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Prioritizing the location of vaccination centres during the COVID-19 pandemic by bike in The Netherlands

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Abstract

Once a vaccine against COVID-19 had been developed, distribution strategies were needed to vaccinate large numbers of the population as efficiently as possible. In this study we explored the geographical accessibility of vaccination centres and examined their optimal location. To achieve this, we used open-source data. For the analysis we assessed the centre-to-population ratio served to assess inequalities and examined the optimal number and location of centres needed to serve 50%, 70% and 85% of the population, while ensuring physical accessibility using a common mode of transportation, the bicycle. The Location Set Covering Problem (LSCP) model was used to determine the lowest number of vaccination centres needed and assess where these should be located for each Municipal Health Service (GGD) region in The Netherlands. Our analysis identified an unequal distribution of health centres by GGD region, with a primary concentration of vaccination locations in the central region of the Netherlands. GGD Region Noord en Oost Gelderland (N=34), Utrecht (N=29) and Hollands-Midden (N=26) had the highest numbers, while the lowest were found in West-Brabant (N=1), Brabant-Zuidoost (N=2), with Kennemerland, Hollands-Noorden, Groningen and Flevoland (N=3) each. The centre-to-population ratio ranged from 1 centre serving 22,000 people (Noord en Oost Gelderland) to 1 centre serving 672,000 people (West Brabant region). The location-allocation analysis identified several regions that would benefit by adding more centres, most of which would serve densely populated regions previously neglected by the existing vaccination strategy. The number of centres needed ranged from 110 to 322 to achieve 50% and 85% population coverage respectively. In conclusion, location-allocation models coupled with Geographic Information Systems (GIS) can aid decision-making efforts during mass vaccination efforts. To increase effectiveness, a nuanced distribution approach considering accessibility and coverage would be useful. The methodology presented here is valuable for aiding decision-makers in providing optimized locally adapted crucial health services accessible for the population, such as vaccination centres.

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Introduction

The COVID-19 pandemic caused significant disruptions to people's lives worldwide, prompting the development of a variety of vaccines to battle the virus (Ball, 2021; Blanford *et al*., 2022). The global need to contain the virus's spread also pressed governments to develop policies for distributing COVID-19 vaccines to their populations (ECDC, 2022). Like many countries worldwide, The Netherlands developed a comprehensive vaccination campaign to safeguard its 17.4 million residents from the virus. Over time, the Dutch vaccination campaign modified its distribution strategy by altering the locations of vaccination centres and introducing new types of vaccination centres, resulting in a change of the levels of accessibility (Al-Huraibi *et al*., 2023). The Netherlands vaccination campaign started in early 2021 (Niessen *et al*., 2022), using several vaccines, including Comirnaty, Spikevax, Jcovden and Nuvaxovid, backed by booster doses to amplify their efficacy (RIVM, 2022). The campaign was initiated by inoculating individuals aged 90 and above, followed by those with specific health vulnerabilities and at high risk of exposure to the virus, such as the frontline healthcare workforce (RIVM, 2023). In addition, the Dutch government carefully prioritized vaccinating people according to their age as a guiding principle as shown in Figure 1. The campaign's overarching goal was to reach an immunization level of at least 85% of the total population (RTL Nieuws, 2020), considerably higher than the 70% the World Health Organization (WHO) recommended to achieve herd immunity (WHO, 2020). To reach as many people as possible, the initial vaccination strategy in The Netherlands was largely based upon large semi-permanent vaccination centres established in spaces, such as sports halls and public parking areas. In this paper we refer to these locations as “fixed vaccination centres” (Markhorst *et al*., 2021). As the nationwide immunization campaign progressed, the strategy was adjusted by discontinuing fixed centres that vaccinated limited numbers of people (van Annemieke, 2021). At the same time, mobile vaccination buses and temporary, so-called pop-up centres were established, especially in areas of lower population density and in regions where the vaccine uptake was relatively low (van Annemieke, 2021). Vaccination buses could reach remote communities, pop-up centres were opened in areas with lower vaccination rates and operated for a maximum of two weeks (Merkelbach *et al*., 2023). The adjusted approach was termed the “fine-mesh” strategy. With the virus spreading quickly, the importance of smartly located vaccination centres became paramount (Ramos *et al*., 2021; Jin *et al*., 2022; Li *et al*., 2022; Pourrezaie-Khaligh *et al*., 2022). The Netherlands has a world-class cycling infrastructure, with bicycles rapidly growing into the “go-to” form of transportation among its population (Buehler & Pucher, 2012; Fishman, 2015). Surveys have shown the popularity of biking in The Netherlands, with the Dutch owning around 23.4 million bicycles, which are used for 28% of all trips (CBS, 2015; Statista, 2023). This is even more pronounced in major urban centres such as Amsterdam, Rotterdam, The Hague and Utrecht (CBS, 2020). For trips related to education and work, bicycles are the preferred means of transportation, particularly for trips within a 5 km range (CBS, 2020). The COVID-19 pandemic also triggered shifts in travel behaviour. The pandemic prompted an increase in the average cycling distance from 3.4 to 4.4 km (de Haas *et al*., 2020). Remarkably, when public transportation (excluding trains) faced disruptions due to the pandemic, a notable 37% of Dutch residents turned to bicycles as an alternative mode of commuting (de Haas *et al*., 2020). With the significant reliance on cycling as a mode of transportation, there was a clear need in The Netherlands to ensure proper accessibility by bicycles to vaccination centres.

Decision-makers can use different scenarios to explore where to position vaccination centres strategically (Mestre *et al*., 2015; Xu *et al*., 2018). Location-allocation models aid in this process by assisting policymakers in identifying a location pattern of facilities that optimizes geographic accessibility for the population (Church & ReVelle, 1974). Several studies have employed location-allocation models to determine the ideal number and location of facilities to optimise the accessibility of services (Polo *et al*., 2015; Rahman & Smith, 2000; Karim & Awawdeh, 2020; Murad *et al*., 2021). Location-allocation models can be loosely classified into three types based on the allocation approach: the P-center model, the P-median model, and the coverage models. The P-center model locates a given number of facilities that minimizes the maximum distance between any demand node and the location in which a facility is placed. In this model, there are no capacity constraints at the facilities (Drezner, 1984). This model has been extensively used for determining the optimal placement of critical services such as fire stations (Çalık, 2013). Minimizing the longest travel distance can be viewed as a benchmark towards equality of accessibility. However, a drawback of the P-center model is that it may result in significantly longer travel times for the majority, while improving accessibility for a few people living in remote locations. In contrast, the P-median model reallocates facilities with the aim of decreasing the overall average travel distance/time between demand and supply locations (Hakimi, 1965). The P-median model thus emphasizes achieving spatial efficiency and is particularly well-suited for optimizing the placement of frequently used facilities, such as grocery stores or offices (Alkhedhairi, 2008). A disadvantage of this approach is that it favours areas with a higher population density, leading to longer travel times for people living in remote areas (Rahman & Smith, 2000). Coverage models, finally, utilize a predetermined maximum travel distance/time threshold. These models aim at solving the Location Set Covering Problem (LSCP) and the Maximal Covering Location Problem (MCLP). Several studies have used both LSCP and MCLP models to identify viable sites for essential facilities (Shariff *et al*., 2012; Erdemir *et al*., 2010; Rahman *et al*., 2021; Yong *et al*., 2021; Lusiantoro *et al*., 2022). The LSCP model identifies the minimum number and location of facilities required to ensure that each demand point remains within the maximum travel distance of at least one service facility (Toregas & ReVelle, 1972). The MCLP model identifies the locations for a prespecified number of facilities such that the maximum population is served within a desired maximal service distance (Church & ReVelle, 1974). These models find widespread utilization among governmental bodies and international organizations (Chaiken, 1978). Given the absence of precise data regarding the capacity of vaccination centres and the primary objective of identifying optimal locations for these centres, the LSCP model emerges as the most suited approach to meet our objectives. The objective of this study was twofold. Firstly, to evaluate the spatial distribution of vaccination centres across all Municipal Health Service (GGD) regions in the Netherlands, and secondly to develop a methodology to aid policymakers in determining the optimal location and number of vaccination centres, to ensure the best possible accessibility by bicycle.

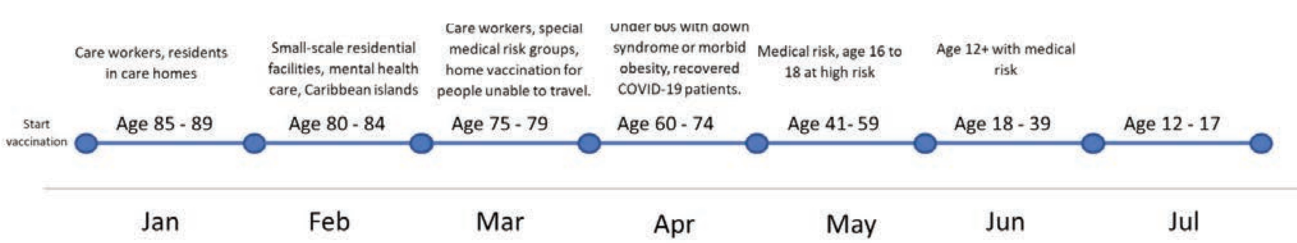

Figure 1. The prioritized age groups and risk groups in the Dutch vaccination campaign.

Materials and Methods

Data

A variety of data were used, all of which available in the public domain (Table 1). Population data for the Netherlands was obtained from CBS (2018), where population information is represented by 100 x 100 m grid cells. In addition to the population number, socio-economic details, such as age and income are included. Grid cells were transformed to points, where the centroids were used for subsequent computations. This official dataset does not include data for cells with fewer than five people to avoid privacy issues. Therefore, these cells were not included in our analysis. The cleaning process reduced the number of cells from 379.139 to 376.301, which implies that 16.5 million people out of the total of 17.4 million were considered in the calculations.

We obtained the addresses of 263 vaccination centres in The Netherlands that were operational at the end of August 2021 from the GGD websites. These addresses were geocoded using ArcGIS Pro 2.7 geocoder. As shown in Table 2, the centres were categorized into three types: Fixed (N=99), Mobile (N=160) and Pop-up (N=4). Each vaccination centre was defined by its address, type and the corresponding municipality and GGD region.

Survey data on cycling travel behaviour in the Netherlands was obtained for 2019 (CBS, 2020). The data were used to determine the average travel speed and the maximum travel time by bicycle. The average travel speed by bicycle using the population travel behaviour data was determined to be 11 km/h and used in this study.The duration and purpose of trips was used to determine the maximum travel time a person is likely to travel by bicycle to a vaccination centre. Based on the travel purpose motivation of "service and personal care", 75% of the trips in this category took 20 minutes or less, 14% 20-30 minutes and 3% more than 45 minutes (Figure 2). For the purpose of this study, we used 20 minutes as the

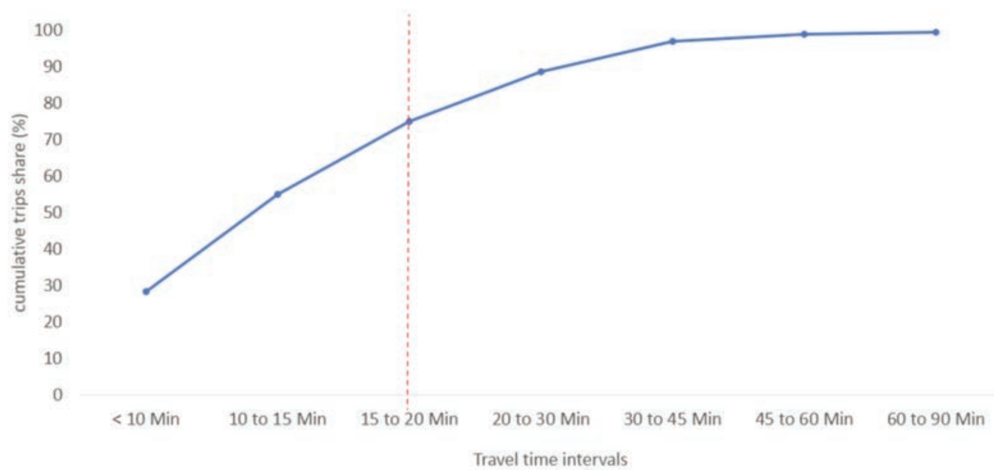

Figure 2. Maximum travel time by bike for trips made for service and personal care.

Table 1. Data sources used.

Name	Source	Type	Year
Population data	Statistics Netherlands (CBS)	Shapefile	2018
COVID-19 vaccination centre locations	Geolocated using location information obtained from each of the GGD regional websites	Shapefile	2021
Population travel behaviour	Statistics Netherlands (CBS)	CSV	2019
Roads and bicycle network	OpenStreetMap	Shapefile	2021
Potential vaccination locations	Points of interests obtained from OpenStreetMap	Shapefile	2021
GGD region boundaries	Statistics Netherlands (CBS)	Shapefile	2021

CBS, Centraal Bureau voor de Statistiek; GGD, Gemeentelijke Gezondheidsdienst.

Table 2. Types of vaccination centres.

Type	Description
Fixed	Vaccination centres established within buildings for periods longer than two weeks
Mobile	Centres that can move to a different location (*e.g.*, bus)
Pop-ups	Temporary centres established within buildings for periods shorter than two weeks)

maximum travel time within which people would likely be willing to cycle to a vaccination centre (Al-Huraibi *et al*., 2023).

Roads and bicycle network data were obtained from OpenStreetMap (OSM) on May 30, 2021. The data included all road types. Topological shortcomings were resolved and only road types that cyclists are permitted to use were selected. Bridleways, bus ways, motorways and stairs were excluded (Ramm, 2022). A total of 2.096,255 features representing cyclable networks, of which 229.487 were designated as cycleways, were used in this study. The length of each road segment was calculated using ArcGIS Pro 2.7 (ESRI, Redlands, CA, USA), and the bike travel time was computed for each segment using the 11km/h average bicycle travel speed.

The geographical location of potential vaccination centres was selected based upon points of interest obtained from OSM. These points represent various location types. For this study, we selected 9,425 OSM points of interest. Location types were chosen in accordance with the location types previously utilized by GGD and accessible to the public, such as playgrounds (Markhorst *et al*., 2021).The chosen locations are parks (N=43), sports centres (N=2,003), playgrounds (N=7,159), malls (N=83) and market-places (N=134) (Ramm, 2022). GGD region boundaries represent the boundaries of the health administration regions in the Netherlands. A total of 25 regions exists. The boundaries were obtained from CBS (2021).

Materials and Methods

The distribution of vaccination centres in The Netherlands operational at the end of August 2021 were examined and evaluated according to their type (fixed, mobile, and pop-up) and distribution for each GGD region. The population-to-vaccination centre ratio was computed for each GGD region and used to enable cross-region comparison.

To examine the optimal distribution of vaccination centres three coverage scenarios were used. Since one of the aims of the COVID-19 vaccination was to break the chain of transmission, a percentage of the population needed to be vaccinated. For the purpose of this study, three vaccination percentages were selected. The scenarios coverage percentages and justifications are detailed in Table 3. To identify the optimal number and location of vaccination centres for the three selected coverage scenarios (Table 3), we utilized the LSCP model, which aims to minimize the total number of centres needed while meeting demand criteria for each level. Hence, the LSCP model determines the minimum number of facilities needed so that each demand point is within a specified travel time from at least one facility (Toregas & ReVelle, 1972). This model was selected as we did not have information on the capacity of the different vaccination centres.

The LSCP model is represented as described by Daskin and Owen, (2003):

$$\text{Min} \sum_{j \in J} X_j$$

subjected to

$$\sum_{j \in M} X_j \geq 1 \quad \forall\, i \in I$$

$$X_i \in \{0,1\} \quad \forall\, j \in J$$

where I is the set of all demand points (population data); J the set of all fine-mesh locations or potential locations; T the 20-minute travel time threshold by bike; M_i the set of all facilities that cover the demand point i within T; t_{ij} the travel time between facility j and demand point i; and X_j as given below:

$$\begin{cases} 1 \text{ if facility located at } j \\ 0 \text{ otherwise (for potential locations only)} \end{cases}$$

$$M_i = \{j \mid t_{ij} \leq T\}$$

The methodology developed involves three steps as shown in Figure 3: i) step 1: we allocated the population within a 20-minute biking time to the nearest operational vaccination centre at the time of the fine-mesh strategy; ii) step 2: the population not allocated in the first step was assigned to the nearest candidate vaccination location, again based on a maximum cycling time of 20 minutes, excluding those allocated in the first step; iii) step 3: the model's results were organized into 25 tables, each representing a GGD region and its allocation data. This included the fine-mesh strategy centres within the region, the potential vaccination locations and the population allocated to each vaccination centre. The percentage of the serviced population per GGD regions was then calculated. Starting from the potential centre with the highest allocated population, we systematically added centres in descending order. This continued until we had reached the target coverage scenario percentages, bridging the gap between the actual service coverage and the targeted coverage for each scenario for each GGD region.

Results

A total of 99 fixed, 160 mobile and 4 pop-up centres were recorded for The Netherlands during this study. As shown in Figure 4, most centres were concentrated in the middle regions of the country, In GGD regions Noord en Oost Gelderland (N=34), Utrecht (N=29) and Hollands-Midden (N=26) had the highest number of vaccination centres, with West-Brabant (N=1), Brabant-

Table 3. Coverage scenarios percentages and description.

Coverage Scenario	Coverage (%)	Justification
Half of the population	50%	Achieving the basic service level
Herd immunity scenario	70%	Achieving the immunization percentage recommended by the World Health Organization (WHO, 2020).
GGD scenario	85%	Achieving GGD immunization goal (RTL Nieuws, 2020).

Zuidoost (N=2) and Kennemerland, Hollands-Noorden, Groningen, Flevoland (N=3) each having the least. Notably, GGD Noord en Oost Gelderland had the highest number of mobile centres (N=32), followed by GGD Hollands-Midden (N=23), and Veilligheids-en Gezondheidsregio Gelderland-Midden (N=20) (Figure 4B). GGD Regio Utrecht had the highest number of fixed centres (N=25) followed by GGD Amsterdam (N=10) and GGD Rotterdam Rijnmond (N=7). The northern regions, except for

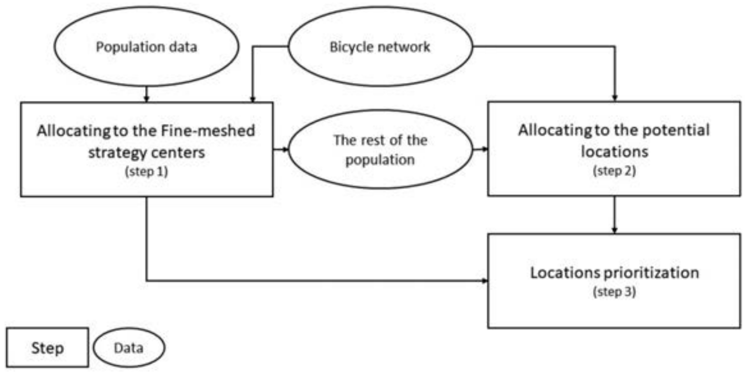

Figure 3. Population allocation process.

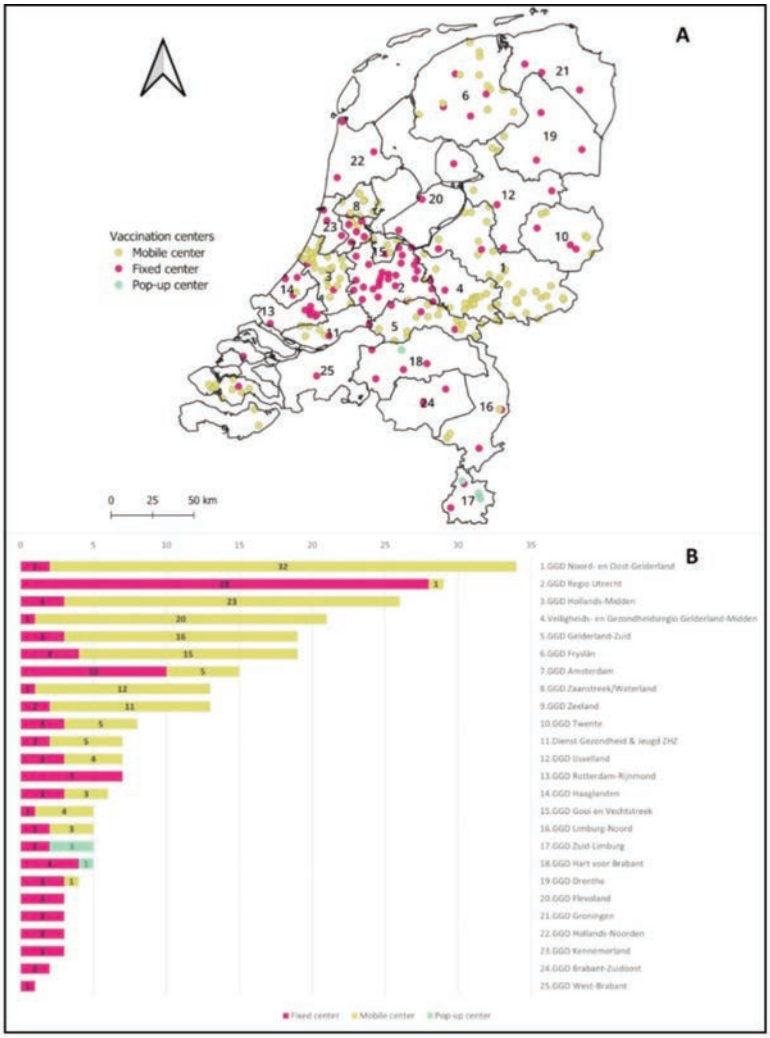

Figure 4. A) locations of vaccination centres during the fine-mesh strategy; **B**) number and type of vaccination centres per GGD region.

GGD Friesland, exhibited fewer vaccination centres than the middle regions of The Netherlands, with the fewest centres overall found in the southern regions. Pop-up centres were not very common, with only four identified there.

The distribution of vaccination centres across the GGD regions in relation to population size are shown in Table 4. The population-to-vaccination centre ratio varied across regions. GGD With a 1:672,000 ratio where one vaccination centre served 672,000+ people, West Brabant had the highest centre to population ratio, while GGD Noord en Oost Gelderland had the lowest (1:22,000). Eleven regions were found to have a 1:110,000+ ratio (range 112,608 to 672,000), five regions were found to have a ratio ranging between 63,000 to 97,000 and nine regions had centres that provided vaccinations to 22,000-50,000 people.

The fine-mesh strategy revealed that some of the GGD regions were able to achieve the three scenarios without the need for additional centres. Fifty percent coverage was achieved in GGD Gelderland-Zuid, 70% in GGD Amsterdam and 85% in GGD Gooi en Vechtstreek. For each of the three scenarios, a number of accessible locations were identified (Figure 5). To ensure 50% coverage, 110 centres would be needed (Figure 5B), for 70% coverage, 213 (Figure 5C) and 322 for 85% of the population (Figure 5D). The geographic location of these varied between the coverage levels. For the 50% coverage scenario, most of the proposed locations were concentrated in regions previously not covered by the fine-mesh strategy where demand was likely to be the highest. These regions are mainly located in the South, as well as specific areas such as GGD Hollands-Noorden, GGD Twente and GGD Groningen. For the 70% coverage scenario, the number of centres increased, particularly in locations serving populations ranging between 20,000 and 30,000 people. In contrast, the northern regions relied mainly on locations with lower demands (less than 10,000). Finally, in the 85% coverage scenario, the locations would serve a population of 10,000 or less.

By analysing the fine-mesh strategy centres with most of the potential vaccination locations needed to achieve the coverage scenarios aimed, we were able to identify which regions would need additional vaccination centres (Figure 6) and the additional number of people that would be covered (Figure 7). For instance, GGD Hart voor Brabant would need an additional 12 vaccination centres to achieve the 50% coverage, while GGD Zuid-Limburg would only need 3 additional centres to reach the same coverage (Figure 6). Furthermore, the centre-to-population demand also varied, with GGD Drenthe needing 11 centres to cover approximately 115,000 people, while GGD Hart voor Brabant needed almost the same number (12 centres) to cover nearly three times the population (300,300) (Figure 7).

Each GGD region has a different coverage depending on the density and spatial distribution of the population. For instance, GGD Groningen mainly relies on centres serving less than 10,000

Table 4. GGD populations and number of centres.

GGD name	Population	Total[a]	Ratio[b]	Rank
1. GGD Noord- en Oost-Gelderland	753,665	34	22,166.62	25
2. GGD Regio Utrecht	1,301,165	29	44,867.76	18
3. GGD Hollands-Midden	775,690	26	29,834.23	21
4. Veiligheids- en Gezondheidsregio Gelderland-Midden	660,975	21	31475.00	19
6. GGD Fryslân	596,275	19	31,382.89	20
5. GGD Gelderland-Zuid	530,170	19	27,903.68	22
7. GGD Amsterdam	1,037,540	15	69,169.33	15
8. GGD Zaanstreek/Waterland	356,070	13	27,390.00	23
9. GGD Zeeland	326,515	13	25,116.54	24
10. GGD Twente	590,675	8	73,834.38	13
11. Dienst Gezondheid & Jeugd ZHZ	1,284,870	7	183,552.90	5
12. GGD IJsselland	485,905	7	69,415.00	14
13. GGD Rotterdam-Rijnmond	444,600	7	63,514.29	16
14. GGD Haaglanden	1,080,920	6	1,801,53.30	7
17. GGD Zuid-Limburg	1,015,860	5	2,03172.00	4
15. GGD Gooi en Vechtstreek	586,755	5	117351.00	10
16. GGD Limburg-Noord	487,245	5	97449.00	12
18. GGD Hart voor Brabant	247,780	5	49556.00	17
19. GGD Drenthe	450,435	4	112,608.80	11
21. GGD Groningen	630,140	3	210,046.70	3
22. GGD Hollands-Noorden	549,835	3	183,278.30	6
20. GGD Flevoland	535,905	3	178,635.00	8
23. GGD Kennemerland	399,300	3	133,100	9
24. GGD Brabant-Zuidoost	738,525	2	369,262.50	2
25. GGD West-Brabant	672,215	1	672,215.00	1

[a]*number of centres;* [b]*of population to vaccination centres.*

people to cover 85% of the population, whereas more urbanized regions, such as GGD Amsterdam, rely primarily on centres serving more than 20,000 people (Figure 8).

Discussion

This study is an extension of our previous work where we examined accessibility by bikes to COVID-19 vaccination centres in The Netherlands during the COVID-19 pandemic and how this would change as the centres closed (Al-Huraibi *et al*., 2023). Our study focused on optimizing the numbers and locations of vaccination centres to ensure accessibility by bike and thus enhance vaccination uptake. We utilized the LSCP model with open data to determine the number of vaccination centres needed for different coverage scenarios and their optimal locations.

The unequal distribution of vaccination centres was found to extend to GGD regions with populations greater than one million, such as GGD Rotterdam-Rijnmond and GGD Hart voor Brabant, where we noted fewer centres than regions with smaller populations, such as GGD Zeeland and GGD Zaanstreek/Waterland. The findings from our study highlights the importance for a more equitable distribution of vaccination centres to ensure that all regions have sufficient access to vaccination centres. By taking population and population density into consideration along with physical accessibility using a common local mode of transportation we were able to identify geographic locations in need of additional vaccination centres, thus ensuring a more equitable distribution.

Our study highlights the importance of including spatial accessibility analyses along with local stakeholders into the decision-making process when establishing new vaccination centres (Moore *et al*., 2021; Chen *et al*., 2023; Vincenzo *et al*., 2023). The result of using three scenarios to examine the number of vaccination centres needed highlighted substantial variations among the regions. For instance, while GGD Utrecht and GGD Hollands-Midden did not require new centres to reach 50% of the population, GGD West-Brabant needed 15 new centres to attain the same percentage. The lack of consideration of planning for accessibility, such as the use of bicycles to reach the centres, may have contributed to this variation. The increase in bike usage in The Netherlands during the pandemic (De Haas *et al*., 2020), along with strict measures that

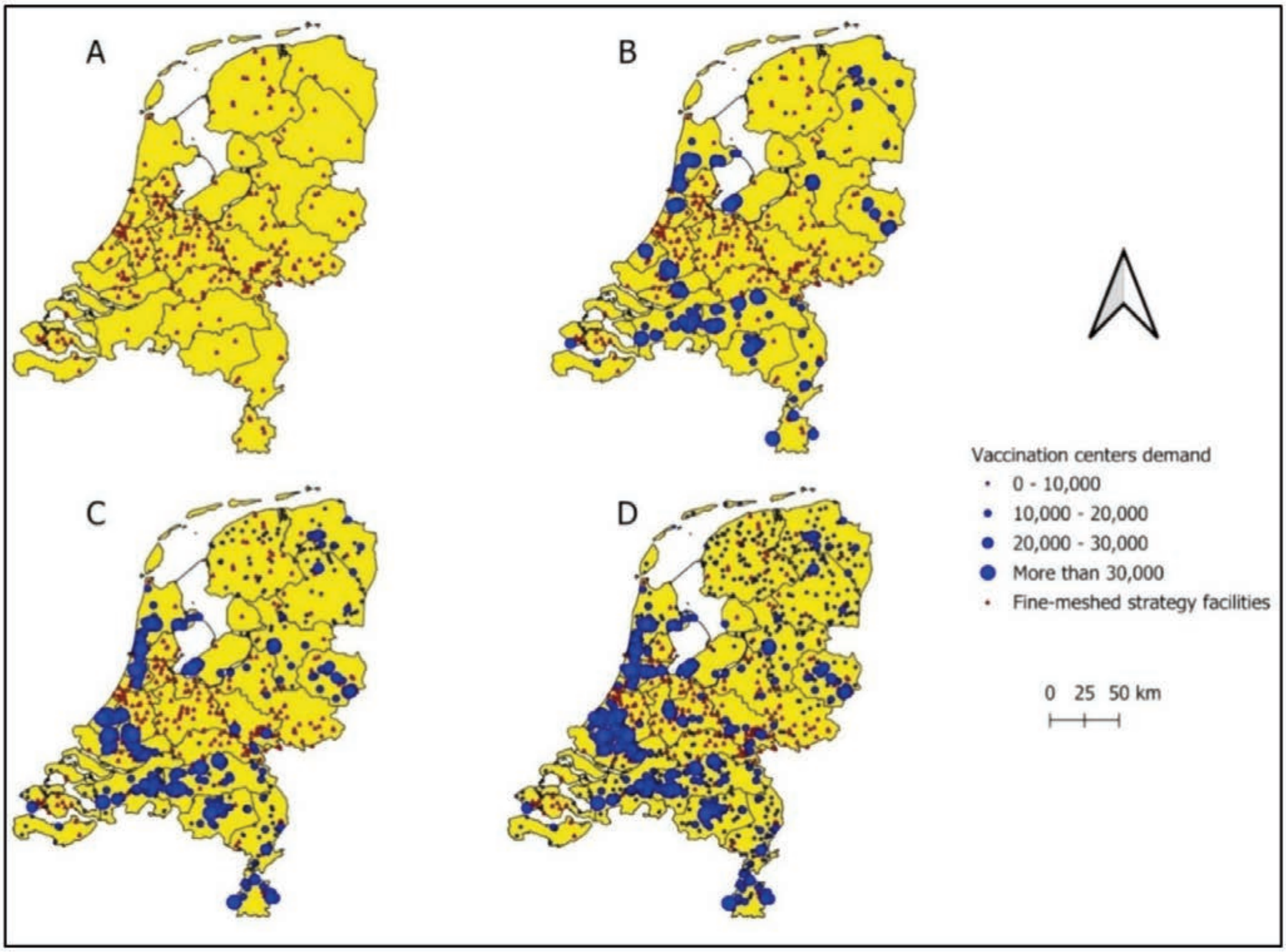

Figure 5. Potential locations for additional vaccination centres. **A**) fine-mesh centres, **B**) 50% coverage; **C**) Herd immunity scenario (70% coverage); **D**) GGD scenario (85%) coverage.

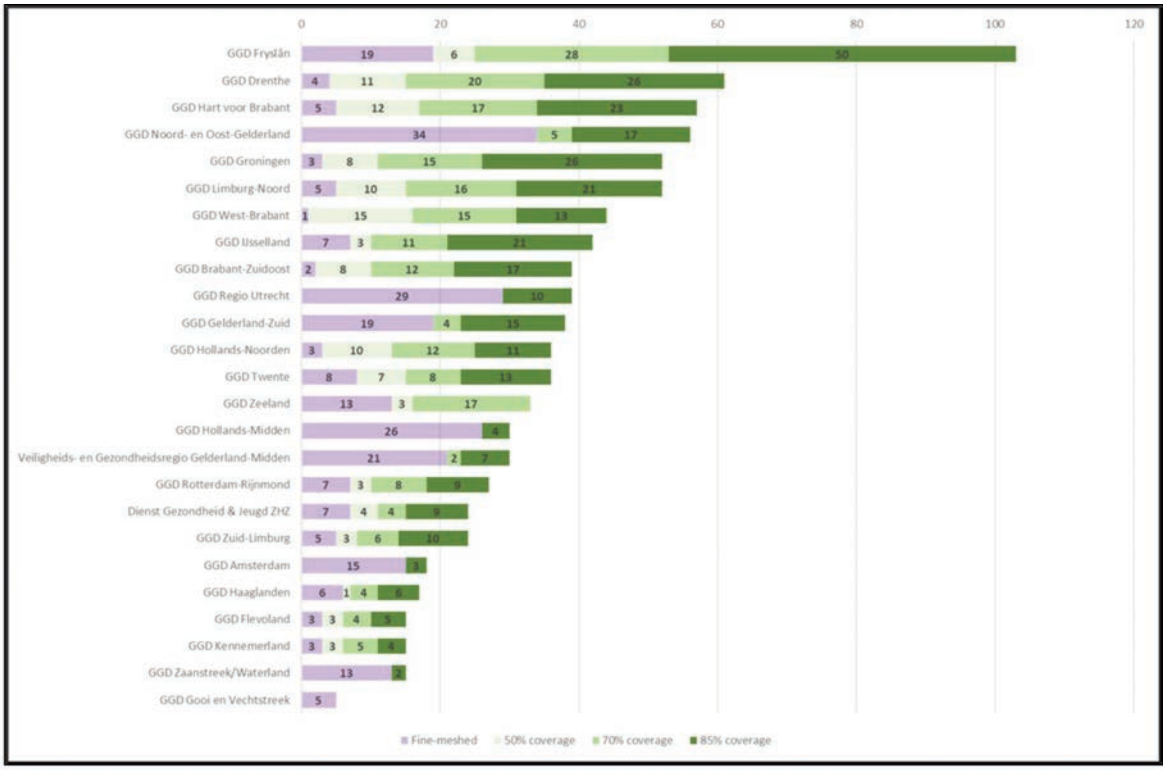

Figure 6. Number of vaccination centres needed to achieve 50%, 70% and 85% coverage.

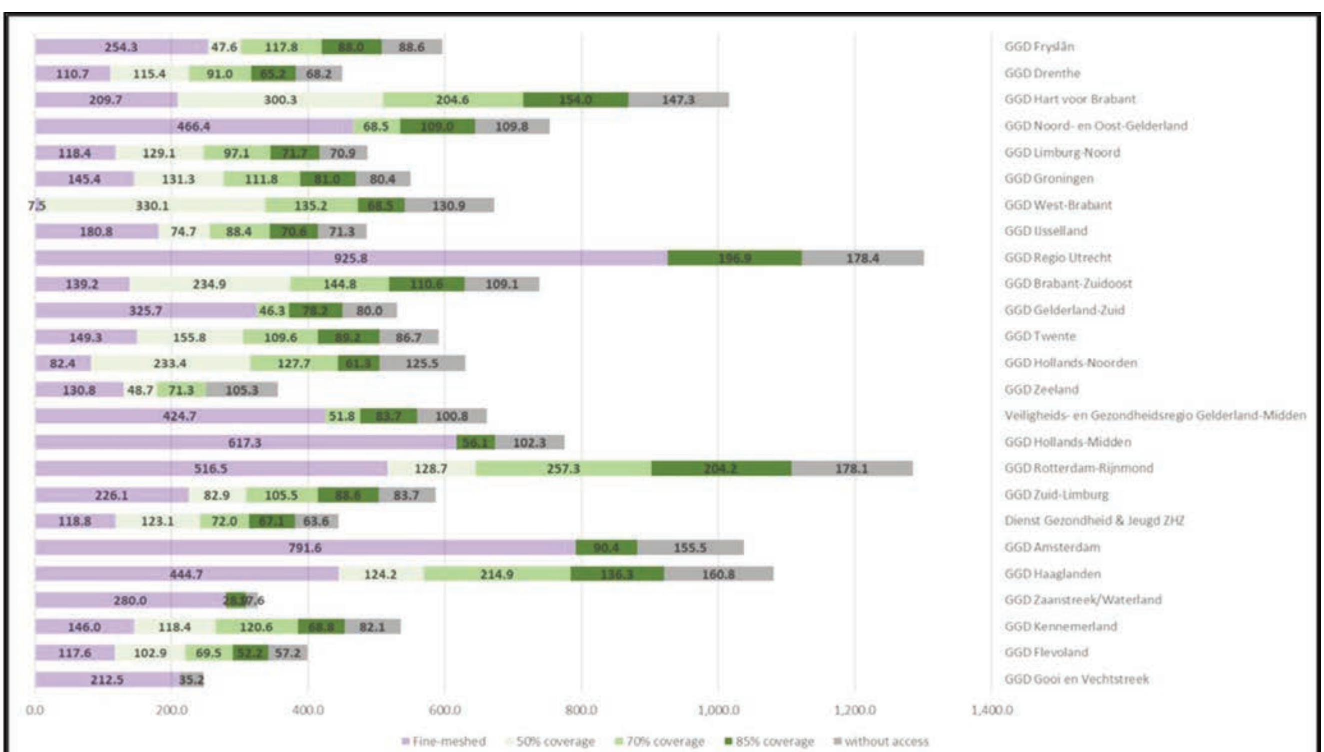

Figure 7. Number of people covered in the three scenarios (number of people shown in numbers divided with 1,000).

limited public transportation use (Blanford *et al*., 2022), emphasizes the need to include local transportation options such as the bicycle in the development of the vaccination strategy. Furthermore, the substantial variation in coverage level per GGD region emphasizes the need for spatial distribution decisions tailored to the needs of each region. The varying coverage level is very evident in the northern GGD regions, which primarily rely on centres with low coverage (less than 10,000 people), while the western GGD regions have centres with high coverage (more than 20,000 people). The variation may stem from varying land usage patterns within the GGD regions, availability of locations of a specific size (*e.g*., sports centres vs parks). The northern areas feature extensive agricultural zones and low population density, with significant distances separating them, such as seen in GGD Groningen and GGD Drenthe (Agricola *et al*., 2009; Sahoo *et al*., 2022). On the other hand, the western GGD regions have a different land use pattern, with less agricultural lands and high-density populations (CBS *et al*., 2020). As such, the use of different types of vaccination centres (e.g., fixed vs mobile vs pop-ups; Table 2) should be considered.

Mobile vaccination centres (e.g., buses) can increase vaccine uptake by reaching underserved regions (Alcendor *et al*., 2022; Zhang *et al*., 2022). Therefore, to enhance the vaccination strategy, mobile vaccination centres can be deployed to low-coverage locations, particularly in northern GGD regions, where a single bus can serve multiple locations according to a publicly known time schedule. In contrast, medium- and high-coverage locations can rely on pop-ups and fixed centres. The results of our study indicate that high-coverage level locations (20,000 people or more) have a significant role in providing accessibility by bicycle (up to 50% of the population), while greater reliance on low-coverage level locations (less than 10,000 people) starts when aiming to reach a higher percentage of the population. Therefore, when there is a need for mass vaccination within a short period of time, low-coverage level locations should also be considered.

There are several limitations to our study that could be addressed in future research. We utilized population data from 2018, which may not reflect the current situation fully. Between 2018 and 2021, population in The Netherlands increased by less than 2%. Thus, utilizing more recent population data may increase the accuracy of our results and further enable us to account for variations in the population that may prevent populations using bicycles, e.g., those who may be less mobile due to age and therefore contribute to the co-designing of urban living solutions (Cinderby, 2018).

The location-allocation model relied on data from OSM to suggest locations for the model, while the GGD administrations may encounter bureaucratic obstacles when considering some of the suggested locations in our calculations. Therefore, future studies should consider using location data suggested directly by stakeholders and investigating ways to overcome potential bureaucratic barriers or rank the locations based on a set of criteria defined by the stakeholders that may include facility size and other characteristics, which may be important in determining the capacity for each facility.

Finally, the LSCP model included a maximum travel distance/time threshold for all locations. In this study we used a 20-minutes travel time threshold based on the willingness of a per-

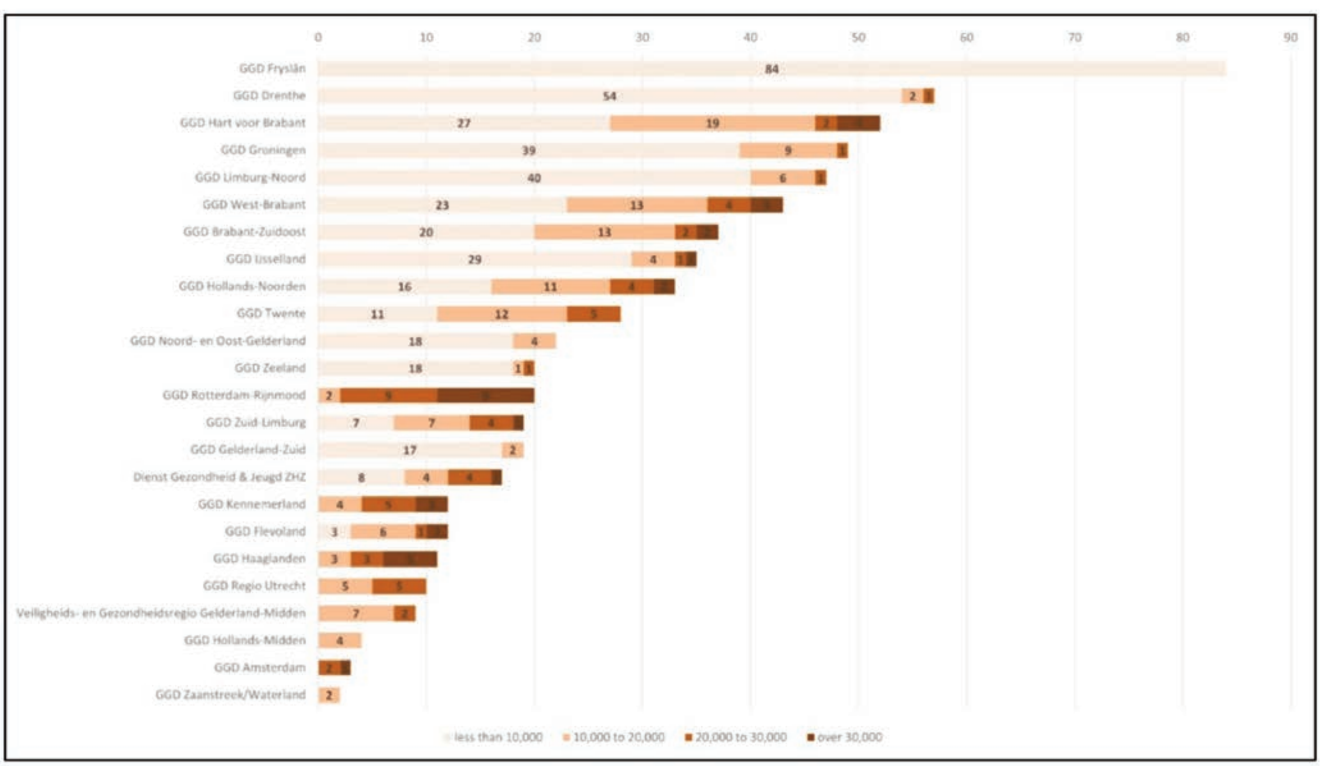

Figure 8. Number of vaccination centres and population coverage to achieve the 85% coverage scenario.

son to travel for personal needs. However, this variable may vary, and future studies would benefit by considering this since results are very sensitive to this kind of fixed thresholds. Future studies should consider exploring gradual shorter travel times to enhance the results. Thus, future studies should consider assessing accessibility using also other affordable transportation options, including electric bicycles, walking and bus travel to obtain a more comprehensive and wider view of accessibility as captured in other studies using different modes of transport (e.g., Lee & Miller, 2018). Although, the LSCP model, as used here, has several limitations, during a pandemic situation, such as occurred with COVID-19, this location-allocation method is useful for performing a rapid assessment based on a set of predefined demand criteria or targets as those defined in Table 3. This would enable public health agencies to achieve their targets during mass vaccination campaigns.

Conclusions

Location-allocation models combined with geographic spatial analysis hold promise for enhancing vaccine accessibility and uptake through effective distribution of vaccination locations. We firmly believe that integrating such methodologies into the planning process will be valuable during mass vaccination campaigns, such as those seen during the COVID-19 pandemic. By doing so, decision-makers can effectively identify the most accessible locations for vaccines based on factors such as predefined coverage levels, accessibility by targeted transportation mode and facility type.

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