Evaluating Spatial Accessibility to COVID-19 Vaccination Centers by Bicycles in The Netherlands and Optimizing Centers Opening and Closing Process

ADEL AL-HURAIBI

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SUPERVISORS:
DR. S. AMER
PROF.DR. J.I. BLANFORD

THESIS ASSESSMENT BOARD:
PROF.DR. R.V. SLIUZAS (Chair)
Dr. Talat Munshi (External Examiner, UNEP Copenhagen Climate Centre)

Abstract

COVID-19 virus has impacted people lives negatively in the recent years. The impact extended to all countries of the world, including the Netherlands. As a response to the virus, the Dutch municipal health service (GGD) started to vaccinate people against the disease in vaccination centers distributed in many locations throughout the country. The GGD vaccination strategy relied on fixed centers that use buildings for a long period of time. To reach vulnerable groups who were not vaccinated in that strategy, the GGD changed strategy by closing some of the fixed centers and relying more on mobile and pop-up centers. This research aims to evaluate the spatial accessibility to vaccination centers by bikes (regular bikes and electrical bikes) in both strategies and assess the effect of the strategy change on the vulnerable groups. It also aims to enhance accessibility by finding locations with high accessibility levels and prioritizing them in flexible vaccination plans. The thesis uses the cumulative opportunity measure to evaluate accessibility to vaccination centers in both strategies. Also, it develops a methodology using a location-allocation model to identify locations with high accessibility levels and prioritize them. The results indicate a decrease in accessibility levels to vaccination centers after changing the strategy, which negatively affected the vulnerable groups. It also shows a significant disparity in accessibility levels among the country regions. The results of the location-allocation model show the need to focus on the country southern regions mainly to improve accessibility in general. In addition, the results show a need to adopt local vaccination plans for each GGD region to provide high accessibility levels for as many people as possible. The thesis helps to understand the impact of vaccination center locations on their accessibility levels and its reflection on vulnerable groups. The method for prioritizing vaccination locations can also be used to build effective future vaccination plans.

Acknowledgment

I want to thank my supervisors, Dr. Sherif Amer and Prof. Justine Blanford, for their kind guidance during the journey of writing this thesis. Their immense support enabled this achievement that I am proud of to come to light.

I would like to thank the ITC staff for giving me the opportunity to be part of their international family and become a spatial engineer.

I am thankful for having a family that supported me and kept me sane during the difficult times

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List of Abbreviations

CDA	The Christian Democratic Appeal
CU	Christian Union
GGD	Municipal Health Service
HLAM	Hierarchical Location-Allocation Models
LSCP	Location Set Covering Problem
MCLP	Maximal Covering Location Problem
RIVM	National Institute for Public Health and the Environment
SGP	Reformed Political Party
SLAM	Single-level Location-Allocation Models

1. Introduction

1.1 COVID-19: Background and The Current Situation

Since its emergence in Wuhan in 2019, the COVID-19 pandemic has caused a severe negative impact on public health and nations economies worldwide (Sarkodie and Owusu, 2021). Many countries have practiced lockdown and imposed mitigations practices such as social distancing and wearing face masks to contain the virus(Girum et al., 2021). However, these efforts had a limited impact as the pandemic continued to spread among people in successive waves over time (Coccia, 2021). In an attempt to address the novel virus, several international pharmaceutical companies have developed various vaccines and successfully licensed them by the World Health Organization (He et al., 2021). The new vaccines have introduced new challenges for governments. These challenges are not only limited to producing or purchasing a sufficient amount of vaccines for their citizens, but also strengthening the local distribution response and facilitating access to vaccination locations to ensure fair vaccine uptake(Wouters et al., 2021). Given the nature of the virus that can mutate to multiple variants, the spatial location of the vaccination centers can become critical, as it is expected to be used several times to distribute new vaccine shots as needed (Ramos et al., 2021).

Like the rest of the world, the Netherlands suffered from the COVID-19 virus. The country had its first case diagnosed in Tilburg on the 27th of February 2020(Government of the Netherlands, 2020a). The Dutch government kept tracing the infected people until the mid of March when the Prime Minister spoke to the people about the seriousness of the virus(Government of the Netherlands, 2020b). Since then, the measures taken by the government have varied over time to include a partial lockdown in mid-October to a hard lockdown at the end of 2020(Government of the Netherlands, 2020c, 2020d). Around 20 thousand people have passed away due to the virus in the Netherlands, while the infection cases have exceeded 2 million (Worldometer, 2021). An extensive vaccination strategy against the vicious disease has begun on the 6th of January, 2021 (Meijer, 2021). The government first vaccinated the front-line workers in the health sector and then initiated a strategy to vaccinate the rest of the people according to their age in descending order(Rijksoverheid, 2020). At the beginning of the vaccination strategy, the Dutch municipal health services (GGD) had relied in their strategy on fixed centers. They were distributed throughout the country to vaccinate people, some of which were located in sports halls, public parking, and next to places of worship(NU, 2020; Van Gameren, 2021).

At the end of March 2021, GGD established the first pop-up center in Zandvoort municipality to make it easier for the elderly to reach the center and have their vaccination shot(Walbeek, 2021). The new type of vaccination centers will remain in their locations for a period of time that does not exceed ten weeks before moving to new areas (Walbeek, 2021). Over time, GGD started to change its vaccines distributing strategy to rely more on temporary pop-ups and mobile centers (vaccination buses) to reach areas with a low vaccination uptake (van Annemieke, 2021). This new strategy is called *fine-meshed vaccination strategy*. It depends mainly on mobile units and pop-ups to reach residential neighborhoods, villages, and remote areas (GGD Zuid Limburg, 2021). As a result of vaccinating a large number of the population, GGD noticed a decrease in the turnout to the fixed vaccination centers that were established at the beginning of the original strategy. Consequently, GGD started to close these large fixed centers and gradually replace them with mobile and pop-up centers to increase the vaccination percentage as possible(van Annemieke, 2021). Therefore, vaccination strategies implemented by the GGD can be defined as follow :

- **Original strategy**: It is the first vaccination strategy that depends only on fixed centers to vaccinate people
- **Fine-meshed strategy**: It is the second vaccination strategy that depends on fixed centers, pop-ups, and mobile centers to vaccinate people

Given the fact that nearly 2.8 million Dutch people have not received any dose of the COVID-19 vaccine by the end of July 2021, this new strategy aims to raise the share of vaccinated people with the first and second does to at least 85% of the population in all municipalities (NL Times, 2021; van Annemieke, 2021; Zurhake, 2021). Moreover, the new strategy can remove barriers for those who have language difficulties or don't know how to use GGD online platforms(van Annemieke, 2021). Also, these temporary centers can help raise awareness and dispel fears among those who still have doubts about the vaccine(Koopen, 2021). According to some GGD representatives, this strategy is trying to facilitate better *physical accessibility* to vaccination centers for vulnerable groups targeted by the GGD. These groups include the elderly (over 60) especially those with walking difficulties, low-income people, people living in remote neighborhoods with limited transportation options, and municipalities with a significant Christian population density(Municipality of Brunssum, 2021; van Annemieke, 2021). Consequently, changing strategies to increase spatial accessibility raises questions about the original strategy accessibility level and the extent of improvement that resulted from the fine-meshed strategy.

1.2 Cycling to Vaccination Centers

In general, Dutch people use several transportation modes to reach health services like vaccination centers. Moreover, the Netherlands has the best cycling infrastructure worldwide, making it the most country that uses bicycles for transportation, as shown in Figure 1 (Buehler and Pucher, 2012; Fishman, 2015). The Dutch use regular and electric bicycles for commuting, showing an increasing reliance on electric bicycles as an alternative to regular bicycles and cars(de Haas et al., 2022). Surveys show that the Dutch use bicycles in 28% of their trips and that their use of bicycles has increased in the largest municipalities (Amsterdam, Rotterdam, The Hague, and Utrecht) in recent years(CBS, 2020a, 2015). Bicycles are the preferred transportation mean in the Netherlands for trips related to education and work, with a maximum limit of 5 km per trip(CBS, 2020a). Despite the decrease in trips average distance for all transportation modes during the early days of the pandemic, the average distance for cycling has increased from 3.4 km to 4.4 km at the beginning of April 2020, as shown in Figure 2. In addition, 37% of the Dutch people have used bicycles as an alternative to public transportation (except for trains) during the pandemic(De Haas et al., 2020).

The Dutch bicycle users are demographically more diverse than in any other country, which makes targeting regular and electrical bicycles useful for studying the impact of changing accessibility levels on multiple social groups in the Netherlands(Fishman, 2015).

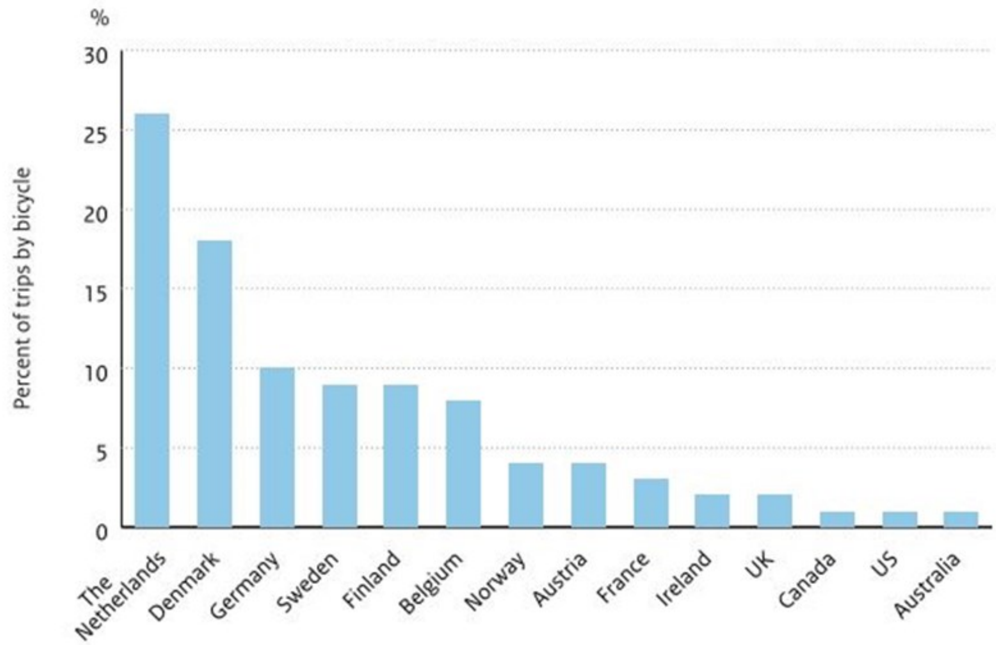

Figure 1: Bicycles modal share of trips in various countries (Buehler and Pucher, 2012)

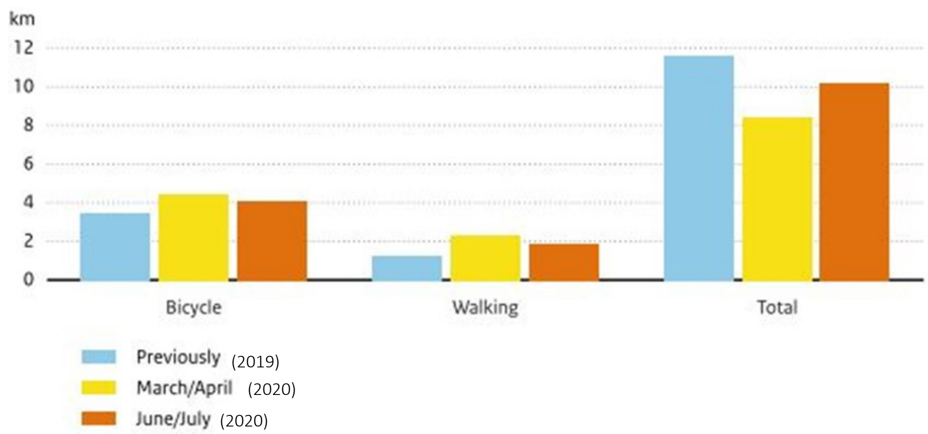

Figure 2: Average distance traveled per trip before and during the coronavirus crisis (De Haas et al., 2020)

1.3 Research Problem

Due to its fast transmission, COVID-19 patients can increase the pressure on hospitals to critical levels that threaten society health systems to collapse, which makes increasing the vaccination rate an urgent matter(Deutsche Welle, 2021).On the other hand, preserving people right to choose to be vaccinated or not delays achieving sufficient social immunity against the virus (Erasmus University Rotterdam, 2021; Rasheed, 2021). A problem can be identified as wicked if there is a lack of information about the problem and there is a disagreement among the stakeholders on how to solve it. The wickedness in COVID - 19 vaccination problem here manifests in the need to vaccinate people while there is a lack of willingness among several groups of people to be vaccinated due to multiple barriers. These barriers include but are not limited to the ability to reach vaccination centers and people misconceptions about the vaccine. Accordingly, the new vaccination strategy can be considered as an intervention to mitigate the wicked problem of low vaccination rates caused by unvaccinated groups, where the GGD is the main stakeholder among other stakeholders represented by population groups with different needs. The GGD is trying to increase vaccination uptake among people in the new strategy by targeting not only the groups who are affected by the trips distance and time, but also those who still have doubts about the vaccine or have a problem booking a vaccination appointment, as shown in Table 1 (Koopen, 2021; van Annemieke, 2021). Therefore, investigating accessibility levels achieved in both vaccination strategies help in improving such intervention. In addition, closing fixed vaccination centers and replacing them with temporary ones requires a search for a scientific methodology to find locations with high accessibility levels for vaccination centers. Moreover, by the time of writing this thesis, the Dutch government has started to distribute a booster shot of the vaccine to maintain people immunity against the virus mutations. Consequently, understanding the spatial accessibility levels for both strategies is important to enhance vaccination strategies for any booster shots in the future(Rijksoverheid, 2021).

Table 1: The wicked problem and Stakeholders

<table>
<tr><td>Wicked Problem</td><td colspan="3">Low vaccination rate municipalities (<85%)</td></tr>
<tr><td>Intervention</td><td colspan="3">Fine-meshed Strategy</td></tr>
<tr><td>Main Stakeholder</td><td colspan="3">Dutch Municipal Health Services (GGD)</td></tr>
<tr><td>Targeted Stakeholders</td><td>- Elderly
- People with walking difficulties
- Low-income people
- People who live in remote areas</td><td>- People with doubts
- Religious people</td><td>- People with insufficient language
- People who don't know how to book a vaccination appointment</td></tr>
<tr><td>Strategy Effect</td><td>Increasing spatial accessibility</td><td>Answering questions by professionals</td><td>Removing barriers
(no appointment, easy to reach)</td></tr>
</table>

1.4 Objectives and Research Questions

Main objective: to evaluate spatial accessibility to COVID-19 vaccination centers by regular and electrical bicycles in both GGD vaccination strategies and to optimize centers opening and closing process

Sub-objective (1): to evaluate spatial accessibility to COVID-19 centers by regular and electrical bicycles for both GGD strategies

Q1: What are the available approaches to measure vaccination center accessibility levels?

Q2: What was the spatial accessibility level to COVID-19 vaccination centers in the original vaccination strategy?

Q3: How has the fine-meshed strategy changed the accessibility level to the vaccination centers?

Q4: Which municipalities need more or fewer vaccination centers to enhance spatial accessibility?

Sub-objective (2): to identify locations for COVID-19 vaccination centers that should be closed or opened in the fine-meshed strategy at the municipalities level

Q5: what is the most suitable approach to achieve the optimum vaccination centers locations to enhance accessibility levels?

Q6: Which vaccination centers should be prioritized to stay open, re-located, or closed in the fine-meshed strategy?

1.5 Structure of the Thesis

The second chapter contains a detailed literature review of spatial accessibility definitions and measures. That review aims to find a suitable accessibility measure that helps with achieving the research first objective. The chapter also discusses different location-allocation models to highlight their role in achieving the second objective of the research. The third chapter presents a brief review of the study area, a detailed description of the study data, and overall methodology developed to reach the results. The fourth chapter focuses on the results of the accessibility measure and location-allocation models. Finally, the last chapter discusses chapter four's results and highlights the research conclusions, limitations, and recommendations for any future research related to the topic.

2. Literature Review

2.1 Access to Health care: Definitions and Classifications

Before investigating accessibility to a health care service such as vaccination centers, the concept of access to health care must be clarified first. The term "access " in the health care field has gained researchers interest as it measures the effectiveness of the existing delivery system and the benefits provided to the service user(Cromley and Mclafferty, 2012). The interest is evident in relevant scientific papers and books, where many researchers have tried to define the term and differentiate between its spatial and non-spatial factors (Aday and Andersen, 1981; Penchansky and Thomas, 1981). Both Aday and Andersen (1981) define access to health care as people's ability to access health services when and where they are needed. Accordingly, Penchansky and Thomas (1981) define access to health care as the degree of fit between the service seeker and the health service system and link that to five factors that affect access to health care (Figure 3).

The factors are as follows:

1- **Availability**: Describes the sufficiency in the relationship between the health services and their users need in term of volume and quality
2- **Accessibility**: Describes the spatial relationship between supply and demand (the health service and the user), taking into account the trip cost between them (distance or time)
3- **Accommodation**: It reflects the relationship between the capabilities of the health service to receive the service user (such as the number of working hours) and the extent of the user's understanding and ability to adapt to them
4- **Affordability**: Describes the relationship between the provided health service financial cost and the user's understanding and ability to pay for it through a deposit or health insurance
5- **Acceptability**: Describes the relationship between the behavioral attitude of the user towards the characteristics of the health service provider and the behavioral attitude of the health service provider towards the characteristics of the users

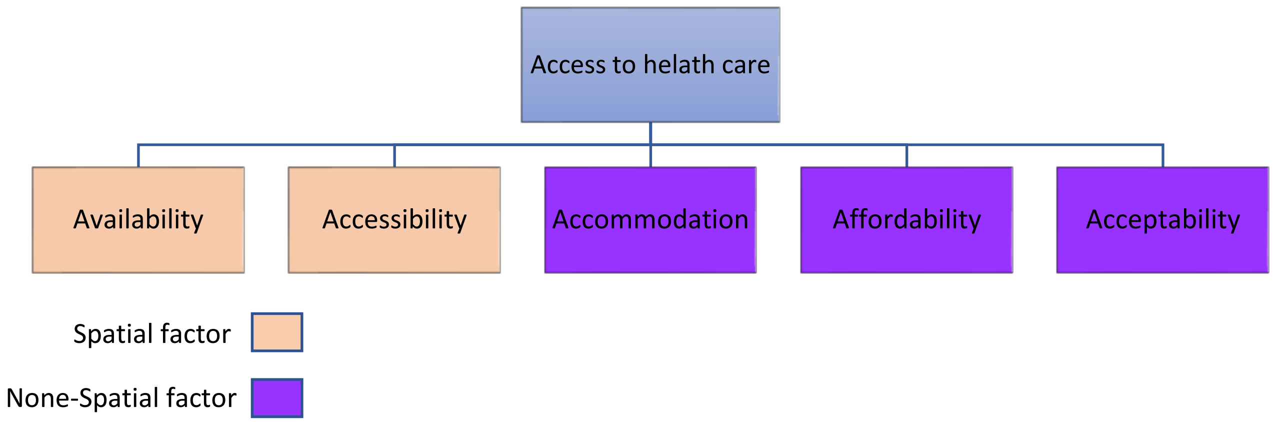

Figure 3:Access to health care factors

These factors can be divided into spatial factors and non-spatial factors. Accessibility is an apparent spatial factor as it depends on the distance and time required for the demand to reach a facility or destination(Penchansky and Thomas, 1981). In addition, availability can have a spatial impact when there are insufficient levels of service or not enough appointments in the facility(Guagliardo, 2004). The rest of the factors don't have a spatial nature as they reflect the economic (affordability) and social aspects(acceptability and accommodation) of the facility users(Bagheri et al., 2005). Some other researchers differ in dividing the factors affecting access to health services and prefer to isolate spatial accessibility from the rest of the factors. Therefore, Joseph and Philips(1984) distinguished spatial and non-spatial factors in similar work as they classified access into locational access and effective access. Locational access reflects the relationship of the service location to the customer's location geographically, which can be similar to Penchansky and Thomas(1981) definition for the accessibility factor. As for effective access, it reflects the practical, social, and economic aspects of the facility users, which can be linked to the rest of Penchansky and Thomas (1981) access factors. In addition, Khan and Bhardwaj (1994) classified access into spatial and aspatial factors. Based on that, they define two terms for access: geographical access and social access. They define geographical access as access controlled by distance, while non-geographical factors control social access.

2.2 Spatial Accessibility: Measures and categorizations

Spatial accessibility is used in several scientific fields, as researchers have been interested in measuring it for many public and private services(Fransen et al., 2015; Jalkanen et al., 2020; Kelobonye et al., 2020). Accessibility is a broad and complex concept that many researchers have attempted to define and develop different measures for (Geurs and van Wee, 2004). Therefore, accessibility can be defined as "the potential opportunities for interaction" or the degree of connection between a point with other points on the same surface(Dalvi and Martin, 1976; Hansen, 1959). Some researchers associate accessibility with freedom and utility, defining accessibility as "the freedom of individuals to decide whether or not to participate in different activities" or "the benefits provided by a transportation/land-use system" (Ben-Akiva and Lerman, 1987; Burns, 1979). Using accessibility definitions in the literature and by studying different accessibility measures, Geurs and van Wee (2004) were able to derive four components for spatial accessibility. Figure 4 shows how these components affect each other and the accessibility levels, and how the accessibility level affects the components in return.

These four components are as follows:

1- **The land-use component**: It is concerned with the volume and locations distribution of both supply (e.g., businesses, hospitals, and schools) and demand (e.g., employees, students, and patients).

2- **The transportation component**: It represents the impedance associated with the transportation system that links supply to demand, such as cost, trip time, and effort of the delivery system exerted on the user.

3- **The temporal component**: Indicates the availability of trips throughout the day and the time that transportation users have to participate in an activity such as work

4- **The individual component**: Reflect the user's characteristics, which include their abilities (such as physical ability), needs (such as education), and qualifications (such as financial capacity) to use the transportation mode.

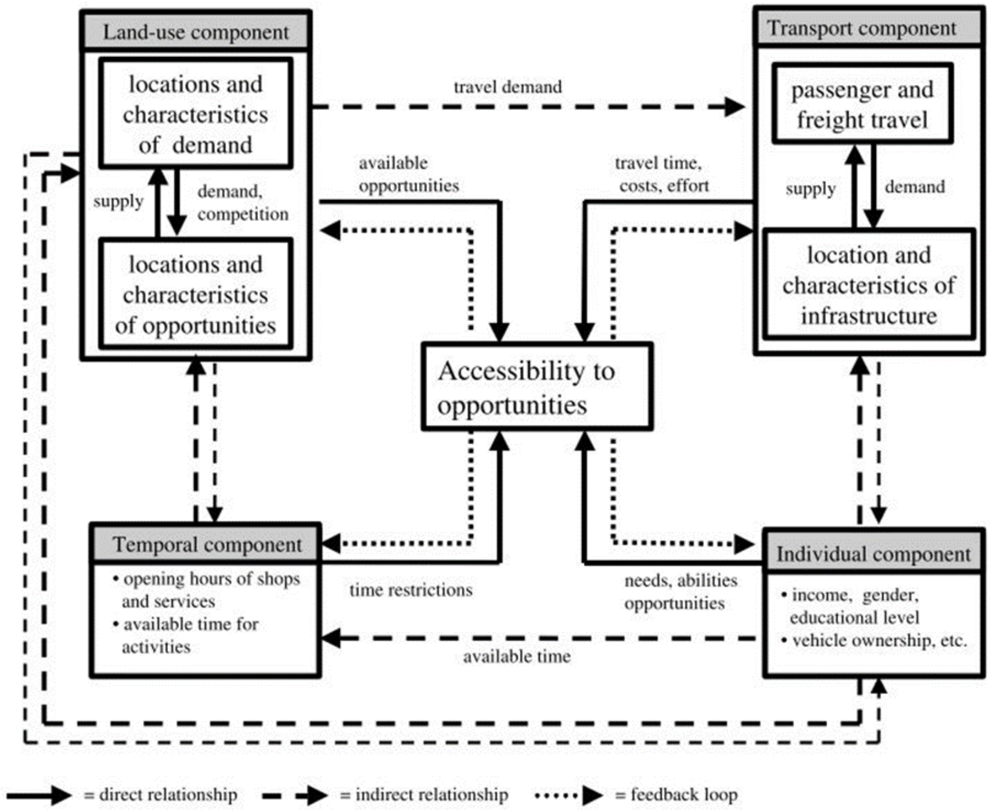

Figure 4: Accessibility components (Geurs and van Wee, 2004)

Theoretically, accessibility measures should include all of the above components to provide comprehensive results about accessibility. However, in reality, such a measure does not exist and would be difficult to interpret by decision-makers; thus, all accessibility measures consist of only some of these components (Geurs and van Wee, 2004). This deficiency can be compensated by using more than one accessibility measure to obtain results covering all components(Curtis and Scheurer, 2010).

Accessibility measures were classified by many researchers interested in the topic(Apparicio et al., 2008; Curtis and Scheurer, 2010; Geurs and van Wee, 2004; Guagliardo et al., 2004; Handy and Niemeier, 1997; Pirie, 1979). This research adopts Geurs and van Wee's (2004) accessibility measures classification shown in Figure 5. They classify accessibility measures as follows:

1 – infrastructure-based measures: Transportation planners mostly use these measures to analyze transportation systems in terms of speed, congestion, and travel time. The data for these measures are easy to be obtained and utilize(Curtis and Scheurer, 2010). Furthermore, This type has already been used in drawing transport plans for several countries, including the Netherlands, as it is easy to be explained and communicate among decision-makers(AVV,

2000). However, these measures don't include the land-use component, nor can they effectively integrate both temporal and individual components in the calculations.

2 – location-based measures: Unlike infrastructure-based measures, these measures incorporate the land-use component. In addition, they can include the supply capacity in the calculations (e.g., hospital beds and job vacancies) and the competition behavior between supply and demand. This competition is based on abundance versus scarcity, whereby different demands may compete for limited supply and vice versa. These types of measures can be divided into three categories as follow

a) ***Distance measure***: considered the simplest form for these types of measurements as it measures the time or distance between two points(Geurs and van Eck, 2001).

b) ***Contour measure***: also named cumulative opportunities measure. This measure helps to highlight the demand locations that are able to reach supply locations within predetermined time or distance catchment areas known as isochrones. The measure results are easy to interpret by stakeholders, requiring less data to be applied compared to other measures. However, it does not reflect the effect of competition nor include the capacity element in the calculations. In addition, the measure results are sensitive to the isochrone values, and usually, these values are randomly chosen(Curtis and Scheurer, 2010).

c) ***Potential accessibility measures***: They are also named *gravity-based measures*(Geurs and van Wee, 2004). These measures are based on the principle of attraction between the supply and demand according to their capacity and the distance between them. Thus, Accessibility results are directly proportional to the volume of supply and demand (e.g., job seekers and job opportunities) and inversely to the distance between them. They are able to include both land-use and transport components as well as reflect individuals perception for using a transport mode by including decay functions in the equations. In addition, some researchers have modified the equations for these measures to contain the competition factor. Although these measures are more realistic than others, they aren't easy to translate for decision-makers. They even become more complex and challenging to use when the competition factor is added.

d) Person-based measures: They measure accessibility based on people's ability to participate in an activity within an available time and space from individuals perspective. These measures use what is known as space-time prisms to reflect access to activity sites in the time available(Hägerstrand, 1970). The use of these measures is still rare, owing to the need for a large amount of information about activities, the difficulty of calculating them, and the lack of a competition factor. However, they efficiently incorporate activity quality into the calculations compared to other types of measures.

e) **Utility-based measures**: They focus on the economic aspect of accessibility as they are based on the principle of the users maximum benefits from having multiple transportation options and the users demographic and economic characteristics(Geurs and van Eck, 2001). They measure user behaviors toward the travel modes alternatives and reflect economic and social gains from using several transport choices. Still, their results are not easy to explain to decision-makers.

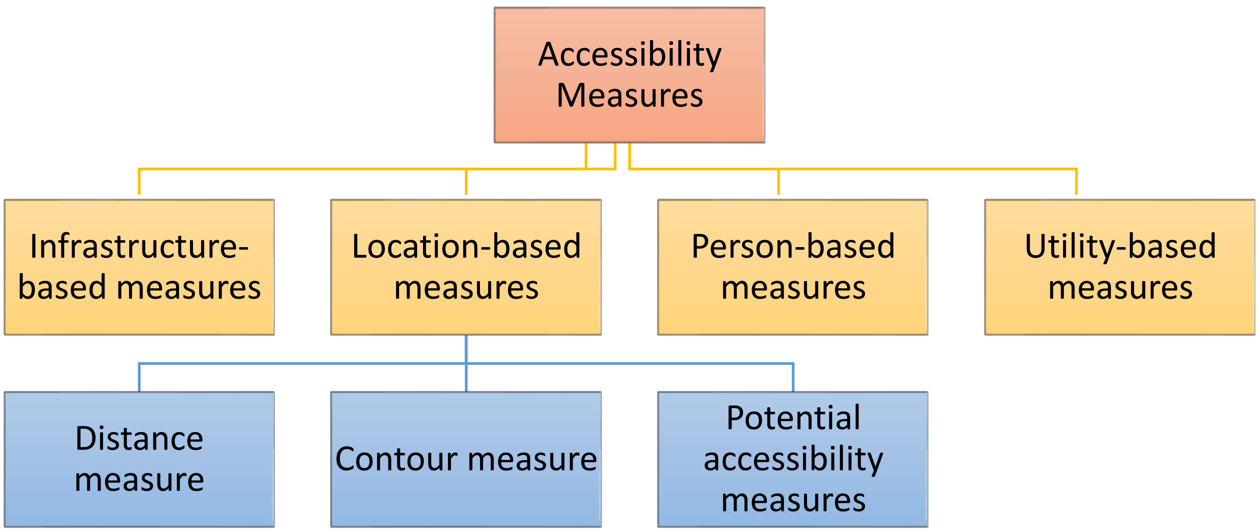

Figure 5:Accessibility measures

In conclusion, choosing an adequate accessibility measure depends on the available data, the accessibility component targeted by the research, and the audience to be communicated with the anticipated results. This research investigates spatial accessibility to different COVID-19 vaccination centers as supply points that provide a health service to demand points representing the Netherlands population. In addition, this research investigates accessibility to these centers by only using regular and electric bicycles as transportation modes. All of that make both land use component and transport component essential in the research calculations, which is mainly found in the location-based measures that are used in many geo-health studies(Lopes et al., 2019). Due to the lack of vaccination centers capacity data, this research uses a cumulative opportunity measure to evaluate accessibility levels without including the factor of attraction or competition. This research uses trips survey data to obtain logical isochrones (trip time intervals) for the measure and uses high-resolution data about population social-economic characteristics and their locations to increase the measurement accuracy.

2.3 Spatial Accessibility & COVID-19: Previous Studies

Prior to the COVID-19 pandemic, epidemiologists had been studying accessibility to vaccines for diseases such as rabies(Polo et al., 2013). Several studies have shown that many African countries have a low level of accessibility to health care due to unfair distribution of healthcare facilities and poor transportation infrastructure, such as Kenya and Ghana(Noor et al., 2006; Poku-Boansi et al., 2010). Consequently, Low health care accessibility can directly impact vaccine uptake, which was the reality of the children vaccination level in a country such as Niger (Blanford et al., 2012). Recently, several studies have proven the effectiveness of mobile vaccination units in overcoming such a problem by enhancing the spatial access of disadvantaged social groups(Alcendor et al., 2022; Gupta, 2022; Zhang et al., 2022).

To date, many studies related to COVID-19 vaccination have been conducted in the United States. In Florida state, a study has been done on the accessibility to Intensive Care Units (ICU) for COVID-19 patients using regular and enhanced two-step floating catchment area method (2SFCA)(Ghorbanzadeh et al., 2021). This method is one of the potential accessibility measures that consider the supply capacity, the demand size, and the travel cost in a ratio to express the accessibility in the calculations(Radke and Mu, 2009). The study concluded that there are low levels of accessibility in the south and northwest areas compared to the rest of the state (Ghorbanzadeh et al., 2021). In another study, Kim et al. (2021) showed a severe lack of accessibility in the same states among Hispanics and Latinos and in rural areas compared to urban areas. Moreover, by measuring spatial accessibility for car drivers and pedestrians to COVID-19 tests centers in Florida, Tao et al.(2020)found that elderly, African Americans, and low-income people struggle with low accessibility levels to the test centers.

At the European level, a study examined the spatial accessibility of 14 European countries residents to the nearest Intensive Care Units (ICUs), taking into account the number of beds for every 100,000 citizens (Bauer et al., 2020). The result of the study showed that Sweden and Denmark have the lowest level of accessibility and that Croatia has the highest average trip time to the nearest hospital (Bauer et al., 2020). In Warsaw, Poland, a study found that the unfair distribution of three types of vaccines among vaccination sites led to vaccines shortages that made people commute to remote vaccination locations rather than reaching the nearest one (Krzysztofowicz and Osińska-Skotak, 2021).

In the city of Mashhad in Iran, a study attempted to identify the best sites for distributing COVID-19 vaccines (Mohammadi et al., 2021). Compared to the central area of the city, the study found that low-income people and those who live in the border areas of the city have low accessibility to COVID-19 vaccines and that using both hospitals and health centers simultaneously to distribute vaccines is the best way to increase vaccination coverage (Mohammadi et al., 2021). Furthermore, in Brazil, a study investigated the accessibility for COVID-19 patients to hospitals on foot and the availability level of ICUs beds and ventilators in 20 Brazilian cities(Pereira et al., 2021). The study found that three cities suffer from a significant shortage of beds and ventilators, and that black and lower-income communities suffer from low accessibility levels to the hospitals (Pereira et al., 2021). In Aotearoa, New Zealand, a study investigated spatial accessibility to vaccination services using the two-step floating catchment area method and found that residents of rural areas, the elderly, and native people of the area have low spatial access to Covid-19 vaccines (Whitehead et al., 2021).

Overall, all of the above indicate that most accessibility studies related to COVID-19 focus on measuring accessibility to hospitals and ICUs for the anticipated patients. In contrast, studies on accessibility to centers only designated for COVID-19 vaccination, such as those used in the Netherlands, are absent, and there is a need for a scientific contribution. Furthermore, studying accessibility to Covid-19-related health facilities using regular and electrical bicycles as transportation modes will be a qualitative addition to the existing efforts as none of the above studies measured accessibility using bicycles as a transportation mode. In addition, the increasing reliance on temporary vaccination centers requires research to find an optimization approach to distribute vaccination centers to increase spatial accessibility.

2.4 Improving Spatial Accessibility

To improve spatial accessibility, location-allocation models can be used as an effective approach to reduce travel distance and time. These models can help examine the effect of the present facilities distribution on travel cost, develop and compare multiple distribution options, and propose a solution that ensures more equitable spatial accessibility to health services demand (Rahman and Smith, 2000). Rahman and Smith(2000)classify location-allocation models into hierarchical location-allocation models (HLAM) and single-level location-allocation models (SLAM). (HLAM) allocates facilities considering the different levels of service provided by these facilities. For example, hospitals provide more services variety than those offered by health centers or clinics; thus, they are allocated according to different criteria than other facilities. In contrast, (SLAM) assigns facilities without taking into account the difference in service levels provided and assumes that all facilities offer the same service. This thesis assumes that all vaccination centers (fixed and mobile) offer the same service level to the Dutch people; therefore, it discusses (SLAM) only. Location-allocation models have the ability to solve facilities distribution problems that can be classified as P-center problems, P-median problems, and coverage problems (Figure 6).

The p-center problem model relocates a (P) number of facilities to reduce the maximum distance traveled by any demand point to its closest facility(Drezner, 1984). The advantage of this model is that it considers the worst travel distance and aims to keep it as short as possible to preserve a high level of service. The model is frequently used to locate emergency facilities such as fire stations(Çalık, 2013). However, this approach can increase the travel time for most demand points to decrease the distance for a limited number of people. The P-median problem model is the most famous of all the models, as it re-distributes a (P) number of facilities to reduce the total weighted distance (or average distance) between supply (facilities) and demand points (Hakimi, 1965). This model is widely used to distribute facilities frequently used by people, such as grocery stores and companies offices (Alkhedhairi, 2008). As with all other location-allocation models, this model is based on the assumption that people will go to the nearest facility and that all facilities have sufficient capacity to handle the assigned demand points. The problem of this model lies in its bias towards urban areas with a high population density to reduce the total traveled distance, thus resulting in unfair accessibility to the residents of rural areas, who will travel a long distance to reach the service (Rahman and Smith, 2000).

Coverage models can overcome such a problem using a distance threshold assigned for all facilities called the maximal distance. One of these models is the location set covering problem model (LSCP), which distributes the least number of facilities so that each demand point lays within at least one service facility maximal distance (Toregas and ReVelle, 1972). This model is popular among governments and international organizations and has been used and enhanced by multiple studies (Chaiken, 1978). It is best used when planners only focus on covering the demand, assuming there is no limit to facilities number assigned, which does not always represent the reality. To include such a limitation factor, the Maximal Covering Location Problem model (MCLP) can be utilized to have a specific (P) number of facilities in the process. It distributes a predetermined number of facilities to cover the largest possible number of demand points within the maximal distance(Church and ReVelle, 1974).

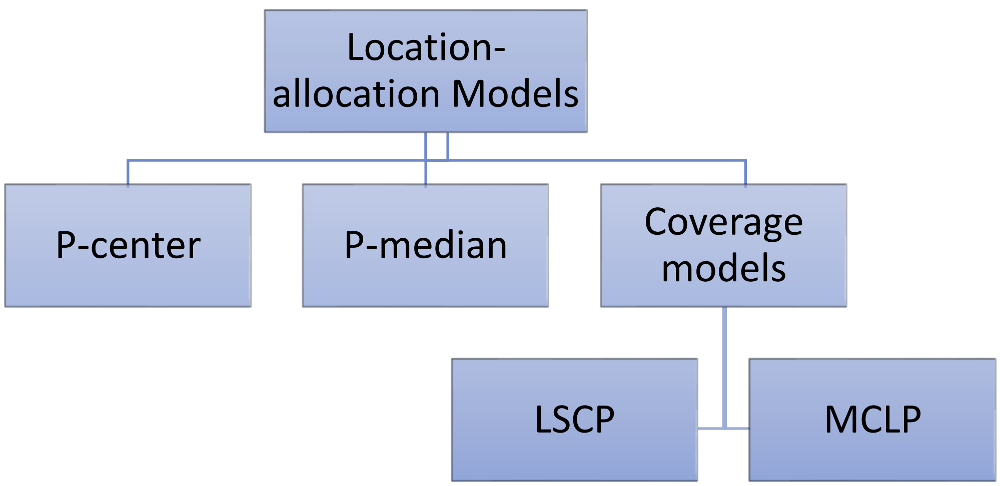

Figure 6: Location-allocation models

Compared to the previous models, (MCLP) model has a more realistic approach as it includes constraints for the number of facilities and maximal distance. In addition to that, MCLP maximal distance (S) can be compared to a national distance standard (N) for reaching health facilities, which helps identify deficiencies and the amount of improvement needed more accurately. Thus, amount of people who have convenient accessibility (<S), national acceptable accessibility level (<N), and unfair accessibility level (>N) can be identified (Church and ReVelle, 1974).

All of these models can be used to study various options for increasing physical accessibility levels. Thus, the choice of model depends on the planning objective and data available for the study. Coverage Models rely on binary calculations (covered and uncovered) and budget constraints, so they are an ideal option for planners who primarily focus on covering as much demand as possible.

In contrast, both P-center and P-median Models calculation relies on reducing the actual travel cost between supply and demand. Thus, they are more suitable for planners who mainly focus on reducing the distance to enhance accessibility

This thesis assumes that people who travel to vaccination centers use bicycles (regular and electrical) as the only transportation mean to reach vaccination centers. Therefore, all facilities can provide the service to only those who live within a time threshold corresponding to bicycles use tendency. In addition, the second objective of the research aims to improve accessibility by increasing or decreasing vaccination centers; hence, the location-allocation model used should be able to add as many vaccination centers as needed to cover most of the demand. Therefore, this thesis utilizes the LSCP model for its ability to include the time threshold for cyclists and add unlimited numbers of vaccination centers as needed.

2.5 Chapter Summary

measuring spatial accessibility to COVID-19 vaccination centers is essential for realizing equitable access to such a health service. Due to the novelty of the virus, only a limited number of studies have investigated spatial accessibility to hospitals and ICUs during the pandemic, and few investigated spatial accessibility to COVID-19 vaccination centers. Therefore, this research provides value to these scientific efforts by analyzing accessibility to all vaccination center types in the Netherlands and considering bicycles as the main transportation mode. Furthermore, Researchers have tried to define and measure accessibility using various measures. This research utilizes cumulative opportunity measure to investigate spatial accessibility to all types of COVID-19 vaccination centers in the Netherlands and uses additional data to increase the accuracy of the results, as will be discussed in detail in chapter 3. Finally, a location-allocation model will be utilized in this research to improve accessibility levels and provide recommendations for stakeholders in that manner. LSCP model was chosen for its ability to add a time threshold and an unlimited number of facilities.

3.Methodology

3.1 Study Area

The research investigates spatial accessibility levels to COVID-19 vaccination centers throughout the Netherlands. The country has 352 municipalities with a population exceeding 17 million, where 47% live in the western part of the country(CBS, 2021a, 2021b, 2020b). People in all municipalities have suffered from the COVID-19 virus and have their share of infection and death cases (RIVM, 2021). The country is divided into 25 health administrative regions (GGD regions) that deal with health matters such as vaccination distribution(GGD GHOR, 2022). Socially, the Netherlands is witnessing an increase in the number of elderly people and a decrease in the number of young people. The average age of the population has increased from 30.8 in 1950 to 42.3 in 2021(CBS, 2021c). Economically, statistics indicate that the average dutch household income has increased from 24,300 eruos in 2000 to 29,500 euros in 20018 (CBS, 2018). As for ethnicity, around one-quarter of the population are immigrants, where Western origin immigrants make up 10.9 percent of the total population, and non-Western immigrants represent 14.4 of the total population(CBS, 2022a). Finally, surveys show that the majority of the Dutch people describe themselves as not affiliated with any religious beliefs; however, Christians represent the most significant proportion of those with religious beliefs(CBS, 2021d).

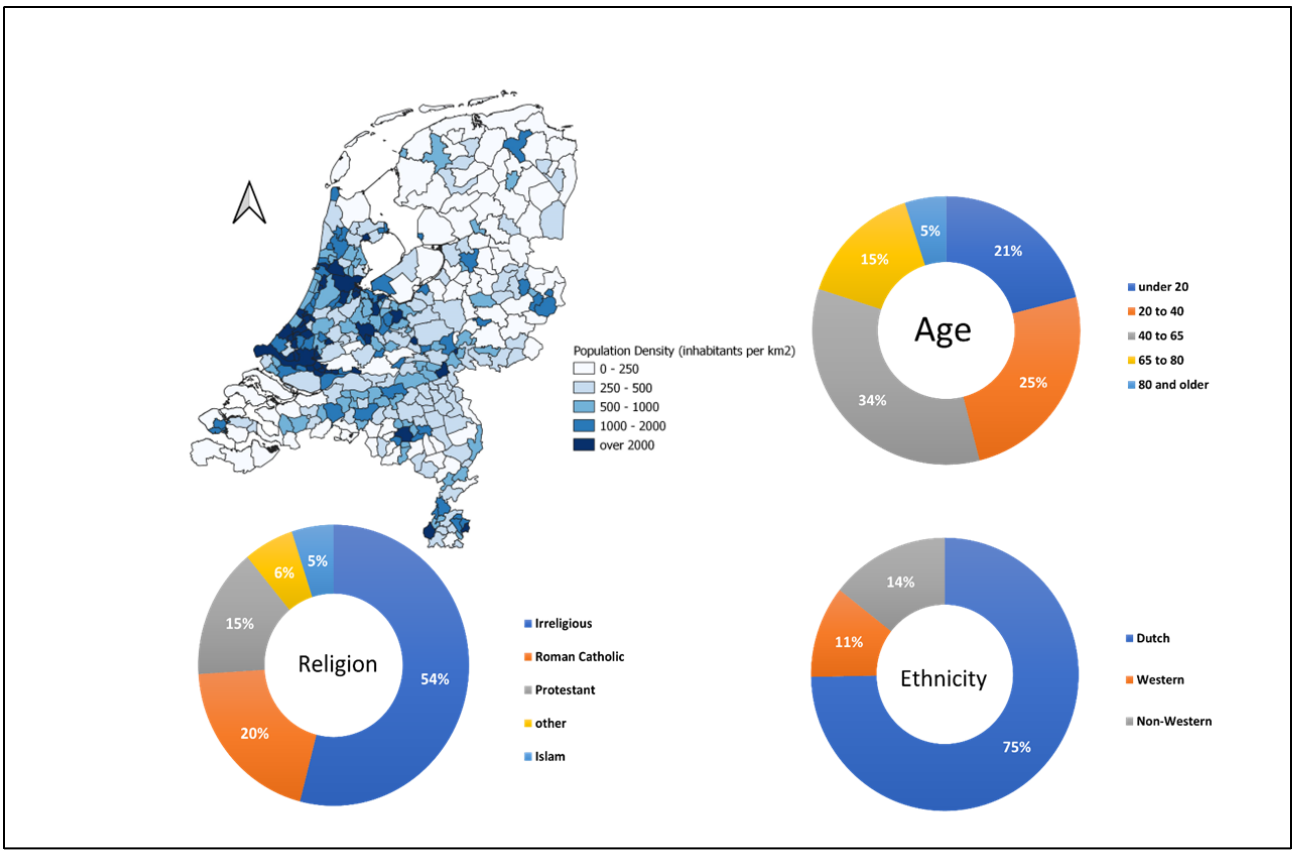

Figure 7: Netherlands population density and social aspects (age, religion, and ethnicity)

3.2 Research Approach

This thesis measures the spatial accessibility to COVID-19 vaccination centers by bicycles in the Netherlands, highlighting the differences in vaccination strategies. It also attempts to enhance accessibility by proposing an optimal number and locations for the vaccination centers in the fine-meshed strategy. Therefore, the research asks six questions (see section 1.4) to reach both objectives and aims to answer them using three stages approach shown in Figure 8. The first stage includes a literature review considering access to health care, spatial accessibility measures, and Location-allocation models. This stage tries to answer the first and fifth questions of the research by finding an accessibility measure and location-allocation model that fits the research goal and the available data. These questions are :

Q1: What are the available approaches to measure vaccination center accessibility levels?

Q5: what is the most suitable approach to achieve the optimum vaccination centers locations to enhance accessibility levels?

Using the chosen accessibility measure in the second stage, it is possible to investigate the spatial accessibility for both vaccination strategies and answer the second, third, and fourth research questions. These questions are :

Q2: What was the spatial accessibility level to COVID-19 vaccination centers in the original vaccination strategy?

Q3: How has the fine-meshed strategy changed the accessibility level to the vaccination centers?

Q4: Which municipalities need more or fewer vaccination centers to enhance spatial accessibility?

Accessibility for both strategies can be assessed based on six criteria inspired by the GGD argument for changing vaccination strategies shown in Table 1. These criteria are population, age, income, religion, ethnic background, and geographic location. Based on the chosen location-allocation model in the first stage and the outcome of the second stage, the third stage answers the last question of the research. The question is :

Q6: Which vaccination centers should be prioritized to stay open, re-located, or closed in the fine-meshed strategy?

The final stage aims to enhance spatial accessibility by presenting a methodology to increase, decrease and relocate the vaccination centers as needed

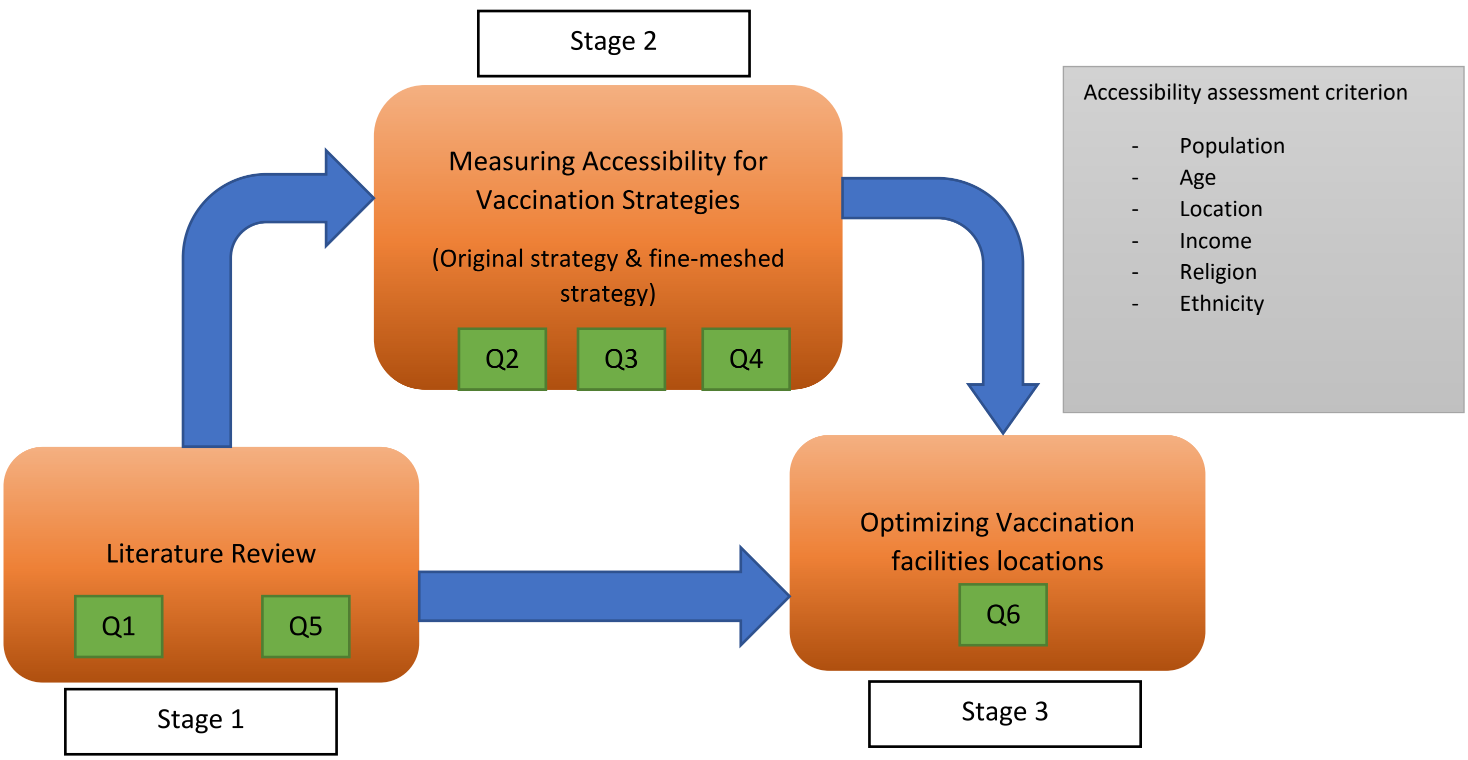

Figure 8: The stages of the research approach

3.3 Data

1- Population locations and demographics

The data contains approximately 380,000 vector squares distributed throughout the country. These vector squares represent the population sizes with high accuracy estimation for their locations. Each square represents 0.01 kilometer square on the ground. The data contains the number of residents living within each vector square, their socio-economic characteristics such as age and income, as well as their proximity to essential services such as schools and hospitals. Therefore, these vector squares can be utilized to become demand points in accessibility calculations. Although there are newer versions of this data file, this research uses the 2018 version as it is the only one that contains information on population income, one of the criteria for evaluating accessibility in this research. A map that illustrates the population vector square can be found in Appendix B

The methodology considers the following characteristics:

A- **Population**: Each vector square contains information about the number of people living within the vector square area. However, the vector squares do not include any population of fewer than five persons, which reduces the population number down to 16.54 million rather than 17.23 million (2018 population).

B- **Age**: The data divide age brackets according to the following format: from 0 to 14, from 15 to 24 years, from 25 to 44 years, from 45 to 64 years, and older than 64 years. Some vector squares do not contain any age data, reducing the population with known age to 14.94 million.

C- **Ethnicity**: The data divide ethnicity into Dutch, Western, and non-western immigrants. Ethnicity is determined based on individuals or one of their parents country of birth. People are considered western immigrants if they were born (or one of their parents) in European countries (except Turkey), Indonesia, Japan, and North America. In contrast, people are considered non-western immigrants if they were born (or their fathers) in countries other than the ones mentioned.

D- **Income**: Each vector square contains information about households median income. The file defines financial income as the net income after deducting taxes and social securities for the household residents. The median income is defined as the middle income if all households incomes are ranked from the highest to the lowest. Median income values are classified as follows: low, under middle, middle, above middle, and high. Each vector square contains one specific income class for its covered population, such as (low income class) and (middle income class). If the vector square covers a population with two different income classes, the income class for that vector is expressed as a range that includes both classes, such as (low to middle income class) and (low to under middle income class). Also, vector squares that contain less than ten households are not included in the income classification and are expressed as (unclassified).

The median income classes represent income values as follows:

i. **Low**: median income is below 17600 Euro
ii. **Under Middle**: median income is between 17600 Euro and 23200 Euro
iii. **Middle**: median income is between 23200 Euro and 29500 Euro
iv. **Above Middle**: median income is between 29500 Euro and 37800 Euro
v. **High**: median income is 37800 Euro and above

2- Roads and bicycle network

OpenStreetMap has a separate network data for each province in the Netherlands. The data contain all types of roads in the Netherlands except for trains and trams. That includes the maximum speed and direction of travel for each road. Networks can be linked together and filtered to simulate the Dutch bicycles network in the accessibility calculations.

3- COVID-19 vaccination centers locations

The data for COVID-19 vaccination locations were collected manually from GGD websites at two different moments in time, the first time in June 2021 and the second at the end of August 2021. Therefore, the data can be used as supply points for accessibility calculations. The collected data contains the locations of the centers, their types, addresses, respective municipality, and respective GGD regions. The vaccination center types can be defined as follow

Table 2: vaccination centers types

Vaccination Center Type	Description
Fixed	Fixed centers in a building. These centers are either open or closed. Where closed means that the center is no longer operating and was closed during the transition from the original strategy to the fine-meshed strategy
Mobile	Centers that are able to move to different locations. In this case, the GGD used busses
Pop-ups	Temporary centers in a building that are open not more than ten weeks

4- Population travel behavior

The data presents a study for the population movement using several transportation modes in the Netherlands(CBS, 2019). The Dutch Central Bureau of Statistics periodically collects trips and movement data from participating groups and shares the results with the authorities for development purposes. The data shows movement behaviors using transport modes, including trips purposes, trips time, transport modes, and users' social-economic characteristics such as education and income. Such data is valuable to determine people tendency to go to a vaccination service by bicycle in the Netherlands.

5- Dutch parliament Elections results

The data contains the voting results of the Dutch parliament second chamber elections in 2021. That includes municipalities voters turnout, parties votes shares, as well as the winner party name in each municipality. The data helps to identify the orthodox Protestant political party (SGP) voters share in each municipality. Unlike other Dutch religious parties, such as The Christian Democratic Appeal party (CDA) and Christian Union party (CU), the SGP party supports people who oppose vaccination for religious reasons(Bikker, 2021; CDA, 2021; SGP, 2021). Therefore, the SGP voting percentage can be used as an indicator of Christian gatherings, one of the targeted groups by GGD in the fine-meshed strategy. A such methodology was used by Lugnér et al.(2010) to identify municipalities with religious populations and low vaccination rates.

6- COVID-19 Vaccination uptake percentage

The data contain numbers on COVID-19 vaccination uptake percentages for each municipality first and second shots. The data divide vaccinated people age into (older than 12, older than 18, and between 12 and 17). The National Institute for Public Health and the Environment (RIVM) updates the vaccinated people percentage on a weekly basis and deletes the previous results(RIVM, 2021). This research was able to obtain the vaccinated people percentage on the 20th of October 2021. Such data is valuable for evaluating the effectiveness of the fine-meshed strategy.

7- Municipalities boundaries

The data contain the geographical boundaries for the 352 municipalities in the Netherlands. Besides that, the data have the population numbers for each municipality and some demographic information that includes people gender, age, marital status, and ethnicities. These data can be utilized to demonstrate accessibility levels geographically for each municipality.

8- GGD regions boundaries

The data contains the geographical boundaries for all 25 GGD regions throughout the country. It can be helpful to show accessibility levels in all GGD regions geographically.

9- OpenStreetMap points of interest

The data show the geographical locations of services and public facilities. The data divide the facilities and services into eight categories: Public, health, leisure, catering, accommodation, shopping, money, and tourism. Each category has its facilities names that describe their function, such as hospitals, hotels, parks, and supermarkets. The data can be used to suggest new locations with high accessibility levels for vaccination centers

All the above data is summarized with their type, publish year, and Sources in Appendix A

3.4 Measuring Spatial Accessibility to Covid-19 Vaccination Centers

The research measures accessibility in four measuring phases representing the transition between the vaccination strategies, as shown in Figure 9. In each phase, the spatial accessibility of the COVID-19 vaccination centers is measured twice, one for regular bikes and the other for E-bikes. The first phase measures spatial accessibility for all fixed vaccination centers only. This phase is called the *Max fixed facilities*. It allows measuring the original strategy accessibility before closing any center. The second phase is called *partial fixed facilities*. In this phase, accessibility is measured for the remaining fixed facilities after closing many fixed centers due to the strategy transition. The third phase measures accessibility after introducing pop-ups and closing some fixed centers. It is called *Partial fixed facilities & pop-ups* .it helps to understand the extent to which pop-up centers can play a role as an alternative to closed fixed centers in the partial fixed facilities phase. In the last phase, the vaccination buses are joined to the third phase to form a new phase called *Partially fixed facilities, pop-ups & mobile units*. This phase represents the new Fine-meshed strategy and helps in studying the impact of vaccination buses on accessibility levels. Definitions and purposes of the four accessibility measuring phases are summarized in Table 3. The thesis uses the term "mobile units" to refer to vaccination buses as they can change their location with time. This part of the methodology will be further described in three sub-sections: Estimating travel time threshold values, building the Netherlands bicycles network, and Analyzing accessibility. This research uses ArcGIS pro software and Excel to do the research calculations. All methodology steps are summarized in Figure 10

Table 3:Accessibility measuring phases

Accessibility measuring phase	Definition	Purpose
Max.fixed facilities	Measuring accessibility to fixed centers only, <u>including</u> the ones that were closed during the strategies transition	Measuring accessibility in the original strategy
Partial fixed facilities	Measuring accessibility to the remaining fixed centers only <u>without</u> the ones that were closed during the strategy transition	Understanding the effect of closing fixed centers
Partial fixed facilities and pop-ups	Measuring accessibility to the remaining fixed centers, including pop-ups	Understanding the impact of pop-ups on accessibility levels
Partial fixed facilities, pop-ups, and mobile units	Measuring accessibility to the remaining fixed center, pop-ups, and mobile centers	Measuring accessibility in the fine-meshed strategy

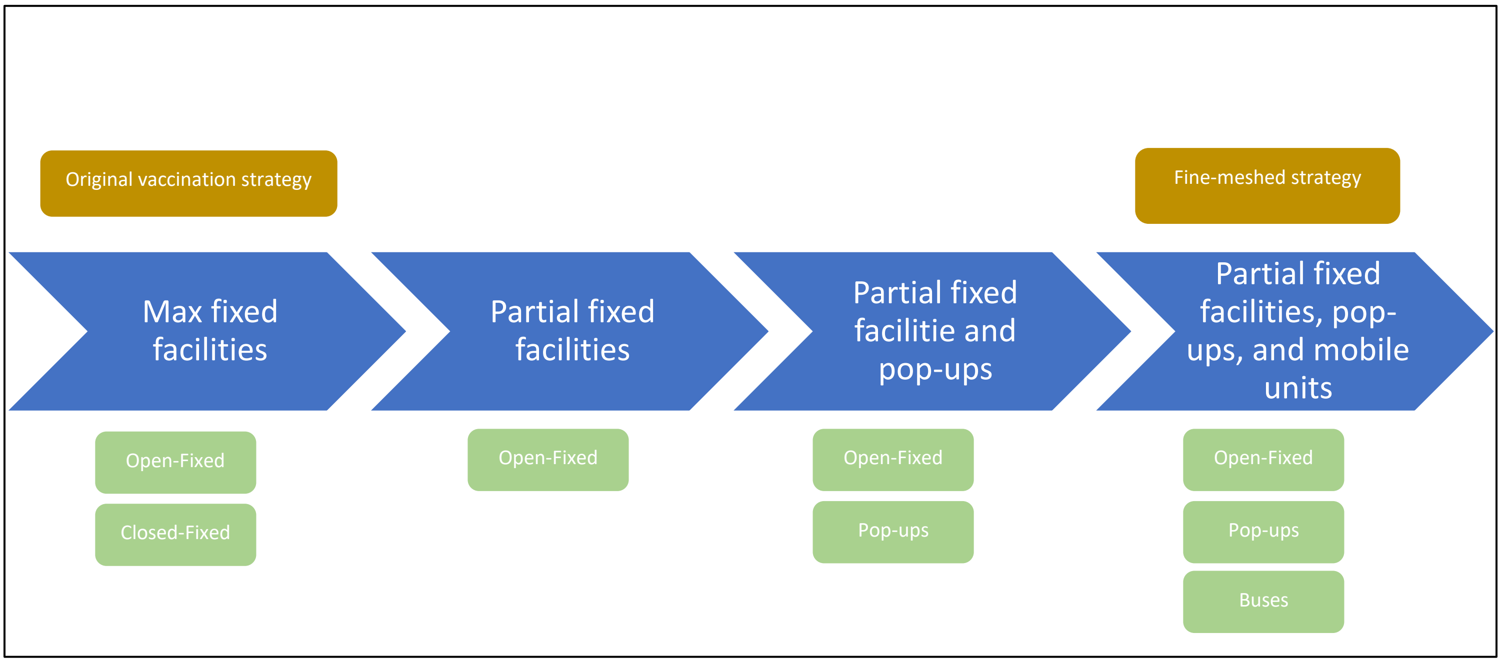

Figure 9: Accessibility measuring phases

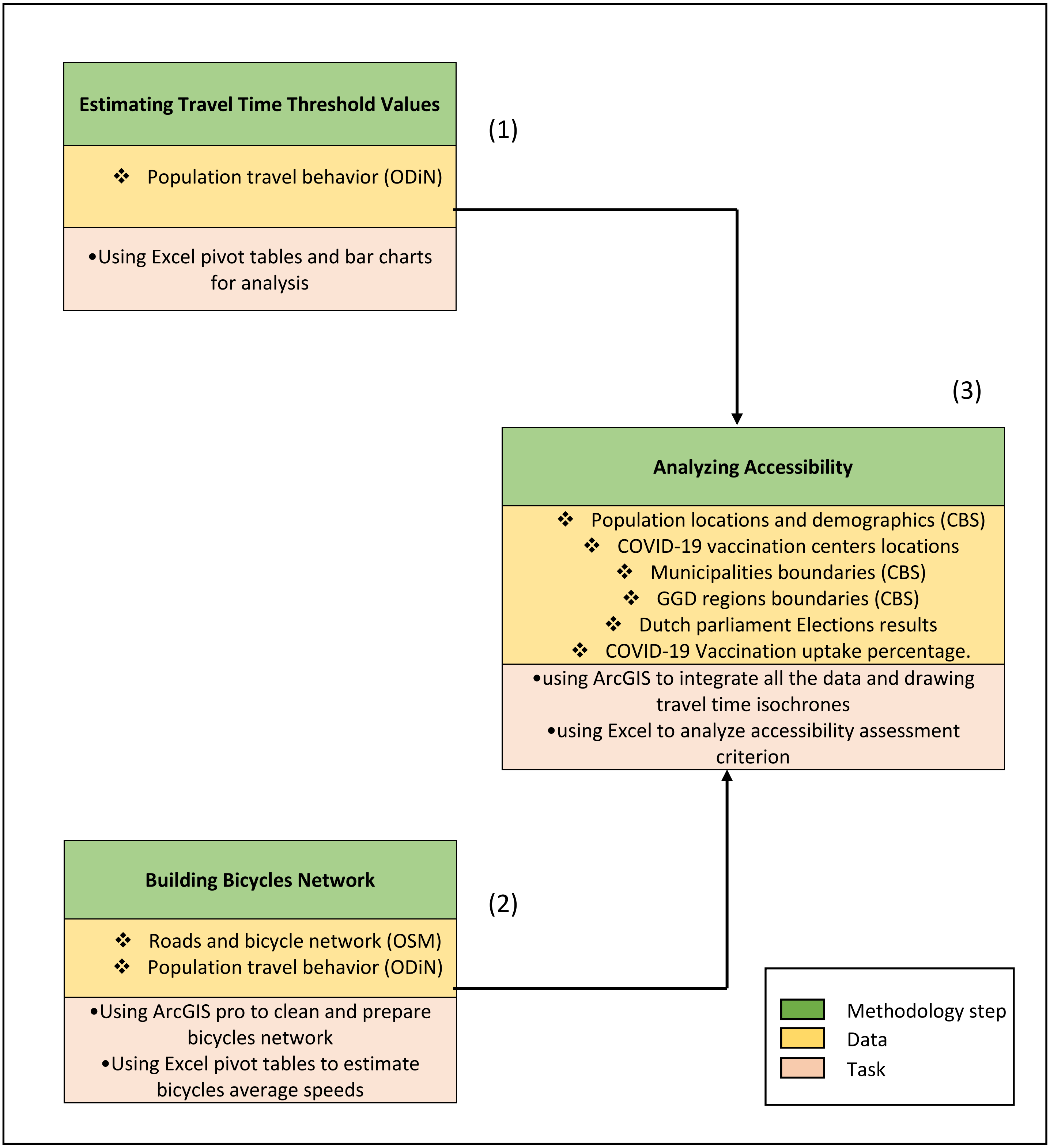

Figure 10:Accessibility measuring methodology steps and data

3.4.1 Estimating Travel Time Threshold Values

Based on a literature review in the second chapter, the thesis adopts the cumulative opportunity measure to examine spatial accessibility to vaccination centers. The measure is easy to use and explain and doesn't require much data to function(Geurs and van Wee, 2004). However, the measure is unable to include the attraction element in the calculations, and its trip cost ranges are randomly chosen(Geurs and van Wee, 2004). Therefore, due to the lack of data on COVID-19 centers capacity, this research assumes that there is no competition between the different vaccination centers. This thesis uses ODiN Data to understand the Dutch people behavior in using their bicycles. Such understanding helps estimate logical travel time intervals that the Dutch might consume to reach vaccination centers by bike. The most important variables to find those intervals can be found in the ODiN data and can be summarized as follows.

- Hvm: represent the transportation modes. Out of 24 available modes in the data, the thesis considers numbers 7 and 8 as they represent electrical bikes and regular bikes, respectively
- KMotiefV: represent the trips motives. The data contain nine motives
- Reisduur: represents trips time in minutes
- KReisduur: represents trips time intervals calculated in minutes. The data has 11 time intervals. They are: (1 to 5 min) , (5 to 10 min), (10 to 15 min), (15 to 20 min) , (20 to 25 min), (25 to 30 min) , (30 to 35 min) , (35 to 40 min), (40 to 45 min), (45 to 60 min) , (60 to 90 min) , (90 to 120 min), and (more than 120 min)
- AfstV: represents trips distances calculated in hectometers

Using pivot tables in Excel, the variables Hvm, KMotiefV, and KResiduur can be analyzed by distributing regular and electrical bicycles trips number for each trip time interval in all trips motives, as shown in Figure 11 and Figure 12(Microsoft Office, 2018). Before using pivot tables, the data was cleaned and organized by deleting missing data and joining several time intervals to each other to show easier comparisons. Therefore, the interval (1 to 5 min) has been merged with (5 min to 10 min), and (20 min to 25 min) has been joined with (25 min to 30 min). Trips absolute number in each trip time interval for all trips motivations are shown in tables in appendix C

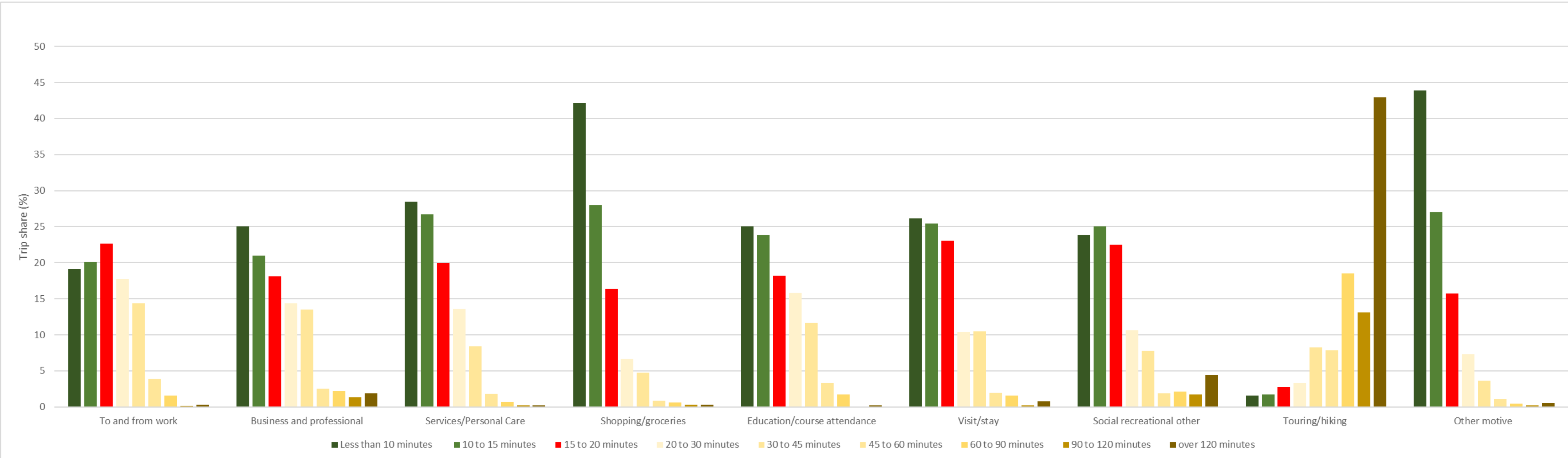

Figure 11: Trips percentages for trips time intervals in all trips motives (Regular bike)

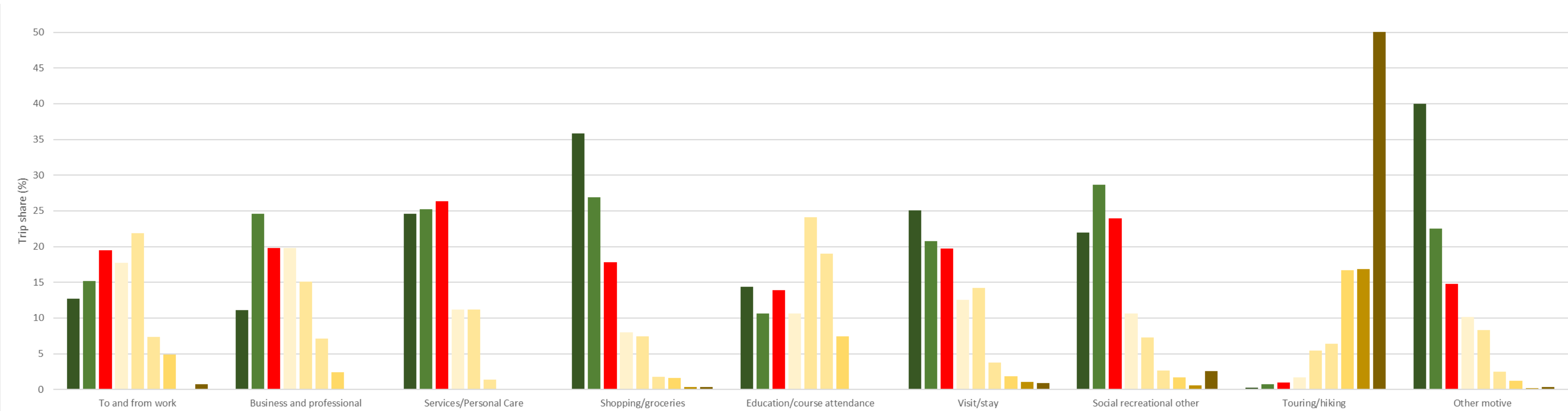

Figure 12: Trips percentages for trips time intervals in all trips motives (E-bike)

Generally, the bar charts in Figure 11 and Figure 12 show a descending pattern in all Dutch cycling motives (except for the touring and hiking motive, which appears in an ascending pattern). Such a pattern indicates that the Dutch desire to use a bicycle is limited to short trips; thus, the longer the trip, the less desire they have to use their bikes. In addition, most motives (6 out of 9 motives) show two sharp drops in trips numbers for trips that last more than 20 minutes and 45 minutes, respectively. Knowing that vaccination is a health service, The activity of going to COVID-19 vaccination centers can be categorized as one of the (services and personal care) motives. Most trips in the (service and personal care) motive are concentrated in less than 20 minutes time intervals. In addition, a sharp fall after (15 min to 20 min) interval reduces trip numbers dramatically for all trip intervals larger than 20 minutes. Although there is another drop that approaches zero in trips that take more than 45 minutes, the number of trips between 20 and 45 minutes constitutes less than half of the motive trips.

Consequently, this research considers the intervals (0 to 10 min), (10min to 15 min), and (15 min to 20 min) as acceptable and logical travel time thresholds to reach the vaccination centers and use them in accessibility calculations. Moreover, the research measures accessibility with binary results in terms of access. That means it considers that all people who live within these time intervals have access to vaccination centers, while those outside do not have access.

3.4.2 Building Bicycles Network

The transportation network is essential for utilizing the cumulative opportunity measure in the ArcGIS pro software. For this research, the network attributions should include bicycle paths and the time taken to travel through these paths using a specific type of bicycle. OpenStreetMap divides the Netherlands transportation network by provinces(Geofabrik, 2019). Thus, all 12 networks must be combined to cover the whole country. After adding all provinces networks to ArcGIS pro, the paths were filtered to keep only those used by cyclists. That includes cycling paths and non-highway paths as cyclists use several street types for commuting. Based on OpenStreetMap streets classification, that consists of all path types except for (bridleway, busway, motorway, motorway links, and stairs steps)(Ramm, 2022). The time spent on the network paths can be found by dividing the path distance by the average speed for each bicycle type. Using the ArcGIS pro "calculate geometry" command, all network paths lengths can be obtained in meters(ESRI, 2022a). The average speed of electric and regular bicycles can be estimated from the ODiN data using the following equation

$$\frac{\sum \frac{AfstV}{Reisduur}}{N}$$

Equation 1: regular and electrical bikes average speeds

AfstV = bicycle trip distance in hectometer (converted to meters)

Reisduur = bicycle trip time in minutes (converted to seconds)

N = the trips count for each bicycle type.

Table 4 shows the trips number and the average speed for each bicycle type. Using path distances and bicycle average speeds, each path's travel time was calculated and added to the network attributions. All networks were added to a features dataset to ensure they have the same geographic projection(ESRI, 2022b). A network dataset can be created from the feature dataset, and a special profile was created for each bicycle type to read the travel time on the network(ESRI, 2022c). Subsequently, a single final network with all previous attribution and profiles was built to be ready for accessibility calculations.

Table 4:ODiN bicycles trips count and average speeds

Bike type	Trips number	Average speed (km/h)
E-bike	6,833	13.4
Regular bike	36,112	11

3.4.3 Analyzing Accessibility

In ArcGIS Pro, the "service area" tool can be used to calculate spatial access as a cumulative opportunity measure(ESRI, 2022d). Based on network paths and attributions, the tool draws trips travel time intervals in isochrones around origins points (facilities). In this research, this tool was prepared using the network built in section (3.4.2) and the vaccination center locations for the four accessibility measuring phases. Each measuring phase was represented in a separate shape file. Isochrones threshold values are set to be 10, 15, and 20 minutes to correspond to the values estimated in section (3.4.1). Population vector squares were added to the ArcGIS pro tool as demand points. The isochrones were computed twice in each measuring phase; one for regular bikes and the other for E-bikes. After drawing the isochrones, their threshold values were added to the attribution tables of the covered or partially covered population vector squares using the "spatial join" command(ESRI, 2022e). In addition, municipalities and GGD regions names have been added to the population vector squares attribution table using the same command. Finally, the population vector squares attributions table was exported to Excel for further analysis.

In Excel, accessibility was analyzed based on population, age, ethnicity, and income. Using the pivot table tool, tables were built for each assessment criterion showing populations with and without accessibility to vaccination centers. Two tables and a bar chart were created for each assessment criterion. The first table shows absolute numbers for people with and without accessibility to vaccination centers. The second table is a comparison table that compares the accessibility measuring phases to the Max fixed facilities phase. Bar charts were developed to represent percentages of the population with and without accessibility as they are easier to understand and compare. After calculating absolute and percentage numbers in Excel, Choropleth maps can be made in ArcGIS Pro using population with accessibility percentages, municipalities names, and GGD area names. These maps provide an overview of accessibility levels in municipalities and GGD regions. The accessibility percentage for each municipality and GGD region Is the ratio of the population that has accessibility to the total population of that region.

As for the religion criterion, the SGP voter percentages can be used to identify municipalities with a relatively high Christian population density. SGP election results can be compared with vaccination uptake rates and municipalities accessibility percentages to determine which municipalities should have more focus on increasing accessibility. Using Excel, 2021 election results were filtered to obtain SGP results. Municipalities were distributed in quantiles according to their vaccination uptake percentage. In addition, scatter plots were established to investigate the relationship between the rate of the first and second vaccination shots and the SGP voters percentages in all municipalities. Based on the investigation results, municipalities with high vote rates and low vaccination uptake can be identified for accessibility level checks.

3.5 Prioritizing COVID-19 vaccination centers to enhance accessibility

To achieve the second objective, finding vaccination centers optimal numbers and locations is necessary to increase accessibility levels as needed. The ability of the Covid-19 virus to mutate and spread in successive epidemic waves makes it difficult to rely on a single scenario to increase or decrease vaccination centers (Wassink, 2020). Therefore, the methodology should help identify locations with considerable accessibility levels allowing decision makers to adjust population coverage as needed. Some scientific articles concerned with location-allocation models assume multiple scenarios to help decision-makers find flexible solutions(Mestre et al., 2015; Xu et al., 2018). Therefore, this research investigates three coverage scenarios to increase or decrease accessibility levels. The scenarios allow the GGD to control the level of spatial access to vaccination centers by opening and closing vaccination centers as needed. These scenarios focus on all populations without favoring any specific group to ensure accessibility for the largest possible number of people. The targeted scenarios are as follows:

1- **Half of the population scenario:** it aims to find the optimal number of facilities to provide accessibility for half the population (50%) in all GGD regions. This scenario allows decision-makers to benefit from the mobility natures of the vaccination centers to cover the other half as needed, and it helps reduce expenses.

2- **Herd immunity scenario**: aims to cover (70%) of the population to achieve herd immunity. That percentage was recommended by the world health organization (WHO) at the beginning of the pandemic (RTL Nieuws, 2020).

3- **GGD goal scenario:** it aims to cover (85%) of the population. The GGD has clearly expressed its ambition to reach that percentage to ensure the success of the fine-meshed strategy across the country(NL Times, 2021).

The three scenarios are established through two consecutive phases; the maximum upscaling phase and the optimum downscaling phase, as shown in Figure 13. In the first phase, suggested locations were investigated to select the locations with the highest demand, allowing accessibility to all populations. However, the maximum upscaling phase produces a large number of chosen facilities that cannot be implemented on the ground at once realistically, as that would need a huge budget. Also, the significant variation of the chosen facilities demands requires prioritizing facilities with the highest demand during on-ground implementation. In the optimum downscaling phase, the number of chosen facilities is reduced according to the targeted coverage percentages in the three scenarios. This phase aims to help indicate high-demand facilities in all GGD regions and prioritize them in all coverage scenarios. All Calculations were made on the GGD regions level for the whole country.

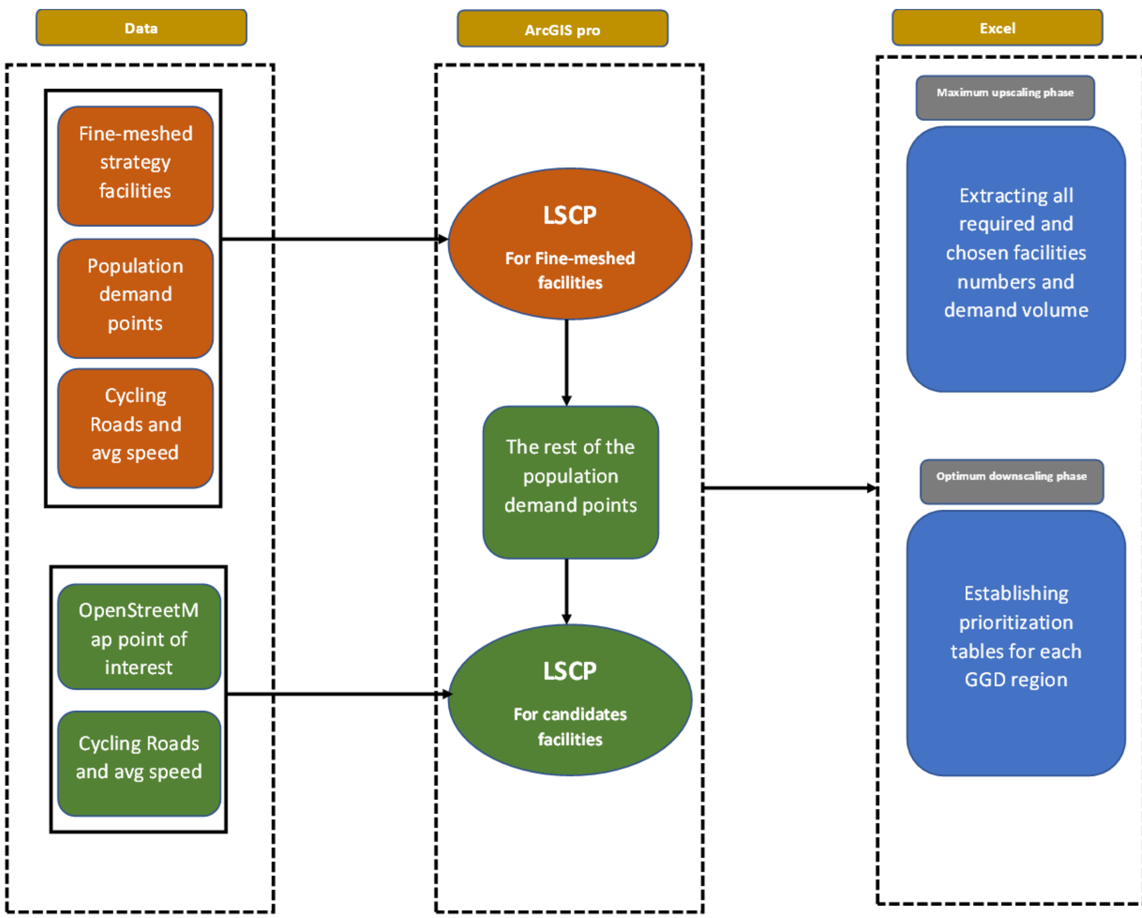

Figure 13: LSCP model data and prioritization phases

In the maximum upscaling phase, the LSCP model was utilized to select the best facilities locations to allocate the highest demand possible. The reason for choosing this model is its ability to cover the entire targeted area and to include time thresholds for the chosen locations. ArcGIS Pro includes a tool to implement the LSCP model within Network Analysis Tools set(ESRI, 2022f).

The tool needs the following input:

1- ***Candidates facilities*** **locations points (supply**): these represent the set of proposed facilities locations, part of which will be selected as a solution. In this research, they are the OpenStreetMap points of interest
2- ***Required facilities*** **locations points (supply)**: they represent facilities locations that should be part of the solution. In this research, they are the fine-meshed centers
3- **Demand points**: they represent population locations. In this research, they are the population vector squares
4- **Transportation network**: it is needed to calculate time thresholds for each facility location.

OpenStreetMap points of interest were used as candidates facilities location points. These points were filtered to include only suitable locations to establish mobile units, including location types used previously by GGD. These location types are Parks, sports centers, playgrounds, malls, and market-places(Ramm, 2022). All fine-meshed strategy facilities locations were used as required facilities points. Population vector squares were converted to centroid points and used as demand points in the tool. Finally, the same bicycle network used in calculating spatial accessibility was used here, but the calculations were limited to regular bike travel time only to ensure access for both regular and electrical bikes.

The tool has been used twice. In the first time, only required facilities points were used, and the allocated demand for the fine-meshed facilities strategy was calculated. In the second time, the candidate facilities points were used, and the rest of the demand points were allocated to them. The tool produces two tables, one for the demand points and the other for the facilities. The following information appears in the demand points table: 1) the name of the demand point corresponding to its name in the population vector squares file .2) the facility number that the demand point is allocated to. As for the facilities table, the following data appears: 1) facility number, 2) the facility name that matches its name in the Openstreetmaps point of interest table or the fine-meshed strategy facilities table, 3) the facility status (chosen/not chosen) 4) number of demand points allocated to the chosen facilities. Names of GGD regions and municipalities were added to all the demand points and facilities using the "spatial join" command. Finally, all tables were exported to Excel for further analysis. In Excel, demand points and facilities tables were linked to the population vector squares table using the "Merge Queries" command. The final merged table was analyzed using Excel pivot tables to extract the number of required and chosen facilities for each GGD region and the volume of the allocated population for each facility in all GGD regions.

The optimum downscaling phase aims to benefit from the first phase results to achieve the three coverage scenarios in all GGD regions. Using Excel, only the chosen facilities were organized into separated tables for each GGD region using Excel pivot tables, as shown in Table 5. population with accessibility to the fine-meshed strategy facilities was calculated to be the start for calculating the cumulative coverage of the rest of the chosen facilities. Each GGD region has a table containing the following: 1) chosen facilities numbers within the targeted GGD region boundaries. 2) facility location type 3) allocated population volume for the facility. 4) cumulative allocated population volume starting with the Fine-meshed strategy allocated population. 5) cumulative coverage percentage. Table 5 shows the facilities that became part of the solution in the Twente region as an example.

The facilities were arranged according to their allocated population volume in descending order to prioritize the highest demand coverage facilities. Subsequently, The allocated populations were calculated cumulatively, starting with the allocated population for the fine meshed strategy and ending with the last chosen facility that covers the targeted population percentage. The cumulative coverage percentages were calculated, and the three scenario percentages were highlighted (indicated in yellow in Table 5). The percentage key and population key columns have been added to help differentiate between facilities in maps and bar charts.

Table 5:GGD Twente prioritization table

GGD region name	GGD Twente
Population	590,675
Population covered by the fine-meshed strategy	149,310
FM coverage (%)	25

Coverage percentage	Number of added facilities	cumulative population
85%	28	503,940
70%	15	414,725
50%	7	305,115

Facility number	Location type	Population	Cumulative population	Cumulative coverage	Count	Percentage key	Population key
1,911	playground	29,330	178,640	30	1	1	3
1,957	Sport center	27,810	206,450	35	2	1	3
1,680	playground	22,540	228,990	39	3	1	3
1,965	playground	22,015	251,005	42	4	1	3
1,776	playground	21,160	272,165	46	5	1	3
1,540	playground	16,905	289,070	49	6	1	2
1,930	playground	16,045	305,115	52	7	1	2
1,655	playground	15,670	320,785	54	8	2	2
1,719	playground	14,775	335,560	57	9	2	2
1,616	playground	14,365	349,925	59	10	2	2
1,610	playground	14,030	363,955	62	11	2	2
1,780	playground	13,460	377,415	64	12	2	2
1,555	Sport center	12,880	390,295	66	13	2	2
1,919	mall	12,450	402,745	68	14	2	2
1,768	playground	11,980	414,725	70	15	2	2
1,964	Market place	11,490	426,215	72	16	3	2
1,686	Sport center	11,140	437,355	74	17	3	2
1,706	Sport center	9,440	446,795	76	18	3	1
1,725	playground	7,165	453,960	77	19	3	1
1,670	Sport center	6,450	460,410	78	20	3	1
1,666	playground	6,250	466,660	79	21	3	1
1,651	Sport center	6,240	472,900	80	22	3	1
1,800	playground	5,850	478,750	81	23	3	1
1,783	Sport center	5,475	484,225	82	24	3	1
1,711	playground	5,155	489,380	83	25	3	1
1,785	Sport center	5,040	494,420	84	26	3	1
1,582	playground	4,830	499,250	85	27	3	1
1,708	playground	4,690	503,940	85	28	3	1

4. Results of accessibility analysis and vaccination centers locations prioritization

This chapter presents the research results in two sections. The first section evaluates the spatial accessibility for both vaccination strategies. The second section presents the results of the proposed method to prioritize vaccination centers locations with the highest demand in three coverage scenarios .in the following sections, the terms "population with accessibility" and "population without accessibility " are used . "Population with accessibility" are the ones who are able to reach vaccination centers in less than 20 minutes using bicycles .in contrast, "population without accessibility" are the ones who can not reach the centers in less than 20 minutes using bicycles. In the first section, the sub-sections will show how accessibility levels have decreased in general due to the change in vaccination strategies; thus, the chapter focuses more on the population without accessibility than those who have accessibility. The evaluation results are shown according to the four accessibility measuring phases in Table 3. Also, accessibility is assessed based on the six criteria shown in Figure 8. These criteria are population, age, location, income, religion, and ethnicity. The second section shows the result of the prioritization methodology. That includes the results of the maximum upscaling phase and the optimum downscaling phase.

4.1. Results of Measuring spatial accessibility to Covid-19 vaccination centers

4.1.1. Vaccination centers locations in both vaccination strategies

Accessibility in any given region is related to the vaccination centers count and locations. This sub-section shows counts and location of vaccination centers in all GGD regions for both vaccination strategies. The locations and counts of the original strategy vaccination centers are illustrated to include only fixed centers that were closed due to the transition and the remaining fixed centers after the transition. As for the fine-meshed strategy vaccination centers, only the locations and counts of the mobile units, pop-ups, and the remaining fixed centers after transition are shown

In general, vaccination centers in the original strategy are highly concentrated in the western GGD regions of the country, as shown in Figure 14. GGD Regio Utrecht, GGD Amsterdam, and GGD Rotterdam-Rijnmond had the highest number of vaccination centers. However, there is a significant disparity in the vaccination centers counts among these three regions, as GGD Utrecht has 32 centers while GGD Rotterdam-Rijnmond and GGD Amsterdam have 20 and 13 centers, respectively. This disparity also extends to the number of closed centers in those regions. Even though GGD Regio Utrecht has the largest number of vaccination centers, the number of its closed fixed centers did not exceed four centers, while 13 centers were closed in GGD Rotterdam-Rijnmond. On the other hand, the number of fixed centers did not exceed ten centers in the rest of the GGD regions, and nearly half of them were closed during the strategies transition process. Compared to the eastern and northern regions, the map in Figure 14 shows a scarcity in the number of open fixed centers in the southern regions, as their number did not exceed two centers in both Brabant and Limburg regions.

In the fine-meshed strategy, mobile centers are concentrated in several regions of the country. Figure 15 shows that mobile vaccination centers are concentrated in the western and eastern regions, passing through the country's central regions. The largest number of mobile centers appears in the eastern regions in GGD Noord en Oost Gelderland (32 centers). As for the central regions, mobile centers are concentrated in both GGD Gelderland-midden and GGD Gelderland-Zuid (20 and 16 centers, respectively). Furthermore, mobile centers in western regions are concentrated in areas that did not have any centers in the original strategy. Thus, they are mainly located in GGD Hollands-Midden, GGD Zaanstreak and GGD Zeeland (23, 12, and 11 centers). The rest of the regions have five mobile centers or less, except for the GGD Friesland (15 centers). The presence of the pop-ups is minimal as there are only 4 of them; three centers in GGD Zuid-Limburg and only one center in GGD Hart voor Brabant

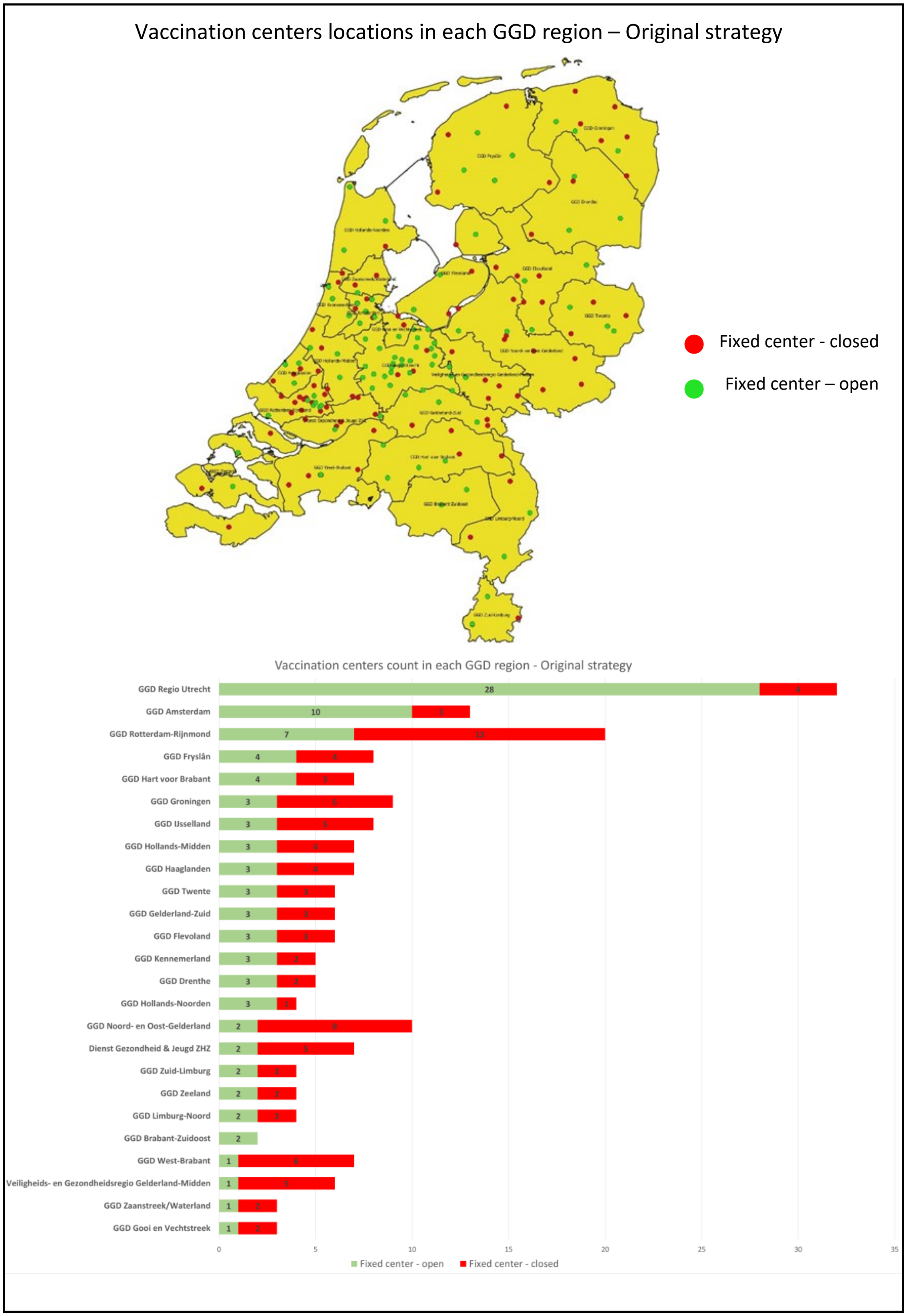

Figure 14: Vaccination centers locations and count in each GGD region – original strategy

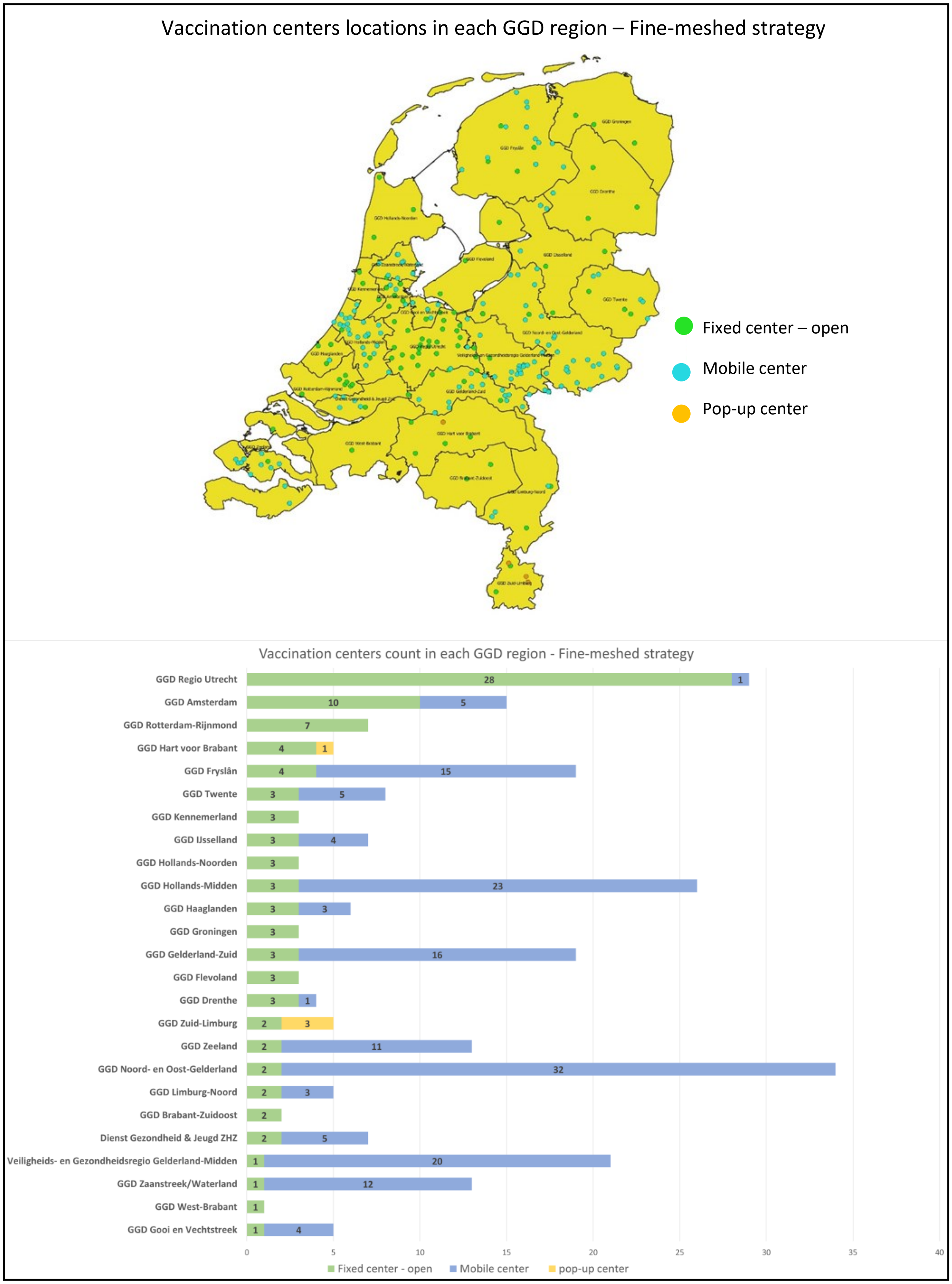

Figure 15: Vaccination centers locations and count in each GGD region – fine-meshed strategy

4.1.2. Accessibility levels based on population locations (Municipalities and GGD regions)

Figure 16, Figure 17, Figure 18, and Figure 19 show the population share for those who can reach vaccination centers by bicycle at the level of municipalities and GGD regions. Figure 16-(A) shows that the original strategy focused on the central and western municipalities as they have the highest accessibility levels compared to other regions. Such a focus has negatively affected the rest of the municipalities, as most of the southern municipalities population cannot reach the vaccination centers. In addition, the negative impact extends to the eastern and northern regions, except for several border municipalities in the north, where only half of their population could reach vaccination centers. On the other hand, the fine-meshed strategy focuses on the western and eastern regions, passing through the central areas as shown in Figure 16-(D). Despite the change in the vaccination strategy, accessibility levels in the southern regions are still very low even after opening four pop-up centers, as shown in Figure 16-(C). In addition, average levels of accessibility in the northern municipalities have shifted from the border to the northeastern municipalities. Also, Figure 16-(B) shows that the closure of fixed vaccination centers affected almost all municipalities, except for the municipalities of the central regions.

By comparing the accessibility levels for regular and electric bicycle users in Figure 16 and Figure 17, a higher level of accessibility can be observed for electric bicycle users due to the difference in average speeds. Furthermore, changing vaccination strategies has helped increase the number of GGD regions with accessibility levels higher than 60%, as shown in Figure 18 and Figure 19. Although almost all GGD regions have been affected by the change in the vaccination strategies, GGD Utrecht has maintained almost the same high level of accessibility in all accessibility measuring phases. In contrast, in southern regions, GGD Brabant Zuid-Oost and GGD west Brabant had the lowest accessibility levels in all phases.

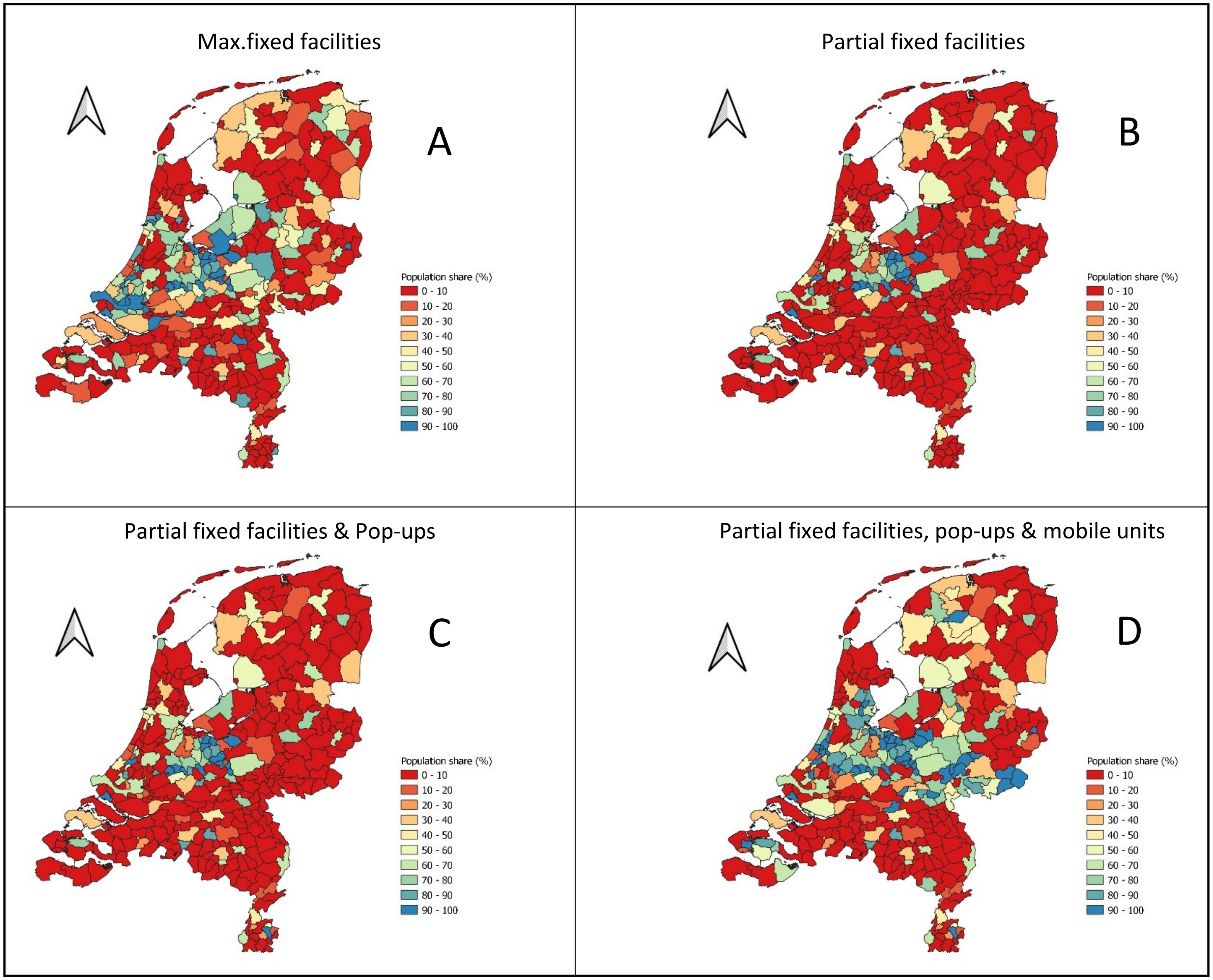

Figure 16:share of population with accessibility to vaccination centers using regular bikes in all municipalities. (A): Accessibility levels in max. fixed facilities phase (original strategy). (B): Accessibility levels in partial fixed facilities phase. (C): Accessibility levels in partial fixed facilities and pop ups phase. (D): Accessibility levels in partial fixed facilities, pop-ups, and mobile units phase (fine-meshed strategy).

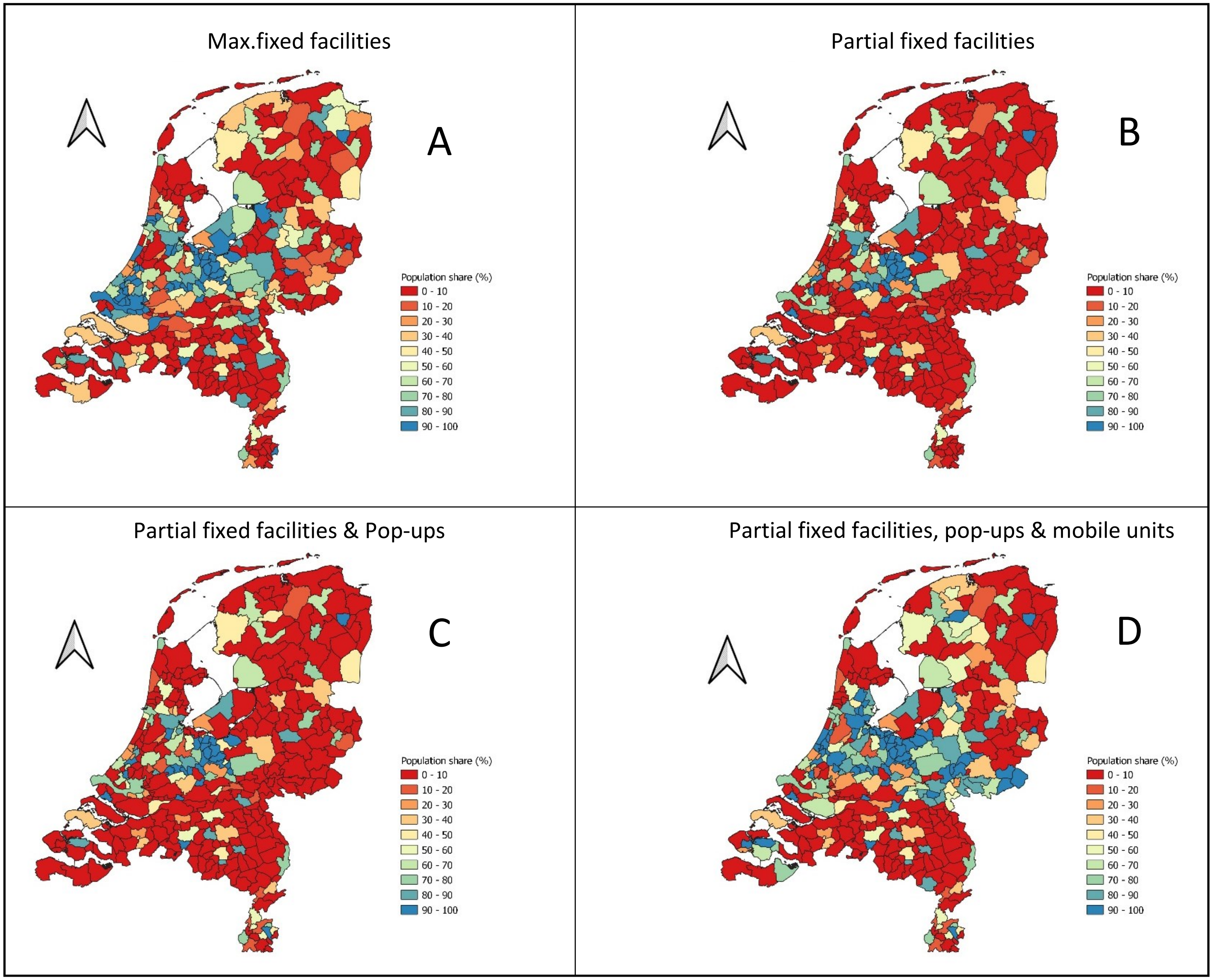

Figure 17:share of population with accessibility to vaccination centers using E-bikes in all municipalities. (A): Accessibility levels in max. fixed facilities phase (original strategy). (B): Accessibility levels in partial fixed facilities phase. (C): Accessibility levels in partial fixed facilities and pop ups phase. (D): Accessibility levels in partial fixed facilities, pop-ups, and mobile units phase (fine-meshed strategy).

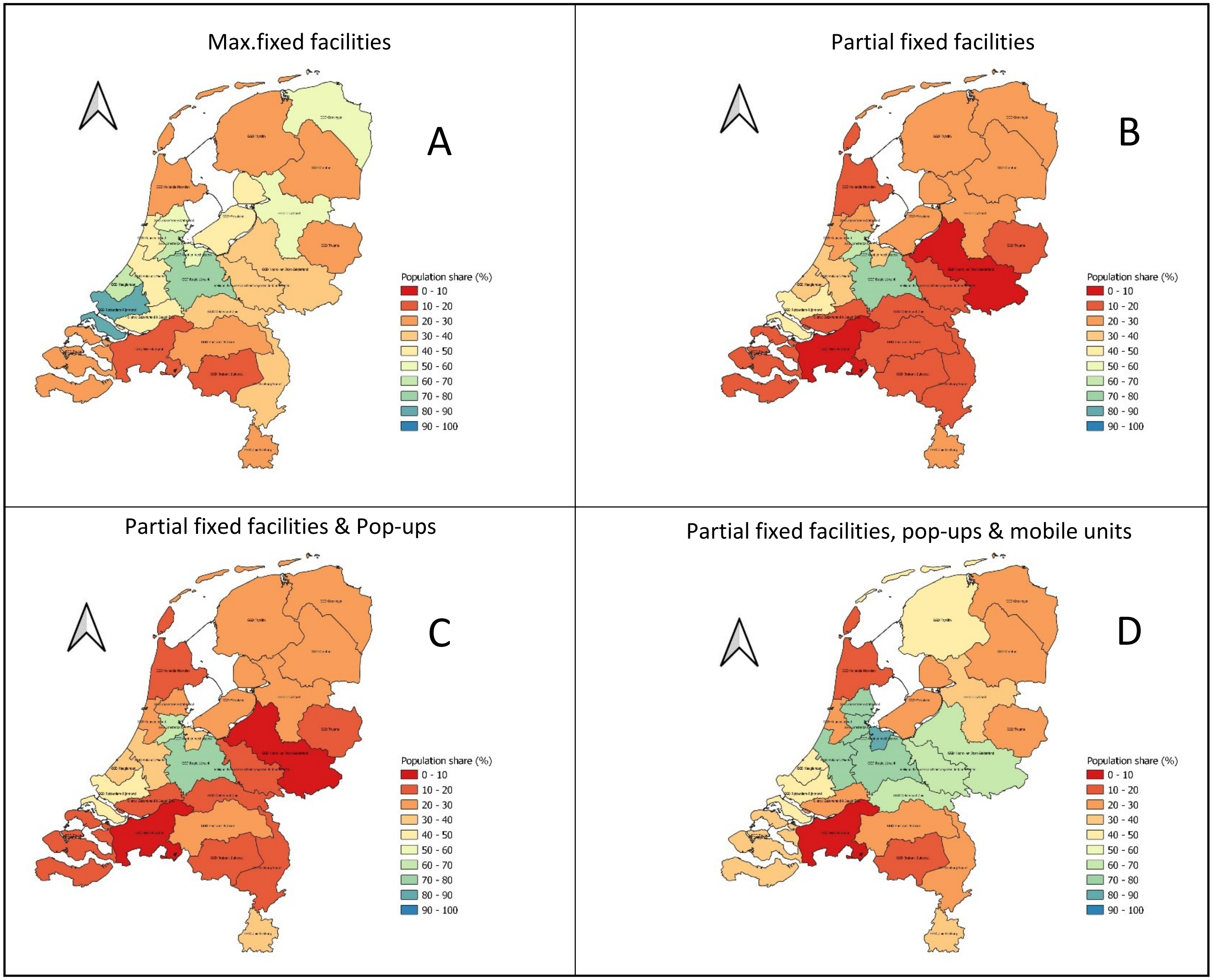

Figure 18: share of population with accessibility to vaccination centers using regular bikes in all GGD regions (A): Accessibility levels in max. fixed facilities phase (original strategy). (B): Accessibility levels in partial fixed facilities phase. (C): Accessibility levels in partial fixed facilities and pop ups phase. (D): Accessibility levels in partial fixed facilities, pop-ups, and mobile units phase (fine-meshed strategy).

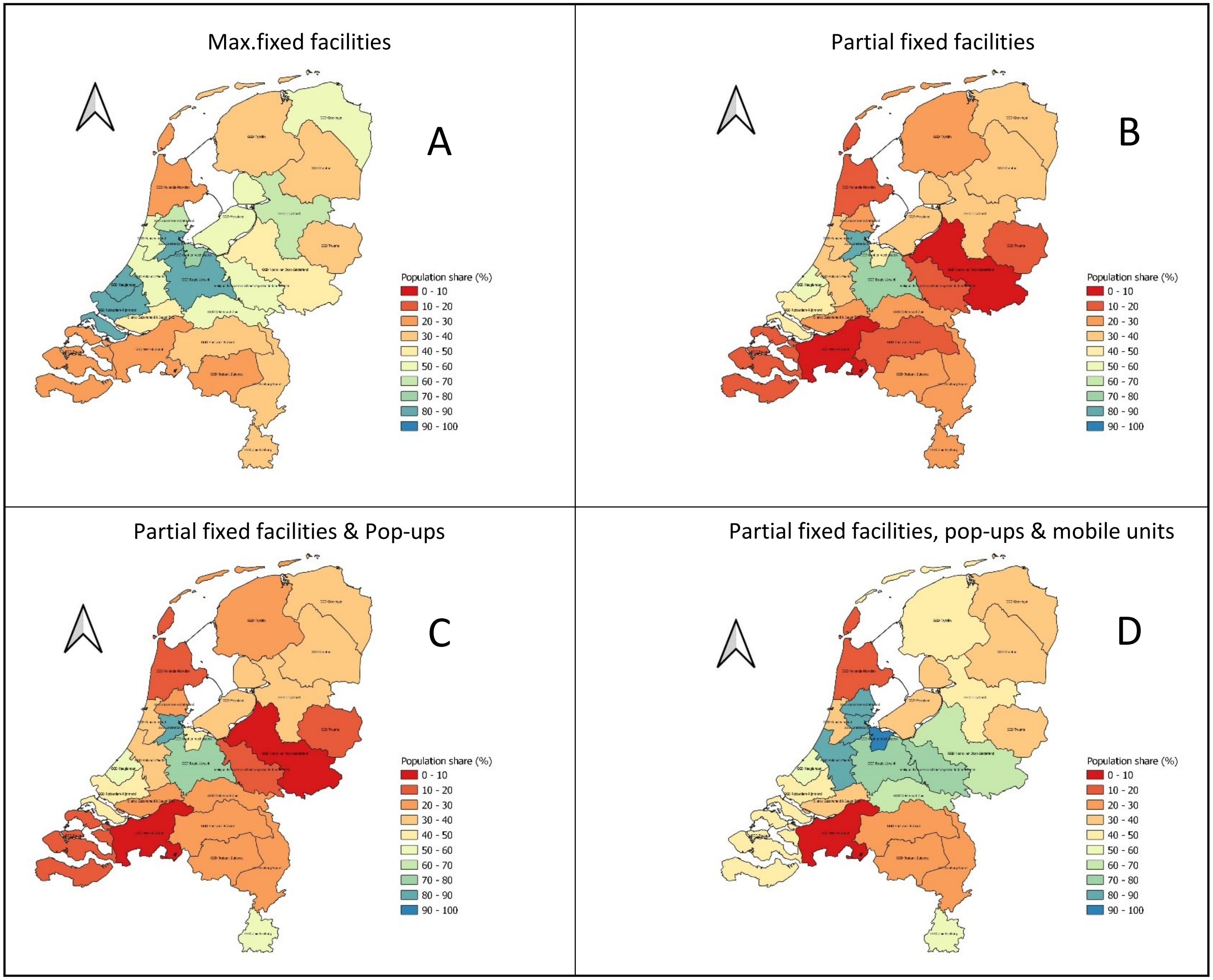

Figure 19: share of population with accessibility to vaccination centers using E- bikes in all GGD regions. (A): Accessibility levels in max. fixed facilities phase (original strategy). (B): Accessibility levels in partial fixed facilities phase. (C): Accessibility levels in partial fixed facilities and pop ups phase. (D): Accessibility levels in partial fixed facilities, pop-ups, and mobile units phase (fine-meshed strategy).

4.1.3. The share of population with and without accessibility to vaccination centers

Slightly less than half of the population had access to vaccination centers by bicycles in the maximum fixed facilities phase (original strategy), as shown in **Figure 20**. Almost the same population percentage appears in the partial fixed facilities, pop-ups, and mobile units phase, but with a 1.6 % and 3.2% lower population for regular and electrical bicycles users, respectively. **Table 6** shows that even though the number of mobile vaccination centers is almost double the number of closed fixed centers, mobile centers were not able to provide the same level of accessibility compared to the original strategy accessibility levels. These closed fixed centers provided access to 17.1% of the population, as shown in the shortage of population with accessibility in the partial fixed facilities phase. Furthermore, pop-ups have provided accessibility for a small fraction of the population (less than 2%) in partial fixed facilities and pop-up phase. It is noticeable that electric bicycle users have better accessibility to vaccination centers than regular bicycle users in all accessibility measuring phases due to the difference in average speeds.

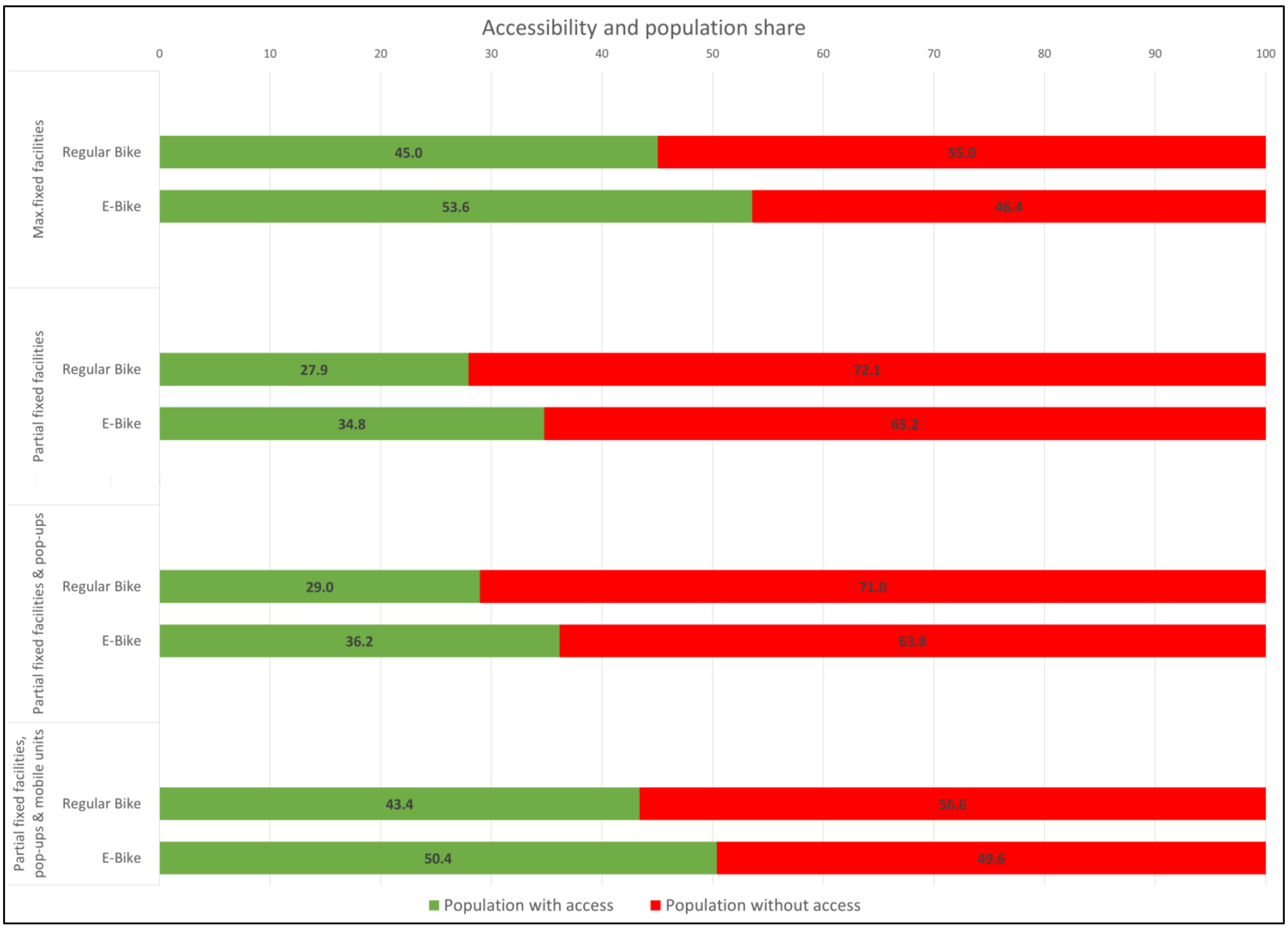

Figure 20 : percentages of people with and without access to vaccination centers

Table 6:Number of Population with and without accessibility to vaccination centers and number of vaccination centers in all accessibility measuring phases

Regular bike

Accessibility measuring phases	Vaccination centers			Population with accessibility	(%)	Population without accessibility	(%)
	Fixed facilities	Pop-ups	Mobile units				
Max.fixed facilities	193	0	0	7,449,640	45.0	9,089,390	55.0
Partial fixed facilities	99	0	0	4,622,325	27.9	11,916,705	72.1
Partial fixed facilities & Pop-ups	99	4	0	4,792,655	29.0	11,746,375	71.0
Partial fixed facilities, pop-ups & mobile units	99	4	160	7,180,075	43.4	9,358,955	56.6

E-bike

Accessibility measuring phases	Vaccination centers			Population with access	(%)	Population without access	(%)
	Fixed facilities	Pop-ups	Mobile units				
Max.fixed facilities	193	0	0	8,859,705	53.6	7,679,325	46.4
Partial fixed facilities	99	0	0	5,752,285	34.8	10,786,745	65.2
Partial fixed facilities & Pop-ups	99	4	0	5,979,990	36.2	10,559,040	63.8
Partial fixed facilities, pop-ups & mobile units	99	4	160	8,330,055	50.4	8,208,975	49.6

4.1.4. Population without accessibility according to their age

Figure 21 shows the percentages of populations without accessibility to the vaccination centers by bicycle according to their age groups. People within the age groups (25 to 44) and (44 to 64) together represent almost half of the population that cannot reach the vaccination centers by bicycles (24% and 30%, respectively). The elderly (over 64), one of the most important target groups in the fine-meshed strategy, represent 20% of the population without accessibility. Furthermore, the proportions of children (00 -14) and youth (15-24) are the lowest among age groups (16% and 10%). Absolute numbers for the population without access according to their age are provided in appendix D

Table 7 shows that children and youth are the most negatively affected by the change in the vaccination strategy. In the last accessibility measuring phase, the number of youth unable to reach the vaccination centers increased by 6% for regular bicycle users and 11% for electric bicycle users, while children increased by 5% and 10%, respectively. The rest of the age groups increased by no more than 4% for regular bicycle users and not more than 9% for electric bicycle users. Moreover, all closed fixed centers served about one-third of the regular bicycle users and around half of the electric bicycle users in all age groups. Also, pop-ups had a limited effect in raising the level of accessibility for regular and electric bicycle users in all age groups (2% and 3%, respectively).

Table 7 : the change percentage of population without accessibility according to their age in all phases compared to max.fixed facilities phase

Regular bike

Accessibility measuring phases	From 00 to 14 years old (%)	From 15 years old to 24 years old (%)	From 25 years old to 44 years old (%)	From 45 years old to 64 years old (%)	65 years and older (%)
Max.fixed facilities	0	0	0	0	0
Partial fixed facilities	34	38	36	32	32
Partial fixed facilities & Pop-ups	32	36	34	30	30
Partial fixed facilities, pop-ups & mobile units	5	6	4	3	3

E-bike

Accessibility measuring phases	From 00 to 14 years old (%)	From 15 years old to 24 years old (%)	From 25 years old to 44 years old (%)	From 45 years old to 64 years old (%)	65 years and older (%)
Max.fixed facilities	0	0	0	0	0
Partial fixed facilities	45	50	47	42	42
Partial fixed facilities & Pop-ups	42	47	43	38	38
Partial fixed facilities, pop-ups & mobile units	10	11	9	7	7

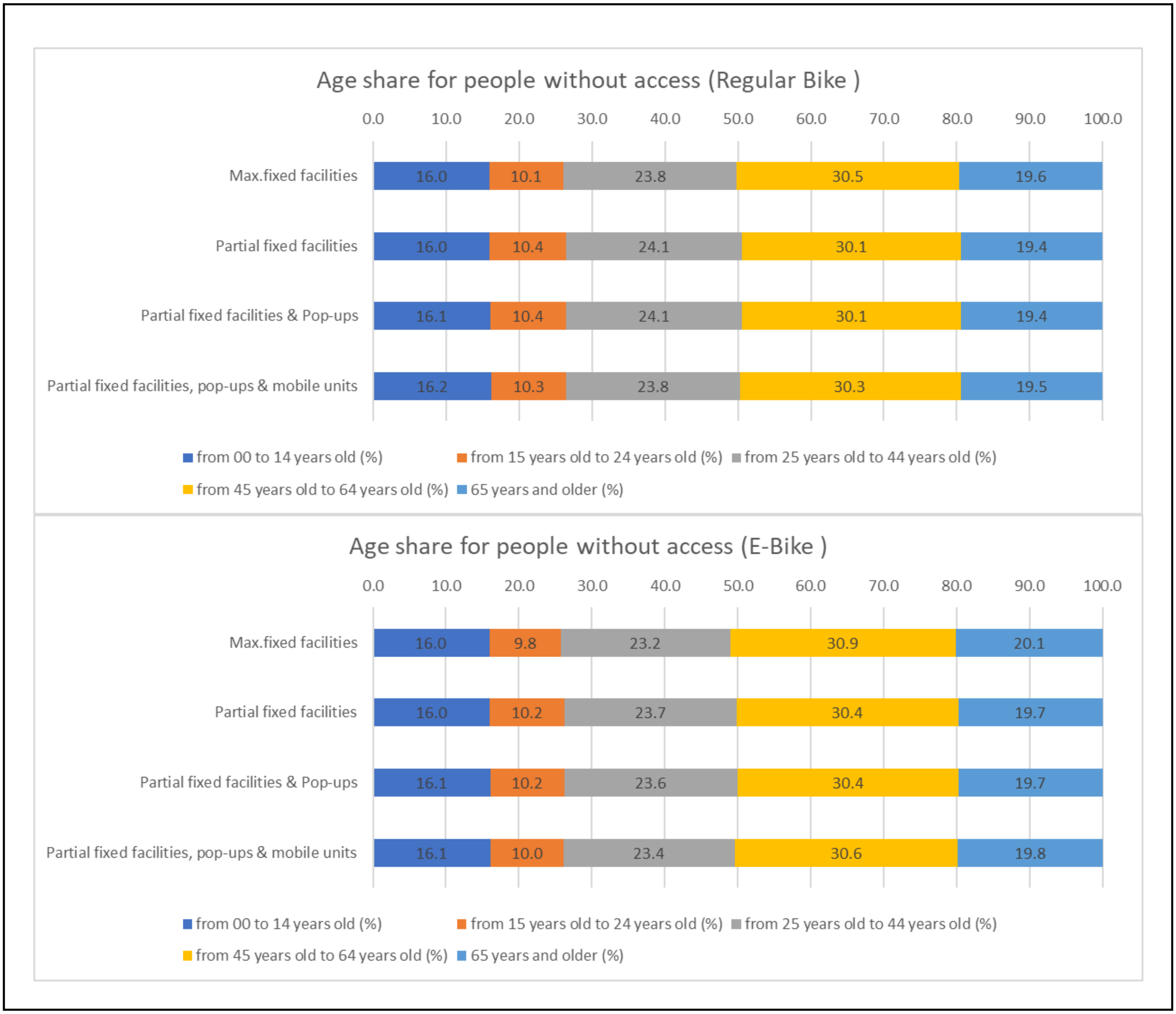

Figure 21:Percentages of population without accessibility to vaccination centers according to their age

4.1.5. Population without accessibility according to their income

Figure 22 shows the percentages of income groups who cannot reach the vaccination centers by regular or electric bicycles. The figure shows similar rates in almost all accessibility measuring phases. Nearly half of those who do not have accessibility to vaccination centers by bicycle belong to the middle-income groups (under middle to middle, middle, middle to above middle, and above middle). Among these middle-income groups, the (middle to above middle) income group has the largest proportion compared to all other income groups. Furthermore, the percentages of low-income groups (low and low to under middle)- one of the target groups in the fine-meshed strategy- do not exceed 9% combined. Furthermore, high-income groups (above middle to high and high) have very low percentages (does not exceed 6%). Absolute numbers for the population without accessibility according to their income are provided in appendix E

Table 8 shows that the low income group is the most affected by the vaccination strategy change as they have increased by 15% for regular bicycle users and 32% for electric bicycle users. They also show that the closed fixed vaccination centers were giving access mainly to low-income people, as the number of low income people without access doubled (93%) for electric bicycle users and increased by (55%) for regular bicycle users after the closure. In addition, the fixed vaccination centers closure had a disproportionate effect on the other income groups. Therefore, people without access increased by nearly 50 % for all income groups, except for (low to middle) and (under middle to above middle) as they were the only groups who benefited from the strategy change. The effect of pop-ups on accessibility level was limited as it did not exceed 7% in any income group.

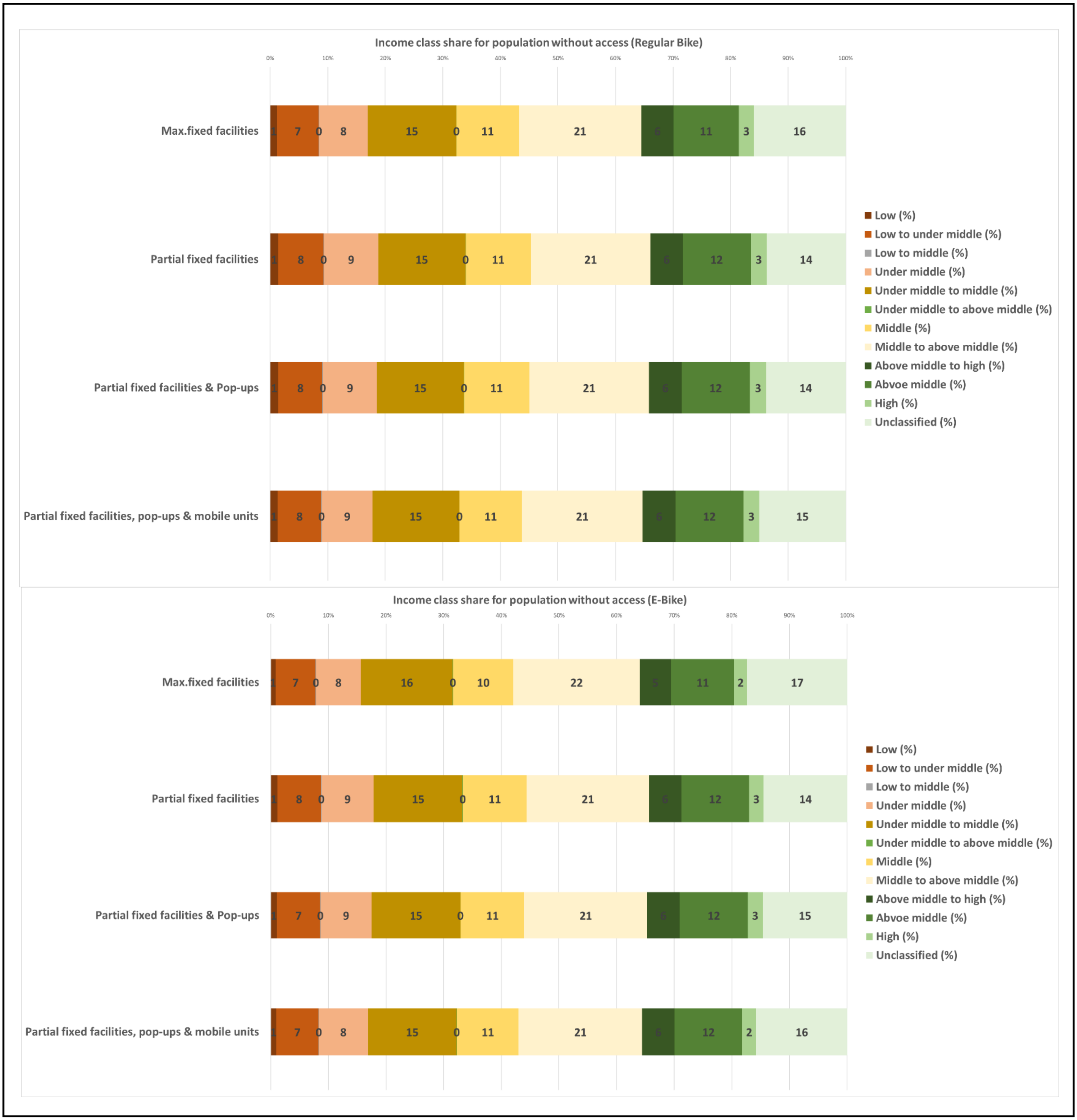

Figure 22:Income class share for people without access to vaccination centers

Table 8 : the change percentage of population without accessibility according to their income class in all phases compared to max.fixed facilities phase

Regular bike

Accessibility measuring phases	Low (%)	Low to under middle (%)	Low to middle (%)	Under middle (%)	Under middle to middle (%)	Under middle to above middle (%)	Middle (%)	Middle to above middle (%)	Above middle to high (%)	Above middle (%)	High (%)	Unclassified (%)
Max.fixed facilities	0	0	0	0	0	0	0	0	0	0	0	0
Partial fixed facilities	55	42	15	47	29	15	37	28	32	37	40	13
Partial fixed facilities & Pop-ups	51	38	15	43	27	15	35	26	31	35	39	12
Partial fixed facilities, pop-ups & mobile units	15	8	-3	7	1	-1	3	1	5	7	8	-3

E-bike

Accessibility measuring phases	Low (%)	Low to under middle (%)	Low to middle (%)	Under middle (%)	Under middle to middle (%)	Under middle to above middle (%)	Middle (%)	Middle to above middle (%)	Above middle to high (%)	Above middle (%)	High (%)	Unclassified (%)
Max.fixed facilities	0	0	0	0	0	0	0	0	0	0	0	0
Partial fixed facilities	93	54	20	64	36	18	48	36	44	51	60	17
Partial fixed facilities & Pop-ups	86	47	19	57	33	18	45	34	42	49	57	16
Partial fixed facilities, pop-ups & mobile units	31	12	-3	17	3	0	9	5	10	15	16	-3

4.1.6. Population without accessibility according to their ethnicity

Figure 23 shows the percentages of the population without accessibility to the vaccination centers based on their ethnicity. People with a Dutch Background are the majority (82% to 86 %), while other ethnicities did not exceed 10% in all accessibility measuring phases. Nevertheless, Table 9 shows that changing vaccination strategy has affected migrants of non-Western backgrounds the most, as the number of those who could not reach vaccination centers by regular and electric bicycles increased by 20% and 34%, respectively. On the other hand, people with a Dutch background were the least affected by the strategy change, as the number of those who could not reach vaccination centers did not increase by more than 5%. Although the change percentage of people with Dutch background was the smallest, the actual number exceeds the numbers of migrants of Western and non-Western backgrounds combined (an increase of nearly 300,000 for Dutch background compared to around 250,000 for migrants combined for E-bikes users), as shown in appendix F. The reason for that difference is that the actual number of people with Dutch background is much greater than that of migrants. Absolute numbers for the population without access according to their ethnicity are provided in appendix F

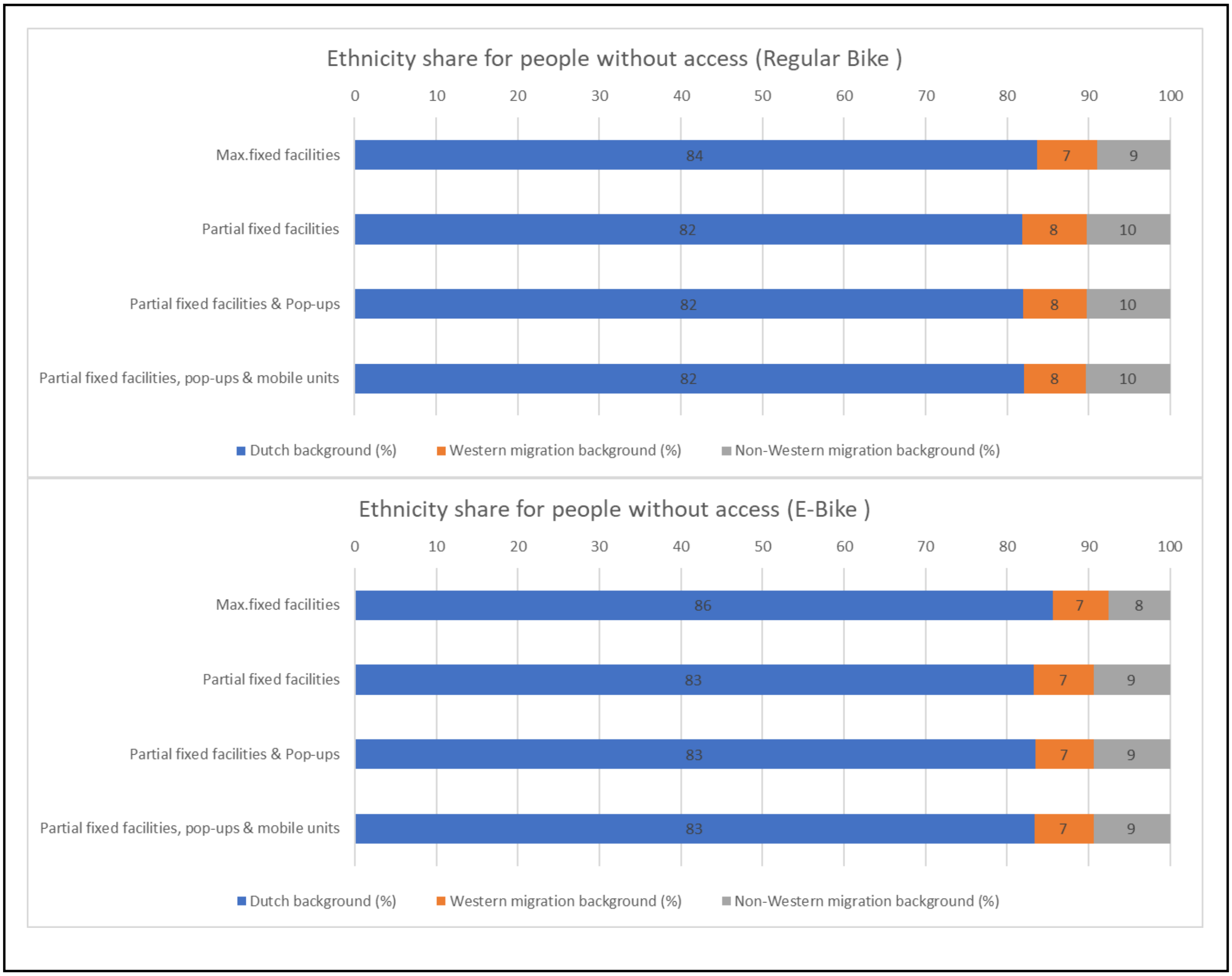

Figure 23:Ethnicity share for population without accessibility to vaccination centers

Table 9: the change percentage of population without accessibility according to their ethnicity in all phases compared to max.fixed facilities phase

Regular bike

Accessibility measuring phases	Dutch background (%)	Western migration background (%)	Non-Western migration background (%)
Max.fixed facilities	0	0	0
Partial fixed facilities	30	39	53
Partial fixed facilities & Pop-ups	28	35	51
Partial fixed facilities, pop-ups & mobile units	2	5	20

E-bike

Accessibility measuring phases	Dutch background (%)	Western migration background (%)	Non-Western migration background (%)
Max.fixed facilities	0	0	0
Partial fixed facilities	39	54	76
Partial fixed facilities & Pop-ups	36	48	72
Partial fixed facilities, pop-ups & mobile units	5	13	34

4.1.7. Municipalities with religious groups and low accessibility levels

Table 10 divides municipalities into quantiles according to their vaccination rate with the first and second vaccination shots. Most municipalities have a vaccination rate between 60% and 100%, except for three municipalities in the first vaccination shot and four in the second vaccination shot, with a vaccination rate equal to or lower than 60%. Figure 24 shows the same four municipalities appear as outliers in the scatter plots. The details of these four municipalities appear in Table 11, and they are (Staphorst, Urk, Riemerswaal, and Neder-Betuwe). The population of these four municipalities had almost no accessibility to vaccination centers in the first vaccination strategy, except for Urk municipality. In the fine-meshed strategy, all these municipalities do not have any level of accessibility except for Staphorst municipality, which has a considerable level of access for regular and electric bicycle users (35.4% and 68.1%, respectively)

Table 10: municipalities counts according to their vaccinated population percentage with the first and second vaccination shot

Vaccinated people percentage	First vaccination shot (municipalities count)	Second vaccination shot (municipalities count)
from 0 to 20%	0	0
from 20% to 40%	1	1
from 40% to 60%	2	3
from 60% to 80%	101	136
from 80% to 100%	247	211

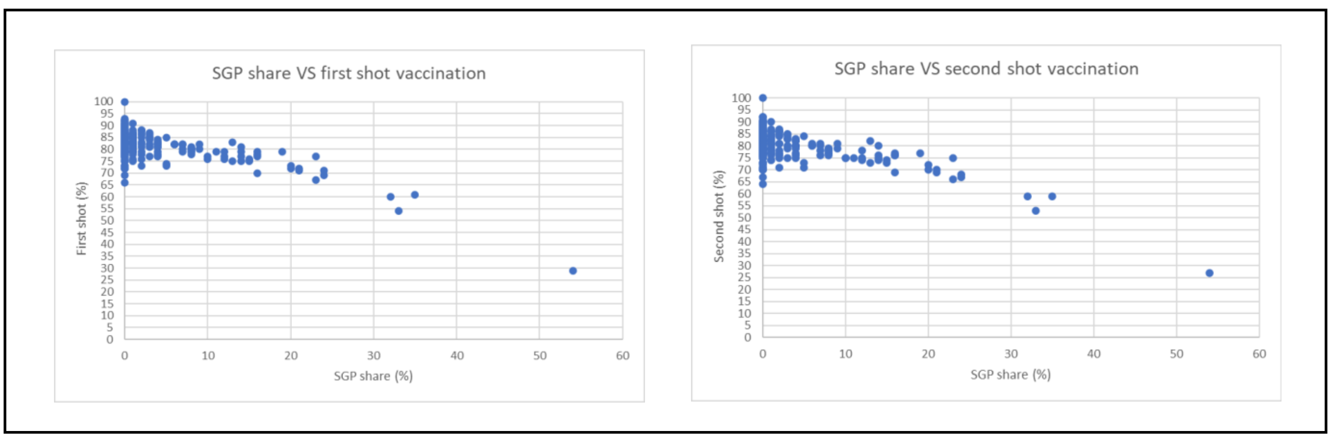

Figure 24: SGP voting percentages against vaccinated population percentages with the first and second shots in all municipalities

Table 11: municipalities with the lowest vaccinated population percentages and the highest SGP voting share

Municipality name	SGP votes share (%)	First shot vaccination (%)	Second shot vaccination(%)	Population with access to vaccination centers (%)			
				Original Strategy		Fine-meshed strategy	
				Regular bike	E-bike	Regular bike	E-bike
Staphorst	33	54	53	0	0	35.4	68.1
Urk	54	29	27	100	100	0	0
Reimerswaal	35	61	59	0	0	0	0
Neder-Betuwe	32	60	59	5.3	19.6	0	0

4.1.8. Trips time percentages

Figure 25 shows the population share for each bicycles trips time interval to vaccination centers in the four phases. Electric bicycle users generally have larger shares for trips that take less than 20 minutes compared to regular bicycle users. Vaccination strategy change has increased the population share who are able to reach the vaccination centers in less than ten minutes by regular and electric bicycles. However, that increase was at the expense of the two trip time intervals (10 min to 15 min) and (15 min to 20 min), as they decreased after changing the vaccination strategy.

Figure 25: Trips time percentages in all accessibility measure phases for regular bikes users and E-bikes users

4.2. prioritizing COVID-19 vaccination centers

4.2.1Maximum upscaling phase results

Out of 9425 OpenStreetMap point of interest locations, LSCP Model has chosen 1883 locations distributed throughout GGD regions to cover almost the whole country, as shown in Figure 26. The Chosen locations differ significantly from one region to another as Frysland has the largest number of locations (163) while the least are in Gooi en Vechtstreek (19). Although the chosen locations provide accessibility for most of the population, they cannot be applied at once realistically, as the number of locations is huge. The LSCP model produces such a huge number of locations as it tries to cover 100 % of the population. The numbers in appendix G show that Complete coverage (100%)could not be achieved in any GGD region, where the highest coverage rate was in Amsterdam (99.8%). The coverage shortage happens because the suggested locations (OpenStreetMap points of interest) are not uniformly distributed in GGD regions, limiting the model from achieving complete coverages. In addition, it can be noted that the coverage percentage in GGD Zeeland is significantly low compared to the other GGD regions (76.3%) due to the lack of sufficient suggested locations

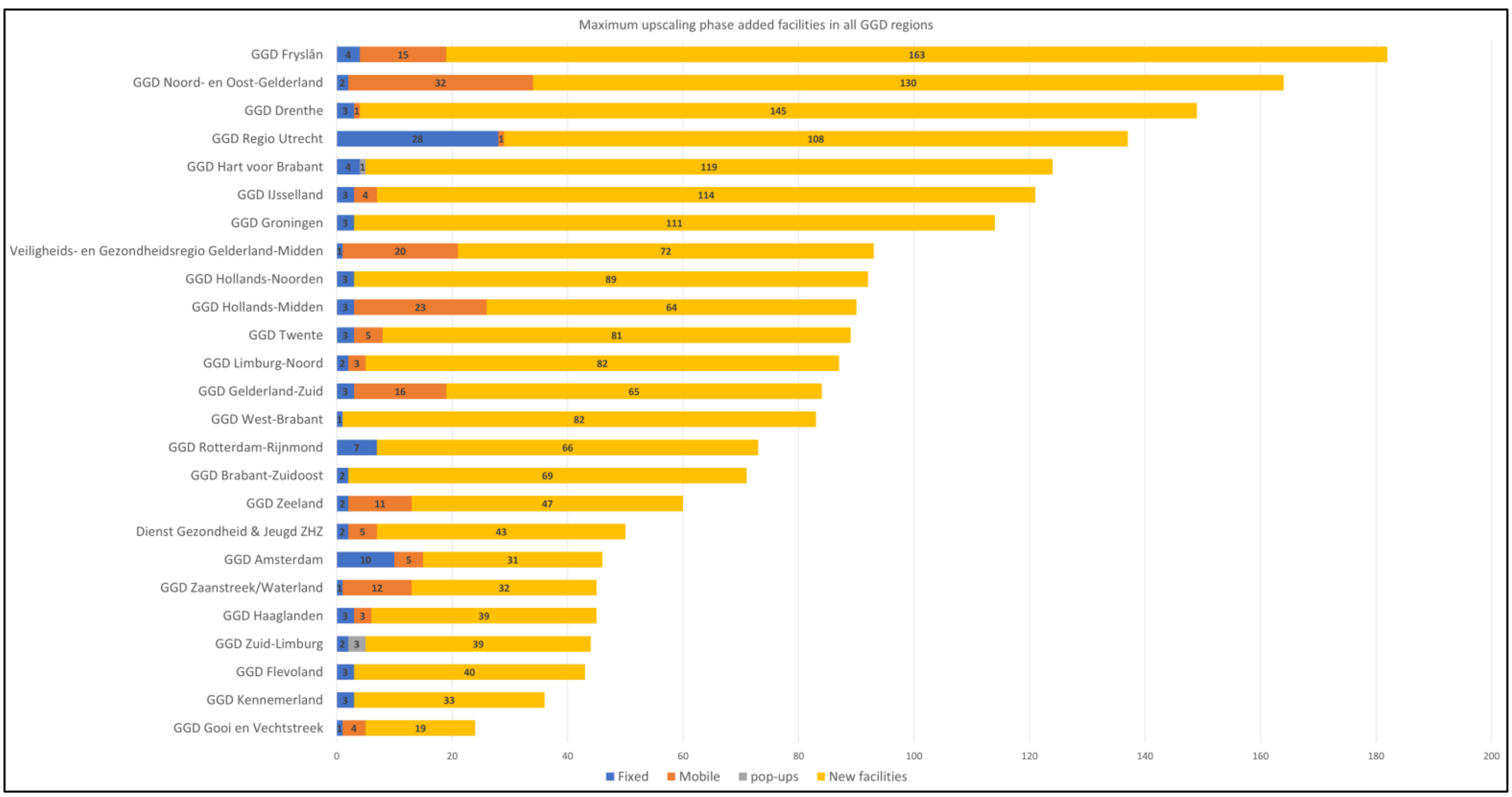

Figure 26:Added facilities by the maximum upscaling phase in all GGD regions

4.2.2. Optimum downscaling phase results -Locations

Figure 27 shows the fine-meshed strategy vaccination centers locations along with the volume and locations of the proposed centers to achieve the coverage scenarios. In the first scenario (50% coverage) shown in Figure 27-B, the proposed locations are concentrated in the regions neglected in the fine-meshed strategy. Most new locations have high demand and are concentrated mainly in the southern regions. They also have some concentrations in specific regions such as GGD Hollands -noorden, GGD Twente and GGD Groningen. Moreover, the new locations are not distributed uniformly throughout the regions to provide accessibility in areas with a considerable population density. In the second scenario (70% coverage) shown in Figure 27-C, the number of centers increased in the same regions. Locations with demand between 20,000 and 30,000 have increased along with those exceeding 30,000 in the western regions. In addition, the northern regions depended mainly on locations with low demand (less than 10,000). Finally, in the third scenario (85% coverage) shown in Figure 27-D, almost all regions depend mainly on locations with less than 10,000 demand to achieve the coverage percentage. Also, new locations are assigned in some central regions where the fine-meshed strategy centers were concentrated.

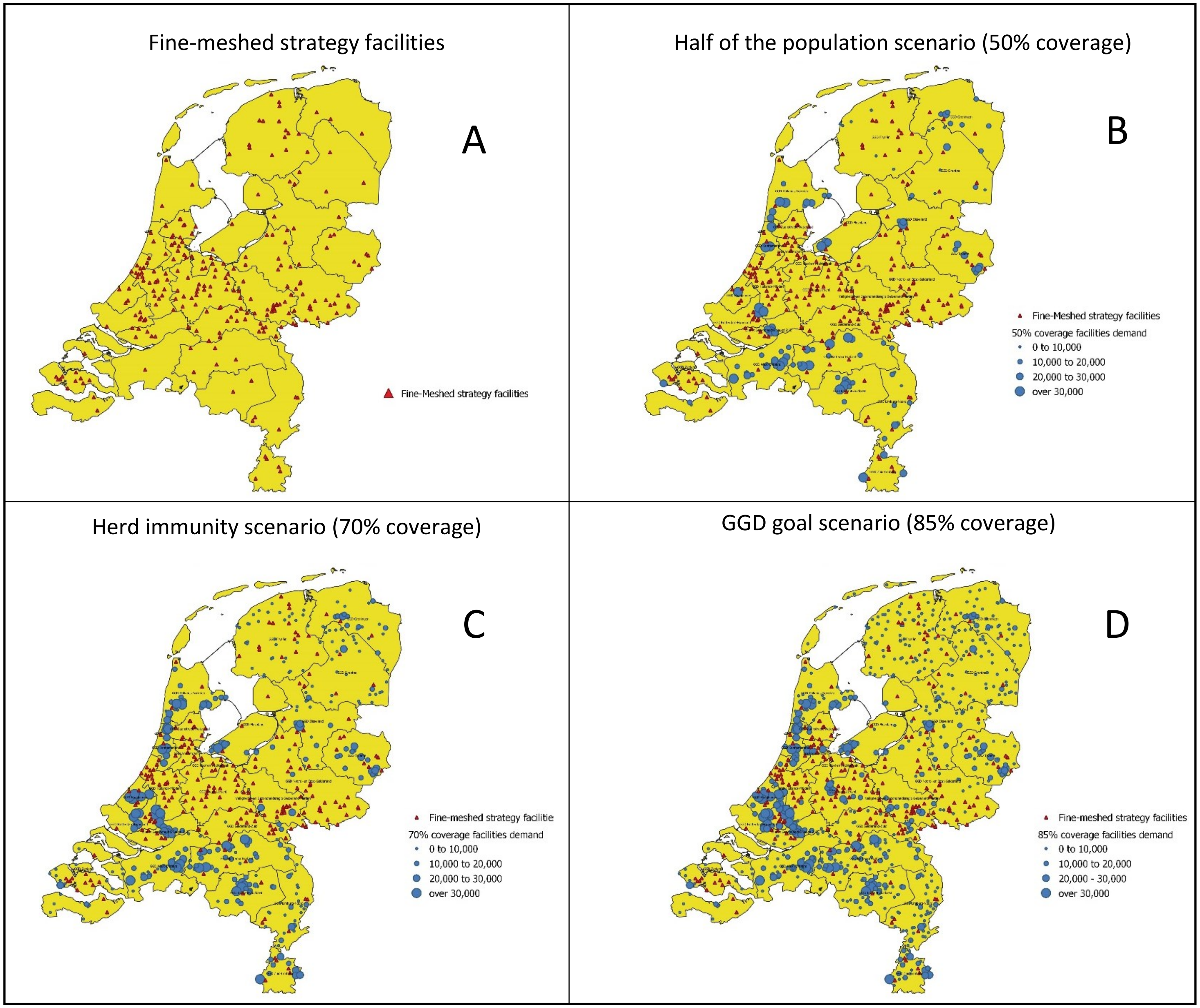

Figure 27:facilities locations and demand volume in all coverage scenarios. (A): Fine-meshed strategy facilities locations. (B): Half of the population scenario (50% coverage). (C):Herd immunity scenario (70% coverage).(D):GGD goal scenario (85% coverage)

4.2.3. Optimum downscaling phase Results – Details Numbers

The figures below show the numbers and demand volumes of the proposed vaccination locations in detail. Generally, there is a large discrepancy in the proposed vaccination centers numbers and demand volumes among GGD regions. For instance, GGD heart voor Brabant region needs 12 new centers to reach 50% coverage, while GGD Zuid-Limburg region needs only three centers to obtain the same coverage. Furthermore, the fine-meshed strategy centers were able to cover more than 70% of the population in some regions without proposing any new vaccination centers (GGD Utrecht, GGD holland-midden, GGD Amsterdam, and GGD Zaanstreak). In addition, they were able to cover more than 85% of the population in GGD Gooi en Vechtstreak. The Demand volume covered by the centers also varies greatly. For example, GGD Dreneth needs 11 centers to enable around (115,000) people to access vaccination centers, while GGD Hart voor Brabant needs almost the same number (12 centers) to cover nearly triple the population (300,300). Moreover, the disparity can be found in the proposed centers demand volume in each region, as they differ according to the population distribution in the regions. For example, an agricultural region such as GGD Groningen depends mainly on centers with low demand volume (less than 10,000) to cover the population. In contrast, more urbanized regions such as Rotterdam and Amsterdam rely primarily on centers with a higher demand volume (more than 20,000).

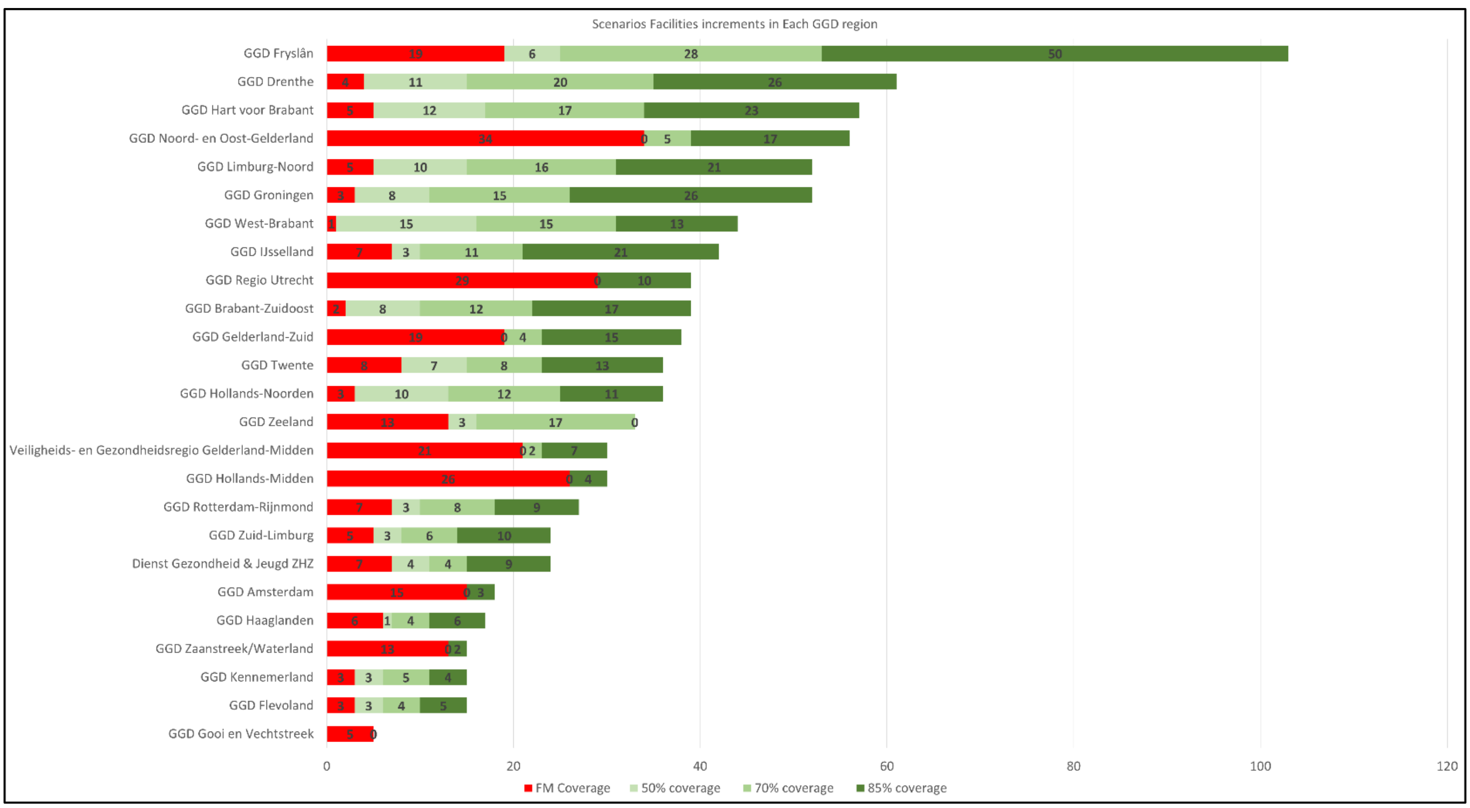

Figure 28 : added facilities for all coverage scenarios in all GGD regions

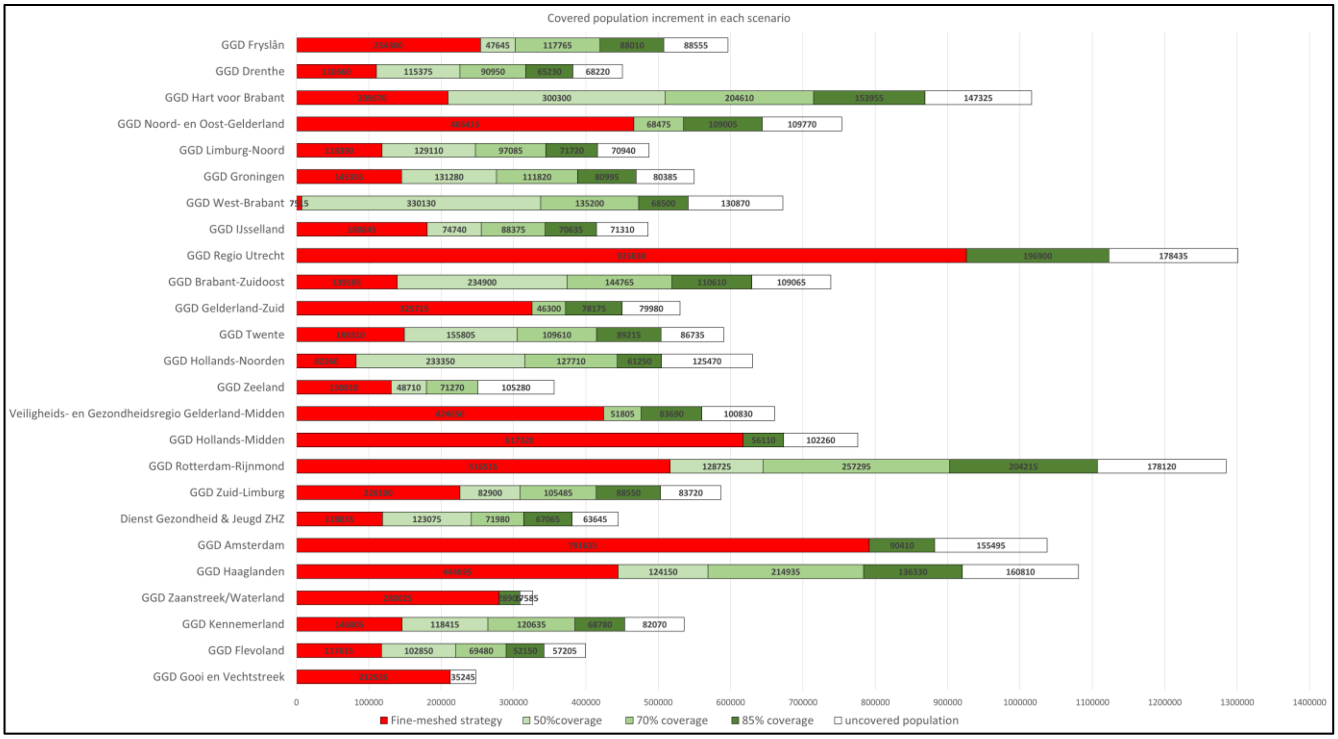

Figure 30:Covered population increments for all coverage scenarios in all GGD regions

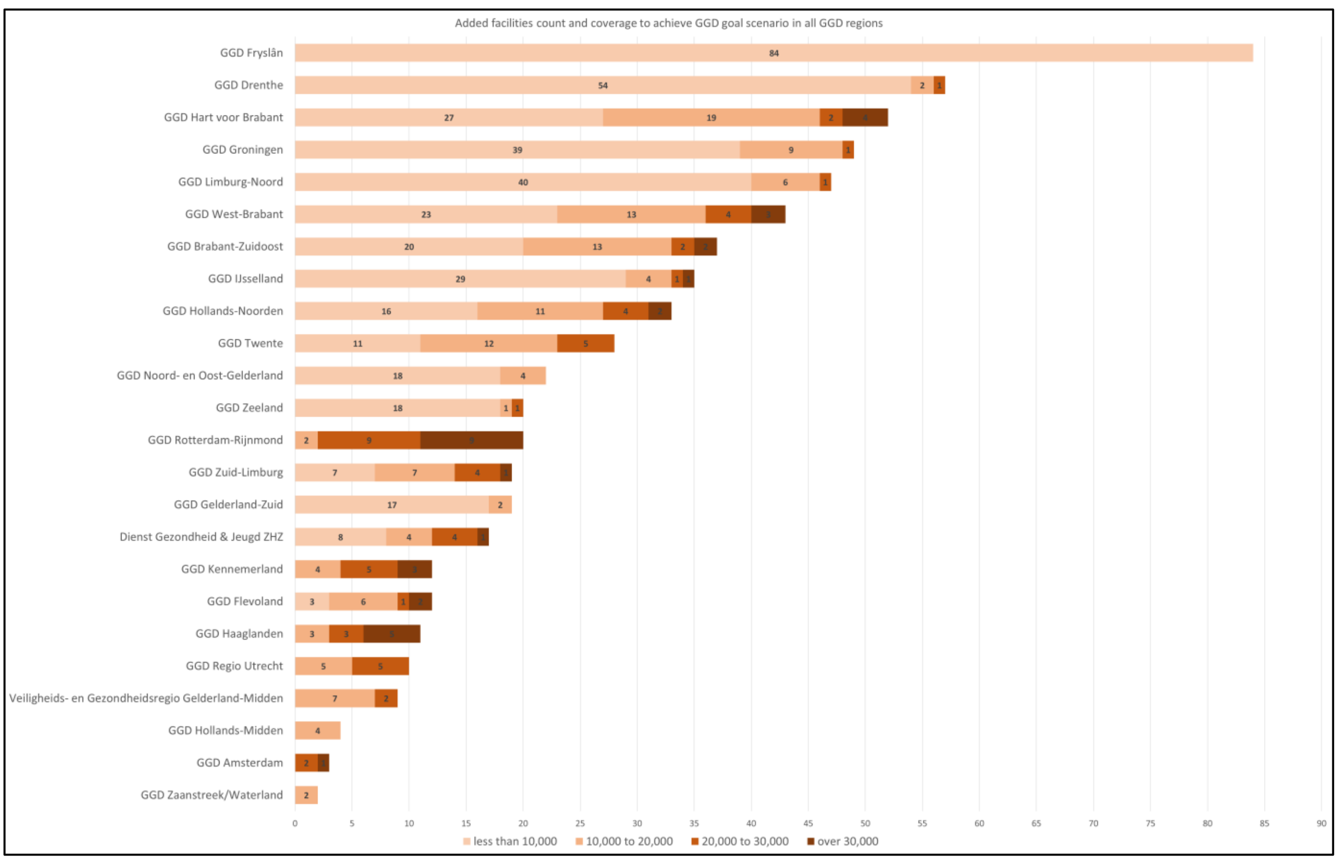

Figure 29:Added facilities count and coverage to achieve GGD goal scenario in all GGD regions

4.2.3. Centers Locations types

Figure 31 shows the location types and their numbers in each scenario. All three scenarios heavily depend on playgrounds and sports centers to cover the population. Both location types have a high accessibility level due to the equitable distribution of sports centers in the Netherlands and the inclusion of children's playgrounds in Dutch urban planning (Hoekman et al., 2016; van Eyck, 2002). Moreover, playground locations are twice the number of sport centers locations, while the number of other location types did not exceed 15 locations.

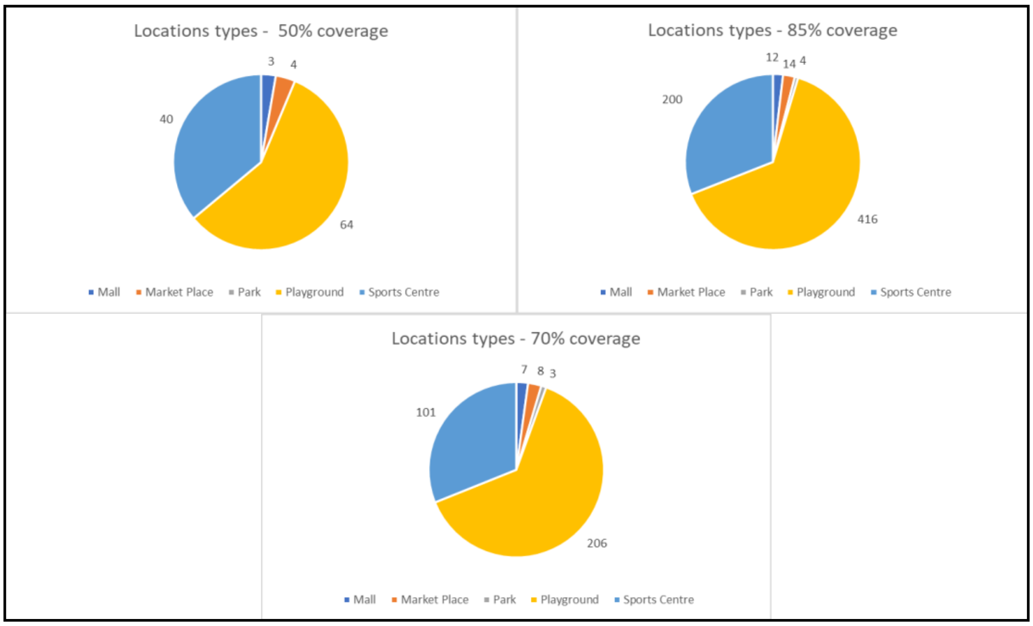

Figure 31: Centers location type

5. Discussion

Changing the vaccination strategy from relying on fixed vaccination centers to including mobile centers to reach vulnerable groups raises questions about the spatial accessibility levels achieved in both vaccination strategies. Also, changing the vaccination centers location during the transition phase introduces the need for a scientific methodology to determine the most accessible locations by bicycle. This research attempts to answer these questions by investigating spatial accessibility to vaccination centers using the cumulative opportunity measure and prioritizing the most accessible locations using the LSCP model. In general, the results have shown that the number of people who have accessibility to vaccination centers by bicycles has decreased due to the change in vaccination strategy by around 2%. Furthermore, changing vaccination strategies negatively impacts several vulnerable groups whom GGD targeted to vaccinate (low-income people, the elderly, several municipalities with religious groups, and migrants with non-western backgrounds). The new centers allocation and prioritization methodology is based on the LSCP model that helps in identifying locations with high accessibility levels. The methodology results indicate significant disparity among GGD regions in the new centers numbers and the volume of the population that has accessibility to them. Such results indicate the need for the methodology to help decision-makers prioritize the most accessible locations according to each region needs.

This research can be considered an addition to the scientific efforts of studying spatial accessibility to medical facilities in general and COVID-19 related facilities in particular. Unlike researches that focus on accessibility to intensive care units (ICUs) or COVID-19 testing centers without time constraints, such as Bauer et al.(2020) and Tao et al. (2020), this thesis has the advantage of investigating accessibility to COVID-19 vaccination centers at two different moments addressed in four accessibility measuring phases. Furthermore, it has the distinction of choosing regular and electric bicycles as transportation modes, which is scarce in accessibility-related scientific papers that mostly look at accessibility by cars or public transportation modes(Boisjoly et al., 2020; Tao et al., 2020).in addition, the thesis tries to enhance accessibility levels by introducing a vaccination locations prioritization methodology to help choose the most accessible location in any vaccination plan in the future.

Around half of the Dutch can reach the vaccination centers within a 20-minute trip using regular and electrical bicycles in the original strategy (max. fixed facilities phase). The country western regions had the highest accessibility levels in the original strategy owing to the concentration of vaccination centers in those regions. Such unequal distribution of vaccination centers may be due to the high population density in the western regions, especially in the Randstad area(CBS, 2022b). The high accessibility levels in western regions were at the expense of the other parts of the country that the fine-meshed strategy tried to cover using mobile vaccination centers. The fine-meshed strategy extended the high accessibility levels from the western regions to the middle and eastern regions. Although the number of mobile centers is much greater than the fixed ones in the fine-meshed strategy, as shown in Table 6, the uneven distribution of vaccination centers among the regions led to a decrease in the number of people able to reach the vaccination centers by bicycles. The inequitable distribution supports the need for a scientific methodology to distribute fixed, pop-ups and mobile centers in locations with high accessibility levels to serve the largest possible number of people.

Several fixed vaccination centers were closed after vaccinating many people in the original strategy leading to the opening and relying more on mobile centers in the fine-meshed strategy (van Annemieke, 2021). The research studies the transition between strategies only in two moments in time. Acquiring precise dates for closing those fixed centers and opening the mobile ones in each region would have made the track of the transition negative impact on accessibility more clear. In general, the results indicate that the closure was uneven among regions and had a negative effect on accessibility levels in most municipalities. Therefore, closing fixed centers must coincide with opening mobile ones to ensure that such a sharp decline in accessibility levels does not occur in the future. In addition, the number of pop-up centers in the fine-meshed strategy was very limited (only four centers in the southern regions), leading to a slight effect in improving accessibility levels compared to fixed and mobile centers. This limited utilization of the pop-ups needs further investigation to be effectively used in the future.

According to GGD, The aim of changing vaccination strategy is to reach the most vulnerable groups mentioned in Table 1(van Annemieke, 2021). However, comparing the fine-meshed strategy spatial accessibility levels to the original strategy indicates otherwise. Changing strategies has negatively impacted accessibility levels in general, as the number of people able to reach vaccination centers using regular and electrical bicycles decreased by 1.6% and 3.2%, respectively. Considering the population data is old (2018 population), and some population vector squares do not have population information, the decrease of the population with accessibility might be even higher for both bicycles users. In addition, most affected people are from poor and middle income classes and non-Western backgrounds. The percentage of elderly (over 65 years) who could not reach vaccination centers has also increased. Moreover, such a change in the vaccination strategy played a negative role by decreasing accessibility levels in municipalities with high percentages of religious groups (more than 30%). These adverse effects indicate that GGD lacks the scientific methodology to target the most vulnerable groups. The only positive change is increasing the number of people able to reach vaccination centers in less than 10 minutes by bicycle. That positive change is due to the concentration of mobile centers in the middle of the country, leading to faster access for those who live in those areas.

The results indicate a correlation between the low vaccination rates in some municipalities (less than 60%) and the high rates of voters for the SGP party (more than 30%). Unlike other religious parties, The conservative political party supports people who don't want to be vaccinated for religious reasons; thus, their voters percentage can be considered an indicator of religious people gatherings who are against vaccines(SGP, 2021). The results are consistent with other Dutch studies that found the same relationship and show the need to focus on these groups with low vaccination rates(Ruijs et al., 2012, 2011). This research adds to these efforts by measuring spatial accessibility to vaccination centers in their regions. The method of tracing municipalities with religious population density using SGP voters percentages is inspired by Lugnér et al. (2010) work. The results indicate an absence of any accessibility levels in some of the municipalities with high voters percentages and low levels in others for both vaccination strategies, which contradicts the goal of GGD for changing vaccination strategy(van Annemieke, 2021). Moreover, The low level of accessibility in municipalities with high religious population density exacerbates the already existing low vaccination levels problem due to their concentration (van Mersbergen, 2021). It is worth noting that GGD is facing difficulties establishing centers in such regions, as some were burned by riots against the vaccine(Dallison, 2021). Also, some of these groups are afraid to be looked down on by other members and find it embarrassing to enter these centers in the open spaces in their areas(RTL News, 2021). Nevertheless, it is crucial to provide higher accessibility levels to vaccination centers in these areas to help increase vaccination uptake.

The LSCP model is a location-allocation model that can help health administrations determine locations where a vaccination center can reach a large number of people. Its results can be adjusted to prioritize locations with the highest accessibility levels and exclude those with lower accessibility levels. Such methodology can help plan new vaccination center locations based on spatial accessibility levels in the future. This method not only addresses randomness in choosing the vaccination centers locations, but also provides implementation flexibility by targeting several coverage percentages and prioritizing locations with high population density and low accessibility levels in any given region. The model results indicate the need to increase the number of vaccination centers in the fine-meshed strategy. The strategy is effective in terms of accessibility only in a few regions such as GGD Utrecht but provides very low accessibility levels in other areas such as southern regions. Furthermore, the model results show a significant discrepancy in the number of required vaccination centers and the number of people they can serve in all GGD regions. This disparity proves the need to localize centers distribution plans for each GGD region separately to reach the targeted percentage of people. By Understanding center locations and their accessibility levels, a decision-maker can determine the needed budget and type of vaccination facility (fixed, mobile, or pop-up). For instance, it is possible to rely on fixed centers in locations with a demand that exceeds 30,000 people and to rely on pop-ups and mobile centers with less than 30,000 people. Also, it is more convenient to use mobile units for locations that provide accessibility to less than 10,000 people in remote areas than pop-ups. That is because they can be more efficient in handling small populations and don't need to use buildings to serve people.

In the second strategy, most GGD regions need to increase the number of vaccination centers; thus, the research does not show a prioritization methodology to close vaccination centers. Nevertheless, the results of the LSCP model can be used to understand the effect of closing vaccination centers based on the reduction needed in accessibility levels. The centers closing process can be implemented in several methods. For instance, closing centers can be prioritized according to the vaccination uptake rate as the centers close after achieving a vaccination uptake threshold in the locations specified by the model. Another method is to reduce the number of centers to meet a coverage percentage desired by decision-makers (due to lower than usual infection rates, for instance). It is also possible to take advantage of locations that provide accessibility to small populations (less than 10 thousand people) and make them stations for mobile unties that relocate periodically among them rather than using pop-up centers and closing them after a period of time. All previous methods utilize the LSCP model results and provide decision-makers with flexible plans for closing their vaccination centers.

The research results were shared with GGD Twente's representatives during a meeting held at ITC. They expressed the importance of this research in revealing the impact of vaccination center locations on the accessibility levels for the targeted vulnerable groups. In addition, they explained how they did not study the effect of the spatial factor in their vaccination strategy before. They stressed the importance of having a scientific model to determine the best locations for their centers, such as the model proposed in this research. During the meeting, they clarified that they depend on three criteria for establishing a new vaccination center: 1) the rate of vaccination uptake at the targeted area, 2) the availability of medical staff and assistants, and 3) the available financial budget. GGD administrations face several challenges when choosing new vaccination locations. The most important are obtaining the necessary permits from the municipalities, the lack of some socio-economic information about residents in the area (due to privacy protection), and the lack of advertisements for the new vaccination centers. Furthermore, The GGD representatives explained that in the event of another pandemic wave, they would depend more on pop-up centers and fixed centers than mobile ones due to the ability of pop-up and fixed centers to vaccinate more significant numbers of people.

5.1. Conclusions

Answering the research questions can conclude the research as follow:

Q1: What are the available approaches to measure vaccination center accessibility levels?

The research showed several accessibility measures in the literature review chapter. Accessibility to vaccination centers can be measured using location-based measures such as cumulative opportunity measure and potential accessibility measure as they contain the land-use factor. Since the thesis examines accessibility to vaccination centers without any data about the capacity for the vaccination centers, the research was conducted using the cumulative opportunity measure as the results of this measure are easy to explain to stakeholders.

Q2: What was the spatial accessibility level to COVID-19 vaccination centers in the original vaccination strategy?

The results show that 45% and 53.6% of the population have accessibility to the fixed vaccination centers using regular and electric bicycles, respectively. Accessibility levels were the highest in the western regions of the country, where most centers were concentrated. The density of vaccination centers in the west was not available for the rest of the country; thus, all other regions have suffered from low accessibility levels, except for several border regions in the north. The results also indicate that most people who did not have access to vaccination centers belong to low and middle-income classes. Also, they belong to the age brackets (25-44), (45-64), and (over 65) and have Dutch ethnicity. In addition, all municipalities with a religious population density (more than 30%) had zero access levels in some regions and low levels in others, except for Urk municipality, which had a 100% accessibility level.

Q3: How has the new strategy changed the accessibility level to the vaccination centers?

The fine-meshed strategy could not provide the same accessibility level that was provided by the original strategy, as the results showed around 2% lower accessibility levels compared to the original strategy. Consequently, 43.4% and 50.4% of the population were able to reach the vaccination centers using regular and electric bicycles, respectively. The strategy focused on providing high levels of accessibility in the western and eastern regions of the country, passing through the central regions. The neglect of the southern regions continued, as they suffered from very low levels of accessibility compared to other municipalities. Also, the accessibility levels changed in the north, as the average accessibility levels shifted from the northern border regions to the northwestern regions. The same groups that suffered in the original strategy suffered in the fine-meshed strategy, except that some groups were more affected than others. The most affected groups by the strategy change are the youth (age 15 to 24), low-income people, and people with non-Western ethnic backgrounds. In addition, the fine-meshed strategy did not improve accessibility levels in municipalities with religious population concentrations (more than 30%). The only positive change was an increase in the number of people able to reach vaccination centers by bicycle in less than 10 minutes compared to the original strategy.

Q4: Which municipalities need more or fewer vaccination centers to enhance spatial accessibility?

Increasing or decreasing the number of vaccination centers depends on the coverage percentage targeted by the decision-makers. In general, the results showed that all southern and some northern municipalities suffer from low accessibility levels in the fine-meshed strategy. In addition, all municipalities with a religious population density (more than 30%) have suffered from low accessibility levels. To achieve 85% coverage that meets the GGD target, all GGD regions need to increase the number of vaccination centers

Q5: what is the most suitable approach for using location-allocation models to achieve the optimum vaccination centers distribution?

The thesis presented several models to determine the best locations to increase vaccination centers accessibility levels. Among these models, the LSCP model was chosen to select new locations with high accessibility levels. The model was chosen for its ability to add an unlimited number of centers, thus covering the entire country. Also, it was chosen due to its ability to include a maximum time threshold for each selected location. The LSCP model was a part of the prioritization approach as its results were used to establish the maximum upscaling phase. That phase was the first step toward building prioritization tables for each GGD region in the optimum downscaling phase.

Q6: Which vaccination centers should be prioritized to stay open, re-located, or closed in the new strategy?

The results indicate that priority is given to opening vaccination centers in locations with the largest population that can reach a vaccination center (more than 30 thousand) in areas not covered by the fine-meshed strategy. Then the priority is given to locations with a smaller population that can reach the center in descending order. Mobile centers (buses) can cover multiple locations with low demand (less than 10 thousand) during their relocation movement. As the fine-meshed strategy did not reach the targeted coverage percentages in most regions, the research did not address the priority of closing the centers in the calculations. However, prioritization for closing centers can be according to the vaccination percentage achieved in the location or the coverage percentage needed to be reduced.

5.2. Limitations

- Some of the data used in this research were not the most recent versions because the recent ones were not available to the public. That includes CBS data for population locations and demographics. Also, CBS data for Population travel behavior (ODiN). Some demographic information (number, age, income) was also incomplete for some population vector squares. Using an up-to-date, complete version may increase the precision if they were available

- Some of the limitations are related to the centers type and capacities. The mobile vaccination centers are constantly changing their locations in short periods (10 weeks maximum), making it difficult to record their locations over time. The centers also have multiple capacities depending on their type (fixed, mobile, and pop-ups), and such information was not possible to obtain while gathering the data. Therefore, in this research, accessibility was evaluated based on the vaccination centers locations at two moments in time without considering the facilities capacities in the calculations. All vaccination centers locations data were collected from GGD official websites. To achieve more precise results, accessibility evaluation should take into account vaccination centers capacities and the more time moments to account for the fast change in mobile centers locations

- The suggested locations to increase the number of vaccination centers are based on the points of interest provided by OpenStreetMap. Obtaining data about locations that GGD can use in reality (such as buildings they can rent) might provide more precise results

5.3. Recommendations

- The research evaluated accessibility to COVID-19 vaccination centers using regular and electrical bicycles. A study that assesses accessibility using cars and public transportations in addition to bicycles might provide more comprehensive results to understand the impact of changing vaccination strategy
- by knowing the vaccination centers capacities, a study can be conducted to evaluate accessibility to vaccination centers with the competition factor. Such a study would provide comprehensive results for accessibility levels among centers

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Appendix

A. Data summary and sources

Table 12:Data table

Name	Source	Type	Year of publish	URL
Population locations and demographics	Dutch Central Agency for Statistics (CBS)	Shapefile	2018	https://www.cbs.nl/nl-nl/dossier/nederland-regionaal/geografische-data/kaart-van-100-meter-bij-100-meter-met-statistieken
Roads and bicycle network	Open street maps	Shapefile	2021	http://download.geofabrik.de/europe/netherlands.html
COVID-19 vaccination centers locations	The government of the Netherlands	Shapefile	2021	https://www.rijksoverheid.nl/onderwerpen/coronavirus-vaccinatie/vraag-en-antwoord/waar-zijn-de-priklocaties-voor-coronavaccinatie
Population travel behavior	Dutch Central Agency for Statistics (CBS)	CSV file	2019	https://www.cbs.nl/nl-nl/onze-diensten/methoden/onderzoeksomschrijvingen/aanvullende-onderzoeksomschrijvingen/onderweg-in-nederland--odin---onderzoeksbeschrijving-2019
Dutch parliament Elections results	Volksgezondheidenzorg	CSV file	2021	https://www.volksgezondheidenzorg.info/sites/default/files/map/detail_data/klikfile_tk2021.csv
COVID-19 Vaccination uptake percentage.	Rijksinstituut voor Volksgezondheid en Milieu (RIVM)	CSV file	2021	https://data.rivm.nl/covid-19/
GGD regions boundaries	Dutch Central Agency for Statistics (CBS)	Shapefile	2021	https://www.cbs.nl/nl-nl/dossier/nederland-regionaal/geografische-data/cbs-gebiedsindelingen
Municipalities boundaries	Dutch Central Agency for Statistics	Shapefile	2020	https://www.cbs.nl/nl-nl/dossier/nederland-regionaal/geografische-data/wijk-en-buurtkaart-2020
OpenStreetMap points of interest	Open street maps	Shapefile	2021	http://download.geofabrik.de/europe/netherlands.html

B. Population vector square map

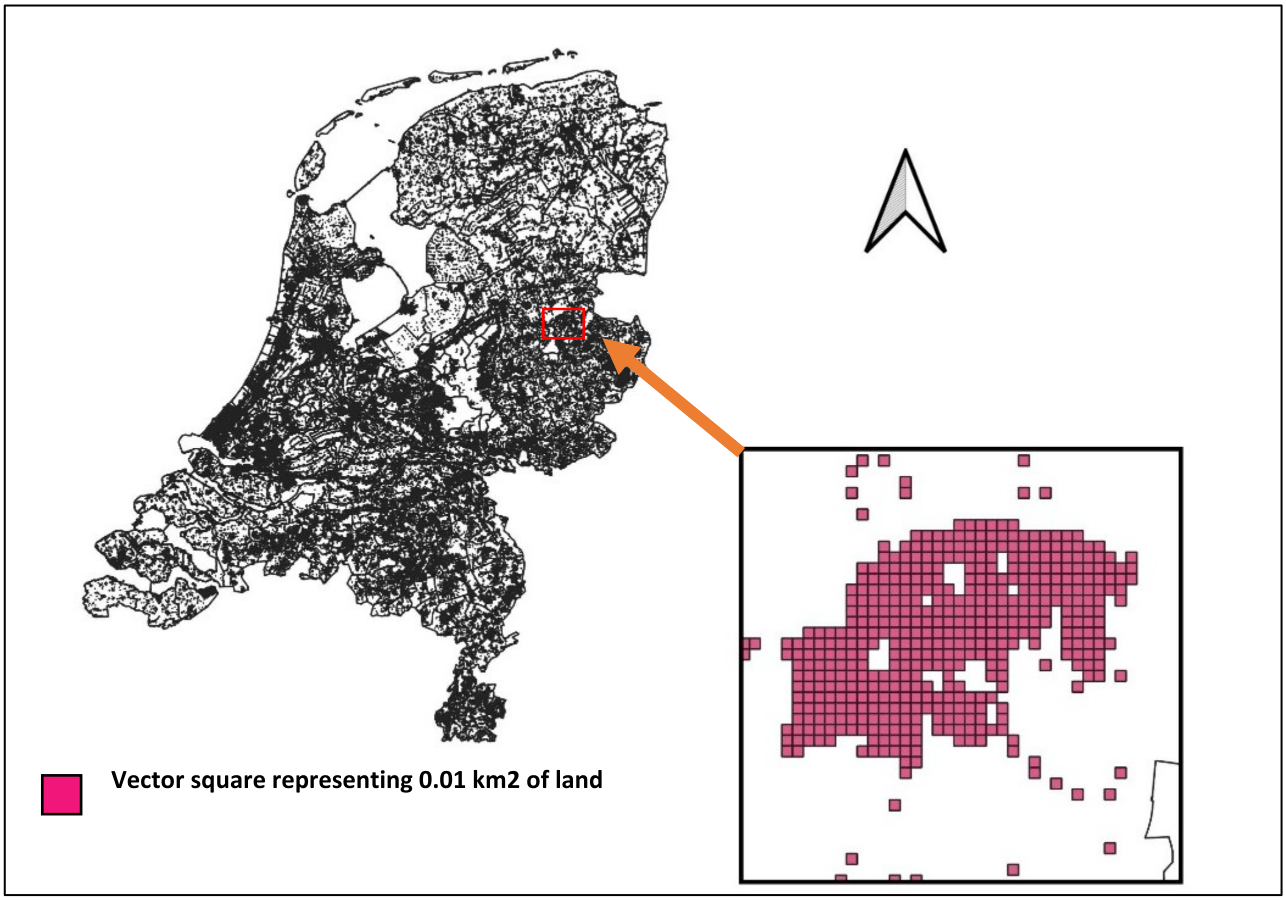

Figure 32:Map showing all the vector Squares that contain population data with a zooming square

C. Trips numbers for each trips time interval in all trips motivations

Table 13: Trips count percentage for each time interval in all trips motivations (Regular bike)

Trip motivation	Trips count (Regular Bike)								
	Less than 10 minutes	10 to 15 minutes	15 to 20 minutes	20 to 30 minutes	30 to 45 minutes	45 to 60 minutes	60 to 90 minutes	90 to 120 minutes	over 120 minutes
To and from work	1,186	1,245	1,405	1,095	892	242	99	11	18
Business and professional	148	124	107	85	80	15	13	8	11
Services/Personal Care	287	269	201	137	85	18	7	2	2
Shopping/groceries	2,904	1,930	1,127	461	328	61	44	20	22
Education/course attendance	1,590	1,515	1,153	1,003	742	212	110	5	14
Visit/stay	687	670	606	274	275	51	42	6	20
Social recreational other	1,958	2,058	1,849	873	639	156	173	139	365
Touring/hiking	19	21	34	40	100	95	225	159	522
Other motive	1,327	817	476	221	111	34	13	7	17
Grand Total	10,106	8,649	6,958	4,189	3,252	884	726	357	991

Table 14: Trips count percentage for each time interval in all trips motivations (E-bike)

Trip motivation	Trips count (E-Bike)								
	Less than 10 minutes	10 to 15 minutes	15 to 20 minutes	20 to 30 minutes	30 to 45 minutes	45 to 60 minutes	60 to 90 minutes	90 to 120 minutes	over 120 minutes
To and from work	181	217	279	253	313	105	70	0	11
Business and professional	14	31	25	25	19	9	3	0	0
Services/Personal Care	70	72	75	32	32	4	0	0	0
Shopping/groceries	657	493	326	147	137	32	30	6	6
Education/course attendance	31	23	30	23	52	41	16	0	0
Visit/stay	146	121	115	73	83	22	11	6	5
Social recreational other	241	314	263	117	80	29	19	6	28
Touring/hiking	2	5	7	12	38	45	117	118	357
Other motive	225	127	83	57	47	14	7	1	2
Grand Total	1,567	1,403	1,203	739	801	301	273	137	409

D. Number of population without accessibility to vaccination centers according to their age

Table 15 : Population without accessibility to vaccination centers according to their age (count)

Regular bike

Accessibility measuring phases	From 00 to 14 years old	From 15 years old to 24 years old	From 25 years old to 44 years old	From 45 years old to 64 years old	65 years and older	Total
Max.fixed facilities	1,256,190	794,655	1,870,190	2,400,735	1,543,795	7,865,565
Partial fixed facilities	1,683,280	1,093,555	2,540,215	3,163,170	2,041,065	10,521,285
Partial fixed facilities & Pop-ups	1,663,980	1,077,855	2,497,675	3,114,860	2,007,710	10,362,080
Partial fixed facilities, pop-ups & mobile units	1,320,880	839,190	1,944,835	2,475,115	1,591,250	8,171,270

E-bike

Accessibility measuring phases	From 00 to 14 years old	From 15 years old to 24 years old	From 25 years old to 44 years old	From 45 years old to 64 years old	65 years and older	Total
Max.fixed facilities	1,046,895	642,050	1,522,605	2,029,205	1,316,510	6,557,265
Partial fixed facilities	1,514,155	964,240	2,238,705	2,873,115	1,866,605	9,456,820
Partial fixed facilities & Pop-ups	1,488,030	944,230	2,184,145	2,807,955	1,820,480	9,244,840
Partial fixed facilities, pop-ups & mobile units	1,147,845	714,005	1,667,055	2,176,390	1,410,780	7,116,075

E. Number of population without accessibility to vaccination centers according to their income

Table 16: population without accessibility to vaccination centers according to their income class (count)

Regular bike

Accessibility measuring phases	Low	Low to under middle	Low to middle	Under middle	Under middle to middle	Under middle to above middle	Middle	Middle to above middle	Above middle to high	Above middle	High	Unclassified
Max.fixed facilities	107,120	656,460	8,925	769,110	1,395,345	5,330	986,575	1,934,090	507,610	1,031,745	235,330	1,451,750
Partial fixed facilities	165,885	934,485	10,300	1,126,920	1,804,260	6,130	1,353,525	2,471,540	667,640	1,409,845	329,835	1,636,340
Partial fixed facilities & Pop-ups	161,960	906,790	10,230	1,099,540	1,772,855	6,105	1,331,065	2,444,080	662,580	1,397,220	326,875	1,627,075
Partial fixed facilities, pop-ups & mobile units	122,845	707,600	8,650	826,040	1,408,145	5,255	1,018,065	1,960,620	534,250	1,105,345	255,185	1,406,955

E-bike

Accessibility measuring phases	Low	Low to under middle	Low to middle	Under middle	Under middle to middle	Under middle to above middle	Middle	Middle to above middle	Above middle to high	Above middle	High	Unclassified
Max.fixed facilities	62,990	535,385	8,210	593,235	1,224,425	5,020	803,005	1,684,655	417,535	840,380	171,485	1,333,000
Partial fixed facilities	121,380	822,355	9,875	970,685	1,666,365	5,940	1,191,495	2,292,260	601,180	1,269,055	274,955	1,561,200
Partial fixed facilities & Pop-ups	117,055	787,485	9,790	934,180	1,624,400	5,915	1,163,330	2,254,805	593,130	1,251,130	270,060	1,547,760
Partial fixed facilities, pop-ups & mobile units	82,220	598,305	8,000	694,595	1,263,820	4,995	876,825	1,761,180	460,160	964,810	198,760	1,295,305

F. Number of population without accessibility to vaccination centers according to their ethnicity

Table 17: population without accessibility to vaccination centers according to their ethnicity (count)

Regular bike

Accessibility measuring phases	Dutch background	Western migration background	Non-Western migration background	Total
Max.fixed facilities	7,023,575	626,997	750,488	8,401,059
Partial fixed facilities	9,117,586	872,916	1,148,501	11,139,002
Partial fixed facilities & Pop-ups	8,993,403	849,535	1,130,894	10,973,832
Partial fixed facilities, pop-ups & mobile units	7,132,883	661,261	900,281	8,694,424

E-bike

Accessibility measuring phases	Dutch background	Western migration background	Non-Western migration background	Total
Max.fixed facilities	6,035,264	480,877	531,568	7,047,708
Partial fixed facilities	8,365,298	741,667	937,245	10,044,209
Partial fixed facilities & Pop-ups	8,196,786	711,318	915,781	9,823,885
Partial fixed facilities, pop-ups & mobile units	6,338,629	544,470	714,878	7,597,976

G. Maximum upscaling phase

Table 18:Added facilities and the coverage in all GGD regions in the maximum upscaling phase

GGD region	Population	Fine-Meshed strategy					LSCP		
		Fixed centers	Mobile centers	pop-up centers	Covered Population	Coverage (%)	Added facilities	Total covered population	(%)
Dienst Gezondheid & Jeugd ZHZ	444,600	2	5	0	118,120	26.6	43	432,380	97.3
GGD Amsterdam	1,037,540	10	5	0	809,695	78.0	31	1,035,795	99.8
GGD Brabant-Zuidoost	738,525	2	0	0	139,185	18.8	69	696,055	94.2
GGD Drenthe	450,435	3	1	0	112,150	24.9	145	431,450	95.8
GGD Flevoland	399,300	3	0	0	117,615	29.5	40	385,640	96.6
GGD Fryslân	596,275	4	15	0	254,240	42.6	163	540,755	90.7
GGD Gelderland-Zuid	530,170	3	16	0	326,675	61.6	65	502,175	94.7
GGD Gooi en Vechtstreek	247,780	1	4	0	220,080	88.8	19	244,915	98.8
GGD Groningen	549,835	3	0	0	144,185	26.2	111	523,005	95.1
GGD Haaglanden	1,080,920	3	3	0	444,945	41.2	39	1,078,525	99.8
GGD Hart voor Brabant	1,015,860	4	0	1	209,670	20.6	119	991,500	97.6
GGD Hollands-Midden	775,690	3	23	0	608,975	78.5	64	771,310	99.4
GGD Hollands-Noorden	630,140	3	0	0	82,375	13.1	89	601,700	95.5
GGD IJsselland	485,905	3	4	0	180,875	37.2	114	467,625	96.2
GGD Kennemerland	535,905	3	0	0	154,015	28.7	33	530,150	98.9
GGD Limburg-Noord	487,245	2	3	0	118,435	24.3	82	450,085	92.4
GGD Noord- en Oost-Gelderland	753,665	2	32	0	465,605	61.8	130	728,675	96.7
GGD Regio Utrecht	1,301,165	28	1	0	911,705	70.1	108	1,286,745	98.9
GGD Rotterdam-Rijnmond	1,284,870	7	0	0	516,515	40.2	66	1,272,060	99.0
GGD Twente	590,675	3	5	0	149,310	25.3	81	570,295	96.5
GGD West-Brabant	672,215	1	0	0	7,515	1.1	82	603,070	89.7
GGD Zaanstreek/Waterland	326,515	1	12	0	259,920	79.6	32	325,125	99.6
GGD Zeeland	356,070	2	11	0	130,810	36.7	47	271,845	76.3
GGD Zuid-Limburg	586,755	2	0	3	226,100	38.5	39	564,625	96.2
Veiligheids- en Gezondheidsregio Gelderland-Midden	660,975	1	20	0	433,575	65.6	72	650,640	98.4

H. Added facilities in all coverage scenarios

Table 19: Facilities counts and covered population for all coverage scenarios in all GGD regions

GGD region	50 % coverage		70 % coverage		85 % coverage		Uncovered population	Remarks
	Added facilities	Total covered populattion	Added facilities	Total covered populattion	Added facilities	Total covered populattion		
Dienst Gezondheid & Jeugd ZHZ	4	241,195	8	313,175	17	380,240	64,360	
GGD Amsterdam	NON	NON	NON	NON	3	900,105	137,435	
GGD Brabant-Zuidoost	8	374,085	20	518,850	37	629,460	109,065	
GGD Drenthe	11	227,525	31	318,475	57	383,705	66,730	has 1 joint facility
GGD Flevoland	3	220,465	7	289,945	12	342,095	57,205	
GGD Fryslân	6	301,885	34	419,650	84	507,660	88,615	
GGD Gelderland-Zuid	NON	NON	4	372,975	19	451,150	79,020	
GGD Gooi en Vechtstreek	NON	NON	NON	NON	NON	NON	NON	covered by FM
GGD Groningen	8	275,465	23	387,285	49	468,280	81,555	has 1 joint facility
GGD Haaglanden	1	569,095	5	784,030	11	920,360	160,560	
GGD Hart voor Brabant	12	509,970	29	714,580	52	868,535	147,325	
GGD Hollands-Midden	NON	NON	NON	NON	4	665,085	110,605	
GGD Hollands-Noorden	10	315,725	22	443,435	33	504,685	125,455	
GGD IJsselland	3	255,615	14	343,990	35	414,625	71,280	
GGD Kennemerland	3	272,430	8	393,065	12	461,845	74,060	
GGD Limburg-Noord	10	247,545	26	344,630	47	416,350	70,895	
GGD Noord- en Oost-Gelderland	NON	NON	5	534,080	22	643,085	110,580	
GGD Regio Utrecht	NON	NON	NON	NON	10	1,108,605	192,560	
GGD Rotterdam-Rijnmond	3	645,240	11	902,535	20	1,106,750	178,120	
GGD Twente	7	305,115	15	414,725	28	503,940	86,735	
GGD West-Brabant	15	337,645	30	472,845	43	541,345	130,870	
GGD Zaanstreek/Waterland	NON	NON	NON	NON	2	288,825	37,690	
GGD Zeeland	3	179,520	20	250,790	NON	NON	NON	could not reach 85%
GGD Zuid-Limburg	3	309,000	9	414,485	19	503,035	83,720	
Veiligheids- en Gezondheidsregio Gelderland-Midden	NON	NON	2	485,380	9	569,070	91,905	