9	1.4	67.4	100	62	70	3,309	2,985
Klungkung	253,385	59	13	13	0	7	13	20	10.6	2.9	2.2	1.1	72.7	100	30	34	2,079	2,126
Tabanan	582,790	133	26	24	0	21	26	45	11.1	3.0	2.8	1.4	64.8	100	67	76	2,560	2,839
Bali	5,631,104	715	151	143	0	112	151	255	34.6	3.0	3.0	1.2	70.1	100	586	648	17,669	17,780

Table 4 summarizes our findings. One highlight from the table is that regions with similar population numbers but different geographical characteristics could lead to different numbers of outreach sites. Consider the case of Buleleng and Denpasar. As shown in the table, Buleleng and Denpasar are the two largest regencies in terms of population size and hence they have similar vaccine demands. However, the two regencies stand opposite to each other in the other aspects. The Buleleng population is spread out across 148 villages—the highest number of villages in Bali province. On the other hand, Denpasar, as the capital of Bali, is a city with 43 sub-districts (a sub-district is the equivalent of a village in terms of administrative level), which is the fewest among the nine regencies. Further, the ratio of the number of health centers to the number of populations for Buleleng is much lower than that of Denpasar.

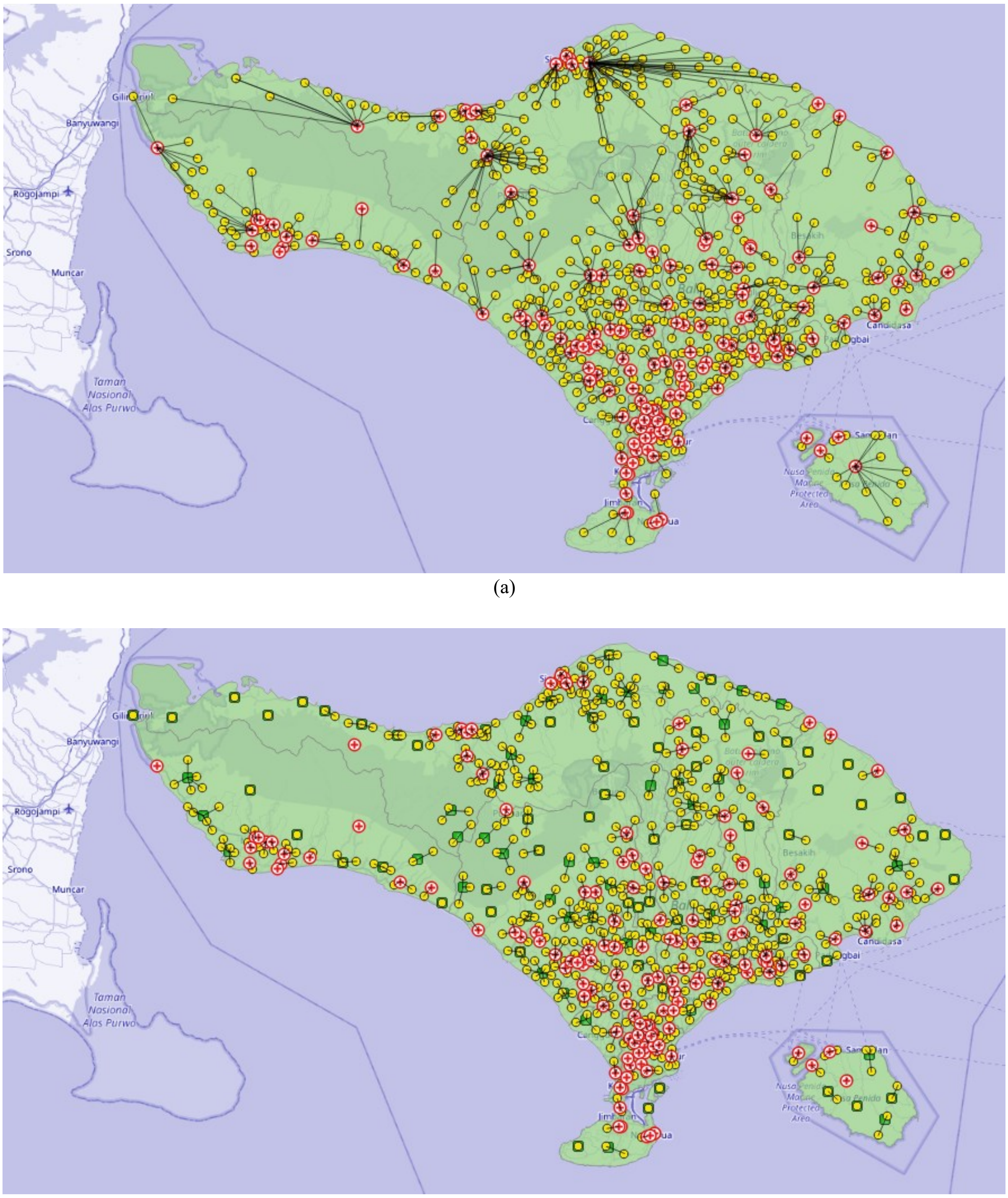
Accordingly, in the 3-km outreach scenario, Buleleng requires 30 outreach sites (see section 3.2), resulting in a substantial reduction of maximum straight-line distance between village and health center from 34.6 km to 3.0 km, and average distance per person from 6.8 km to 1.1 km. On the other hand, Denpasar requires only one outreach site, with a reduction of maximum straight-line distance from 3.6 km (base case) to 2.3 km (outreach case), and no notable difference in the average distance per person at 0.9 km, for both base case and outreach case.

In general, **Table 4** shows that typically the number of outreach sites in a regency increases when the average distance per person (base case) is higher. As the average distance per person is directly influenced by the number of distant villages, more outreach sites need to be set up to meet the threshold of 3-km distance from a vaccination site. However, this is not always the case. For example, Tabanan has an average distance per person (base case) of 2.8 km and requires 21 outreach sites. On the other hand, Jembrana with an average distance per person (base case) of 3.5 km requires only 10 outreach sites. This difference in the trend is caused by the geographical spread of the villages. When several distant villages are close to each other, one outreach site would be sufficient to cover them. On the other hand, two distant villages not in the same proximity would demand two outreach sites be set up within 3 km from their locations. All these factors have been inherently considered in the GFA model in optimizing the number of outreach sites and their locations.

Table 4 also shows that servicing 715 villages for the whole Bali province would require a total of 143 health centers and 112 outreach sites. The total number of vaccinators needed is 648. With a such number of vaccination sites, we can accordingly increase the 3-km coverage from 70.1% (base case) to 100%. Further, the average distance per person can be substantially reduced from 3.0 km (base case) to 1.2 km.

Figure 7 shows the comparison between the vaccination network in the base case and the 3-km outreach scenario. We can see that the connecting lines in the outreach case scenario (**Figure 7b**) are much shorter than in the base case scenario (**Figure 7a**), indicating a much shorter travel distance taken by the residents. Again, these results demonstrate the benefits of implementing an optimal outreach strategy in Bali: better public health service by reducing the traveling burden of residents, increasing vaccination access, and eventually raising the nation's vaccination coverage. Our results are thus in line with the findings by Leithäuser *et al.* (2019) and Bertsimas *et al.* (2021), who highlighted the critical role of locating the mass vaccination facilities as close as possible to the population residences for an effective vaccination campaign.

The number of vaccinators and the required vaccine sets have also been accordingly identified based on a vaccination period of one year. This would help in planning the needed stocks and resources to meet the vaccination goal. Assuming that the vaccine doses and other supporting resources are not constrained, the vaccination period can be shortened by increasing the number of vaccinators and administering more parallel vaccination sessions. If the vaccination target of 80% is increased, the resulting vaccination network will remain the same because vaccine demands across all villages will be increased in tandem with the same proportion. However, the number of vaccinators and vaccine sets will change following the new vaccination target.



(a)

(b)

Figure 7 Vaccination network for the whole Bali province: (a) base case scenario without outreach sites, (b) outreach scenario with 3-km threshold (red crossed circle: health center; yellow circle: village; green square: outreach site)

While the overall results from our outreach planning approach are very encouraging, it should be noted, however, that in this study we have not considered real roads and detailed geographical conditions of the areas, infrastructure availability, and other suitability factors for opening outreach sites in the identified optimal locations. Therefore, while our results could provide a guideline in finding the optimal outreach sites, local geographical conditions and constraints need to be taken into account to determine the actual outreach locations.

4. CONCLUSIONS

Timely distribution and administration of COVID-19 vaccines hold the keys to winning the war against COVID-19. We propose a new approach for optimal planning of vaccination outreach and vaccine distribution strategies using a two-step Greenfield Analysis. First, we find the required number and locations of vaccination sites, i.e. current health centers and newly set up outreach sites. Next, we optimize the vaccine supply network to determine the connections between health centers and outreach sites and the allocated vaccine supplies. We demonstrate the benefits of our approach using a case study involving a vaccination scheme for Bali province. The results show that servicing 715 villages for the whole Bali province would require a total of 143 health centers and additional 112 outreach sites. With a such number of vaccination sites, the 3-km population coverage is increased from 70.1% (base case) to 100%, and the average distance per person is substantially reduced from 3.0 km (base case) to 1.2 km. This demonstrates the effectiveness of our approach in reducing the average traveling distances taken by residents from population sites to outreach sites. The number of vaccine doses that need to be delivered to the vaccination sites could also be specified. All these would help in regional vaccination planning leading to improved vaccine access for the benefit of public health.

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