# A Just City: Optimizing Low Emission Zone Allocation

## Using socio-demographic vulnerability to air pollution and transport poverty to identify adequate Low Emission Zone locations

EPA2942: Master Thesis

Suzanne Ansems

Delft University of Technology

TU Delft
STUDIO BEREIKBAAR

# A Just City: Optimizing Low Emission Zone Allocation

## Using socio-demographic vulnerability to air pollution and transport poverty to identify adequate Low Emission Zone locations

by

Suzanne Ansems

| | |
|---|---|
| Student number : | 5416612 |
| Chair: | N. Doorn |
| First Supervisor: | T. Verma |
| Second Supervisor: | V.J. Cortes Arevalo |
| External Supervisor: | M. Barten |
| Project Duration: | September 2022 - February, 2023 |
| Faculty: | Technology, Policy and Management, Delft |



TUDelft

# Preface

A trip to Paris with my friends in January 2022 sparked my interest on the topic of which I know now is called transport justice. The announcement of a low emission zone in the 10th arrondissement, a place that is dominantly inhabited by rich people, made me curious who benefit from them. This topic lingered on my mind in search of a thesis topic. In collaboration with my first supervisor, Trivik Verma, and Manus Barten, from Studio Bereikbaar, I am proud to have come up with the topic of this thesis. Additionally I would like to thank my second supervisor and chair, Juliette Cortes Arevallo and Neelke Doorn for their excellent feedback and support on my work. With great pleasure I worked on it for the past half year, gaining more understanding on spatial injustices, vulnerabilities and transport poverty. I am grateful for the fact that I was able to combine the topics of my interest and the use of quantitative methods into my thesis.

First and foremost, I would like to thank my friends and family, in particular my parents and my sisters, for supporting me unconditionally. I am both sad and excited that my time as a student has come to an end. Sad as I have thoroughly enjoyed it, and in particular my time as an Engineering and Policy student. I can only hope for career that will bring me such joy. But I am also excited to see what the future holds.

I immensely enjoyed writing this thesis, and hopefully you will enjoy it as much while reading it.

*Suzanne Ansems*
*Delft, February 2023*

# Abstract

Low emission zones tend affect different groups in society disproportionately and there is an urge to include injustices into policy making. Therefore, this research aims to aid the decision making process on recommending adequate locations for low emission zones and the evaluation of existing ones in the Hague based on the vulnerability to air pollution, in combination with vulnerability to transport poverty. Air pollution was operationalised by the NO2 concentration, and the transport poverty was operationalised by a neighbourhood-based mobility indicator that was corrected for proximity of key services to indicate the risk of social exclusion. A single- and multi-objective optimisation was employed. LEZ locations were optimised for either the total population or the total vulnerable population. For the application of the Hague, some neighbourhoods dominantly come forward from the analysis. These neighbourhoods have favorable transport poverty values and in combination with poor air pollution and a higher number of (vulnerable) population it is only logical that they come forward from the analysis. Also, results for the Hague show that shifting the priority from the total population to the total vulnerable population does not have a significant effect on the outcome, especially when employing the multi-objective problem formulation. This can be explained by the fact that the highest number of vulnerable people are present at the highest populated neighbourhoods. For the case of the Hague, when employing a single-objective problem formulation, shifting from the total population to the total vulnerable population also has insignificant effects on the solution set when considering transport poverty. However, when considering the air pollution objective, there is a significant change in solution set. This implies that when taking a multi-objective approach, optimising for both air pollution and transport poverty vulnerability, the priority within the population has only minor effects on the outcomes, in stead, the trade-off between the objectives is the determining factor in the solution sets for the case of the Hague. Nevertheless, this work proposes a way to transition to a just LEZ allocation and evaluation method, that includes socio-spatial vulnerabilities to air pollution and transport poverty by employing an optimisation tool.

# Contents

# List of Figures

# List of Tables

# 1 Introduction

Climate change contributes to an increase in air pollutants, which is one of the major health concerns in Europe (Orru et al., 2017). Air pollution is the biggest environmental health risk and if no action is undertaken, it is expected that there will be 400.000 premature deaths in the EU alone, attributed to air pollution (EEA, 2021). Therefore, in 2019, the European Green Deal was introduced, which aims for Europe to be the first climate neutral continent by 2050. At the same time, the European Green deal also entails that nobody is left behind, ensuring a just transition to a climate neutral continent (EU, 2022). Cities in particular play a huge role in climate change because of their high pollution-to-surface ratio. Whilst only covering 3% of the Earth, cities emit almost 72% of all greenhouse gasses (GHG), which is a form of air pollutants (Gronkiewicz-Waltz et al., 2020). For this reason, the European commission has initialised an EU Mission that aims for 100 climate neutral cities by 2030 (Borsboom et al., 2021).

One of the means to reduce greenhouse gas emissions, and thus air pollution in cities, is the implementation of low emission zones (LEZs). Above that, LEZs are considered to increase the cities' liveability and safety (Moore, 2021). LEZs have already been implemented in big cities in Europe such as Milan, Barcelona and Paris. The LEZ implementations vary per city, sometimes only highly pollutant cars are prohibited to enter and in another case all cars are prohibited. Additionally, charges or time-frames can be put in place (di Milano, 2015; Valdivia, 2020; Porter, 2022). Notwithstanding, research has also showed that LEZs could affect different groups in society disproportionately, as some marginalised groups can experience social exclusion because of them (Vrij and Vanoutrive, 2022). This implies that implementing LEZs is not a just policy for everybody, going against one of the European Green Deal pillars.

In means to facilitate a just transition to a climate neutral continent it is important to both consider the effects of pollution as the risk of social exclusion in the decision-making process for LEZ implementation. On one hand, LEZs are desired to reduce pollution and the corresponding health risks, but simultaneously, they affect different groups in society disproportionately. LEZs have benefits and burdens that are not homogeneously distributed over society. This research aims to contribute to make a shift in policy making for LEZs, by including socio-spatial vulnerabilities to health risks and unforseen effects of LEZs into the process, by means of a geo-spatial analysis for the case study of the Hague and in particular by means of single- and mutli-objective probem formulations. This is in line with the Engineering and Policy Analysis (EPA) program as it aims to aid the Municipality of the Hague in better decision making for their LEZs.

The thesis is structured as follows: in the second chapter the theoretical background is layed down, on which this thesis is build upon. In this chapter, the main research question and sub questions are introduced as well as the chosen case for which the methods are applied to. In chapter 3, the research approach is established and the research method is explained upon. In chapter 4 the spatial data is analysed. In chapter 5 the results of the single- and multi-objective problem formulations will be described and analysed. In the last chapters, the discussion with the main findings, posistioning in literature and recommendations for policy makers and future research will be discussed. In the conclusion, the sub-questions and the main research questioned will be answered.

# 2
# Theoretical Background

This chapter aims to give an overview of existing literature of the core concepts as well as a combination if them. These include climate change, air pollution and health implications, low emission zones, social justice, transport justice and transport poverty. After discussing these main concepts, the relevant academic knowledge gap can be identified.

## 2.1. Climate change, air pollution and health implications

The increase in industrial and economic growth, contributes to climate change and has led to a vast increase of air pollutants. However, it is not a simple cause-effect, instead a loop of enhancing cause-and-effects, as greenhouse gasses, a form of air pollutants, also contribute to climate change, as they enforce global warming, resulting in a vicious circle (D'Amato et al., 2014).

Exposure to air pollutants has major health implications. Research shows that an increased exposure to air pollutants increases the mortality and hospital admissions (Kampa and Castanas, 2008; Anderson et al., 2012; Seaton et al., 1995). Distinct relationships between particular air pollution and health effects remain slightly unknown as air pollutants are often not separable when relating them to health effects (Brunekreef and Holgate, 2002). Major health effects include effects on the respiratory system, such as (chronic) bronchitis and asthma (Künzli et al., 2000), or on the cardiovascular system (Brunekreef and Holgate, 2002). Other systems are also at risk, but less dominantly. These include the urinal, nervous and digestive system, as well as exposure during pregnancies (Kampa and Castanas, 2008).

The European Union has identified seven major air pollutants and exposure to these pollutants is not only bad people's health. Entire eco-systems are also targeted and negatively affected when exposed to air pollutants (Sicard et al., 2020):

1. Amomonia (NH3)
2. Nitrogen oxides (NOx)
3. Carbon monoxide (CO)
4. Particular matter (PMx)
5. Sulfur oxides (SOx)
6. Tropospheric ozone (O3)
7. Non-methane volatile organic compounds (VMVOCs)

Groups that are more vulnerable to adverse health effects because of air pollution can be distinguished. Women are considered to be more vulnerable than men because of higher cardiovascular risks, even when exposed to lower levels of air pollution (Tibuakuu et al., 2018). Especially pregnant and migrant women are more at risk. This is because of the adverse effects air pollution can have on pregnancy outcomes. Additionally, migrant women are more likely to have poor living conditions, that worsens the situations (Liang et al., 2019). Furthermore, age is a determinant in vulnerability. Children are particularly at risk because of their physiologic immaturity and development changes. They inhale more air per body weight, leading to higher risks than compared to grown-ups (Gordon et al., 2014). Also, elderly are more vulnerable because of their weakened immune system, as well as possible other underlying health conditions (Makri and Stilianakis, 2008; Medina-Ramon and Schwartz, 2008; Seaton et al., 1995). Also, ethnic minority groups have an increased risk for cardiovascular diseases, bringing them more at risk when exposed to air pollution (Tibuakuu et al., 2018). Additionally, ethnic minorities often live in poor living conditions and have limited health knowledge, increasing the risk even more (Liang et al., 2019). Lastly, low-educated an low-income people are more vulnerable because of the increased likeliness of poor living conditions, leading to more exposure to air pollutants (Makri and Stilianakis, 2008). An overview of the vulnerable groups can be seen in Table 2.1.

**Table 2.1:** Identified vulnerable groups to air pollution in literature and their corresponding metrics

| Socio-demographic vulnerable groups | Metric | Source |
|---|---|---|
| (pregnant) Women | Number of women | Tibuakuu et al. (2018); Liang et al. (2019); Makri and Stilianakis (2008); Medina-Ramon and Schwartz (2008) |
| Children | Number of people younger than 19 years | Gordon et al. (2014); Makri and Stilianakis (2008) |
| Elderly | Number of people older than 65 years | Seaton et al. (1995); Tibuakuu et al. (2018); Makri and Stilianakis (2008) |
| Ethnic Minorities (African American, Hispanic and Asian) | Number of ethnic minorities | Tibuakuu et al. (2018); Makri and Stilianakis (2008); Medina-Ramon and Schwartz (2008) |
| Low income | Number of low income people | Makri and Stilianakis (2008) |
| Low education | Number of low educated people | Makri and Stilianakis (2008) |
| People in bad health | Number of people with one or more long-term illnesses or conditions | Tibuakuu et al. (2018); Makri and Stilianakis (2008); Medina-Ramon and Schwartz (2008) |

## 2.2. Low emission zones

One of the interventions to decrease air pollution in cities is the implementation of low emission zones (LEZs). LEZs are places where access is limited because of the emissions from specific road vehicles (Holman et al., 2015). Cars are a big contributor to greenhouse gas emissions (Franco et al., 2013). In particular in Europe, where transport accounts for a quarter of all GHG emissions, of which 60.6 % came from cars. Additionally, car-related emissions have grown over the past decade (and European Environment Agency, 2022). This means that more than 15% from all GHG is car-related. Nitrogen dioxide is an important air pollutant that is related to vehicles. LEZs implementations are considered to decrease these vehicle-related air pollutants, and the assessment of LEZs ex-ante has been mainly focused on emissions modelling (Holman et al., 2015; Bernardo et al., 2021).

The effects of LEZ implementations are not always the same. Effects are city-specific and depend on the LEZ implementations and the enforcement's taken (Börjesson et al., 2021). Different LEZ dimensions, on which the LEZs change can be distinguished, as can be seen in Table 2.2. This makes comparability between cities' LEZ implementation difficult. In London, the overall improvement in air

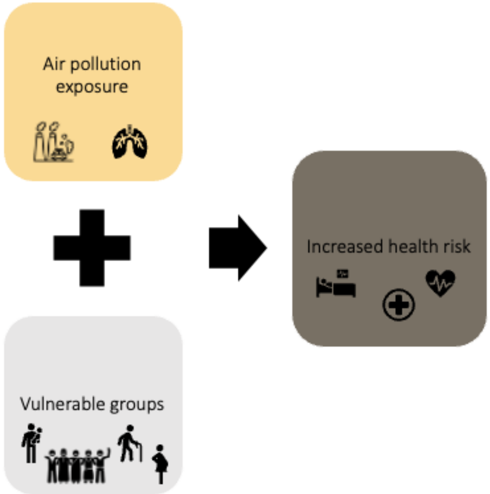



**Figure 2.1:** Graphic of the air pollution vulnerability. When vulnerable groups are exposed to air pollution, there is an increased health risk

quality was considered small after implementation of the LEZ in 2007(Ellison et al., 2013), and these insignificant results asked for stricter measures. Subsequently, London implemented ultra low emission zones (ULEZs) in 2019 in order to achieve the goals set by the EU quicker, prohibiting any vehicles that met the ULEZ standards unless they payed a daily charge, not only targeting heavy duty vehicles. Also in this case a significant decrease in air pollutants was not achieved, showing only negligible effects (Ma et al., 2021). Contradictory, Amsterdam, Munich and Milan showed a significant decrease in traffic-related air pollutants when comparing the air quality ex- and post-ante (Qadir et al., 2013; Panteliadis et al., 2014; Invernizzi et al., 2011).

**Table 2.2:** Identified LEZ dimensions: the temporal, spatoal, monetary and targeted vehicles and their description

| Dimension | Explanation |
|---|---|
| Temporal | Time frames that are put in place that indicate when the LEZ is active |
| Spatial | Demarcation of the area in which the LEZ is implemented |
| Monetary | Whether cars can enter the area when a charge is payed or if a fine is put in place |
| Targeted vehicles | What kind of polluting vehicles are prohibited to enter the area |

The distribution of benefits and burdens of LEZs over society is also not homogeneous. Research has proven that the LEZ implementation in Rome has had a bigger positive effect on the air quality in higher-income areas than in the lower-income areas (Cesaroni et al., 2012). Similar results came forward from a data-driven simulation model of Paris (Poulhès and Proulhac, 2021). The implementation of LEZs in Paris resulted in the smallest changes in air quality for the most vulnerable groups. All whilst the wealthier groups gained the most, but this group was also the group that had the worst air quality initially (Poulhès and Proulhac, 2021). Research also showed that the ULEZ in London targeted the lower-income areas significantly more, as these areas had a higher ratio of cars that were charged to enter the ULEZ. This relation did not hold as strongly for Brussels, where there was only a slightly higher ratio of polluting cars in lower-income areas than in higher-income areas that were targeted (Verbeek and Hincks, 2022). Furthermore, in Antwerp it was shown that their LEZ had undesirable social effects on some marginalised groups, such as elderly car dependent and vulnerable people who sensed social isolation because of the measure (De Vrij and Vanoutrive, 2022). Just as the assessment for the emissions, assessment methods for the social justice also differs per city.

## 2.3. Transport justice and transport poverty

To better understand the distribution of benefits and burdens of low emission zones, it is also important to discuss social justice, and in particular transport justice. Transport justice has emerged over the years, a term that applies social justice principles to urban transport system. Social justice is broadly discussed by the philosopher John Rawls, who focuses on the justice as fairness principle, opposing the utilitarian view (Rawls, 2004). Rawls's theory of justice entails two main principles: *liberty* and *equality*. His fairness principle entails that everyone should be treated with fairness and should experience the same basic liberties, equal opportunities and offering the most benefits to the less advantaged members of society. In line, only allowing inequalities if it facilitates the least-advantaged group the most (Rawls, 2004).

As discussed, transport justice relates to the urban transport systems in relation to the social justice theory. It captures the unfair distribution goods, accessibility for people and affordability of goods and services over society. More explicitly, it aims for greater equality whilst simultaneously eliminating injustices (Gössling, 2016). Recently, research on transport justice has been of more interest and there is a call to actively include transport justice in policy making (Verlinghieri and Schwanen, 2020; Martens, 2017; Pereira et al., 2017). The focus herein lays mainly on capturing the burdens of transport systems (Lucas et al., 2019).

Transport poverty is a recurring term in many articles in relation to transport justice, where there is no clear consensus on the meaning of it. Martens (2017) describes it as the lack of access to key resources, such as health, education, employment and social support that can eventually lead to social exclusion. Lucas et al. (2016) proposes a clear distinction of transport poverty as a subset of:

1. Mobility poverty, the lack of available transportation.
2. Accessibility poverty, the lack of accessibility to key services such as health, education and jobs.
3. Transport affordability, the inability to afford different transportation modes, for example, having a car or bike, fuel and public transportation fares.
4. Exposure to transport externalities, the more indirect burdens of transportation systems, such as air pollution, traffic accidents and noise pollution

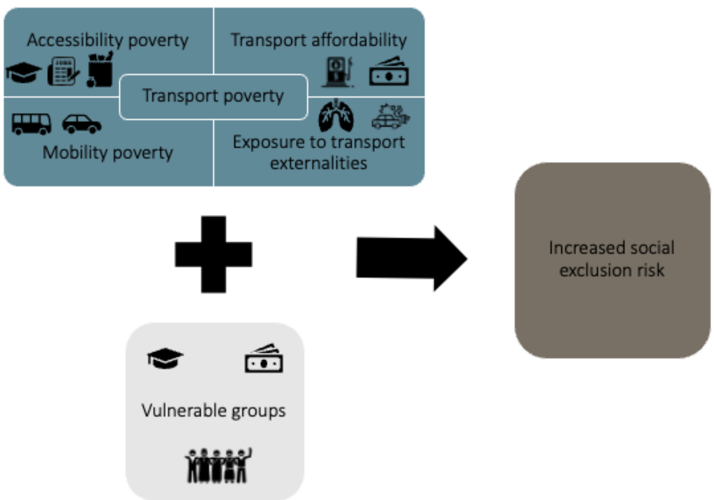



**Figure 2.2:** Graphic of transport poverty vulnerability. The four subsets of transport poverty and the vulnerable groups lead to an increased social exclusion risk

But generally, the definition that Lucas et al. (2016) gives is the following: 'An individual is transport poor if the transportation system can not let them satisfy their basic activity needs', which is in broad lines the same as the definition of Martens (2017). In this thesis, the definition of Lucas et al. (2016)

will be used, as their aim was to articulate the problem of transport poverty better, and this definition has been used in a lot of papers since then.

As Lucas et al. (2019) also mention, 'Assessing whether the benefits of transport are fairly distributed invariably implies the identification of population sectors and social groups who are most likely to experience transport disadvantage'. So, besides the subsets of transport poverty, it is also important to distinguish vulnerable groups in society, as can be depicted in Figure 2.2. In literature, these groups are well defined, as well as other transport poverty vulnerability metrics, as can be seen in Table 2.3. They are placed under their corresponding sub-section, according to Lucas et al. (2016). Below, more explanation on why certain groups are more at risk to actually experience transport poverty are mentioned.

#### Socio-demographic vulnerable groups regarding transport poverty

*Women* are identified as a group to be more at risk when considering the transport poor, as they are more inclined to experience sexual harassment while travelling. Not only the personal safety of women during transportation, but also the travel patterns of women is a reason for increased risk. Their travel pattern is often different as they take on different roles than men, usually being the prime responsibility in child care, as well as other domestic tasks, the travel behavior that corresponds to this is not always suitable for public transportation (Simcock et al., 2021; Lucas et al., 2019). Furthermore, *children* can also be considered as more vulnerable because raising children increases the cost of transportation services. This then implies a greater need for travel and, maybe more importantly, a greater reliance on the cars. Additionally, children are more dependent on other people in their transportation as their preferred transportation modes are usually not accompanied in the setting of urban environments, that are very focused on motorised modes of transportation (Simcock et al., 2021; Lucas et al., 2019). *People with health conditions* are also considered to be more vulnerable, as they are often discouraged from walking and cycling, making them more car-dependent (Simcock et al., 2021). In the same line, *people with mobility impairments* are more at risk when considering transport poverty as some mobility impairments make it impossible for them to use low cost transportation options such as walking, cycling and public transport (Simcock et al., 2021). This is often attributed to the fact that street design and public transportation is often is inaccessible for the more mobility impaired in society. Additionally, travel expenses are usually higher as they are dependent on the more expensive modes, such as taxis. *Elderly* are more at risk because they are often less mobile which makes active travel, such as walking and cycling, more difficult. They are also inclined to lose their driving license at some point, that decrease transport options even more, especially in more car-dependent areas (Simcock et al., 2021; Lucas et al., 2019). For *ethnic minorities*, in some cases, the barrier to use public transport is high, increasing the risk for transport poverty (Simcock et al., 2021; Lucas et al., 2019). People with a *low income* have less money to spend on transport and are it is less likely that they have a car, and if so, older and not very fuel efficient cars (Simcock et al., 2021; Lucas et al., 2019). Continuing on the notion of low incomes, a lot of pre-identified vulnerable groups are also more at risk of having a low income, increasing the risk of transport poverty even more for these people (Simcock et al., 2021).

## 2.4. Trade-offs in LEZ allocation

As discussed, the implementation of LEZs can be seen from different perspectives and considering different values. The different point of views are in line with common objectives in transportation projects, that include, equity, efficiency, environment and safety (Yannis et al., 2020). When considering air pollution and transport poverty, some groups in society can be more of risk because of their physiology or increased exposure to these air pollutants. One of the means to decrease these air pollutants is by implementing low emission zones (LEZs). The idea is that air pollutants are decreased because polluting vehicles are prohibited to enter certain areas. But a burden of these LEZs is that some groups in society can experience social exclusion because of them. This social exclusion is reflected in the notion of transport justice, which aims for the fair distribution of benefits and burdens of transport systems over society. Or to at least diminish existing inequalities in the transport system. Transport poverty relates to the possible social exclusion of groups in society because of lack of affordability, accessibility and mobility. Lucas et al. (2016) distinguishes four subsets within transport poverty and also notes that some groups in society are more vulnerable when considering transport poverty. This relation can be seen in Figure 2.2.

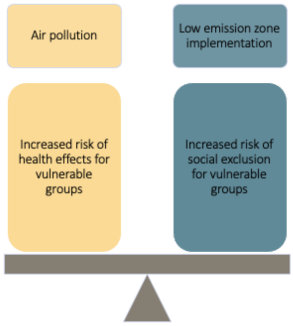



**Figure 2.3:** Visualisation of the trade-off between implementing LEZs and exposure to air pollution.

The socio-demogrpahic vulnerable groups have been identified for both air pollution and transport poverty. Notable is that these groups largely overlap. The only difference is that low educated people are only a vulnerable group to air pollution and people with mobility problems are a vulnerable group to transport poverty. This can be seen in Figure 2.4. Relating this to the integration of transport poverty and air pollution vulnerability, this means that the people who are more vulnerable to experience transport poverty also have an increased risk of adverse health effects when exposed to air pollution. The point here is that given the overlapping demographic subgroups, prioritising a reduction in air pollution is likely to disadvantage the transport poverty aspect. A neighbourhood with a lot of vulnerable subgroups to air pollution and also an increased air pollution might benefit from an implementation of a LEZs. But when implemented, they are more inclined to experience transport poverty and thus social exclusion because of this. This results in a trade-off that is visualised in Figure 2.3. On one hand, exposure to air pollution increases health risks, especially for vulnerable groups, and solving this air pollution by introducing an LEZ can result in social exclusion of these vulnerable groups.

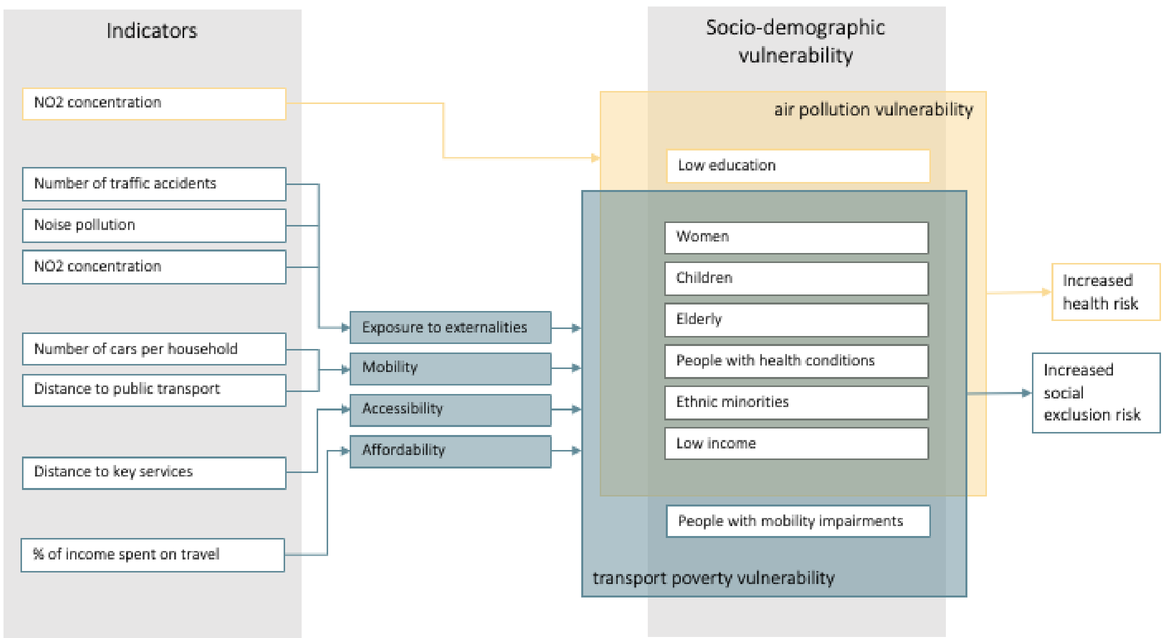



**Figure 2.4:** Conceptualisation of transport poverty and air pollution. The indicators of transport poverty and air pollution are visualised on the left, and the overlapping socio-demographic vulnerability is visualised on the right, as well as the increased risks

This trade-off implies that the decision-making process for the LEZ implementation is getting more complicated, taking into account multiple objectives, that of maximising air pollution reduction as well as minimising social exclusion as a result of transport poverty. An appropriate method to cope with these multiple objectives is the application of multi-objective optimisation techniques (Marttunen et al., 2017). The use of multi-objective optimisation on transport related issues is not uncommon and has been used for bicycle facility planning and commuters or for railway extensions (Yannis et al., 2020; Rybarczyk and Wu, 2010).

## 2.5. Knowledge gap and research questions

From the theoretical background, it becomes clear that Low Emission Zones are a policy lever that are used to reduce air pollutants, as well as aiming to make parts of the city more liveable. LEZ implementations tend to have a focus on air-pollution reduction. This focus neglects the fact that vulnerable groups to air pollution can be identified, who are more at risk when exposed to air pollutants. At the same time, research also shows that some groups in society can experience social exclusion as a negative effect of these implemented LEZs. In accordance, the urge to actively include transport justice in the implementation of policies has grown over the last decade (Verlinghieri and Schwanen, 2020; Martens, 2017; Pereira et al., 2017). Therefore, this research aims to develop an approach to include transport justice and social vulnerabilities in the decision-making process for LEZ allocation. To ensure a more just LEZ allocation process, it is important to identify vulnerable groups in relation to both air pollution and transport poverty. Coupling the vulnerability to air pollution and vulnerability to transport poverty has not been done before and can facilitate a just decision-making process, where the focus is on prioritising vulnerable groups in society. Therefore, this study aims to employ a framework that uses multiple-objectives, considering air pollution and transport poverty and their corresponding vulnerable groups, in order to identify adequate LEZ locations. Subsequently, also evaluation of existing low-emission zones can be carried out in relation to this as well. In line with this objective, The following research question can be established:

*How can the combination of social-spatial vulnerability to transport poverty and air pollution guide LEZ evaluation and implementation?*

The application of this research will be the Hague, and will elaborated on further. In line with the research objective and the main research question, sub-questions are formulated. They are listed below, accompanied by their research method. A global visual representation of this can be seen in Figure 2.5.

1. *How can the least vulnerable neighbourhoods to transport poverty be identified?*
   The aim is to identify critical neighbourhoods, based on vulnerability to transport poverty. To achieve this, the metrics will be used as described in Table 2.1. To operationalise these metrics, neighbourhood data from Den Haag in Cijfers will be used and, if necessary, it will be complemented using data from Centraal Bureau voor Statistiek or other data sources. From this analysis, neighbourhoods that are least vulnerable to transport poverty can be identified. These neighbourhoods would be fit to be a Low Emission Zone, when only considering the transport poverty aspect.
2. *How can the most vulnerable neighbourhoods to air pollution be identified?*
   The aim is to identify critical neighbourhoods, based on vulnerability and exposure to air pollution. To achieve this, the metrics will be used as described in Table 2.1. Additionally, the Hague is monitoring the nitrogen dioxide concentration in different locations in the city, this data is publicly available and will be used to map out the air pollution in the Hague per neighbourhood (DHN, 2022). From this analysis, neighbourhoods that are most vulnerable to air pollution can be identified. These neighbourhoods would be fit to be a Low Emission Zone when only considering the air pollution aspect.
3. *How can adequate LEZ locations be selected, considering both air pollution and transport poverty vulnerability?*
   The aim of this sub-question is to develop an optimisation algorithm that selects neighbourhood that are fit for LEZ locations, considering both the transport poverty aspect, as well as the air pollution aspect. The algorithm will be employed using different scenarios, that indicate different vulnerable groups to be considered, as well as a combination of them. The output of each scenario

is a set of neighbourhoods, where LEZs can be implemented based on the chosen objectives. Results of the multi-objective approach will be discussed and analysed, as well as results on feasibility will be discussed with decision makers on LEZs in the Hague. Discussing the results with the Hague will give insights in the limitations of the study, as well as the applicability to the Hague.

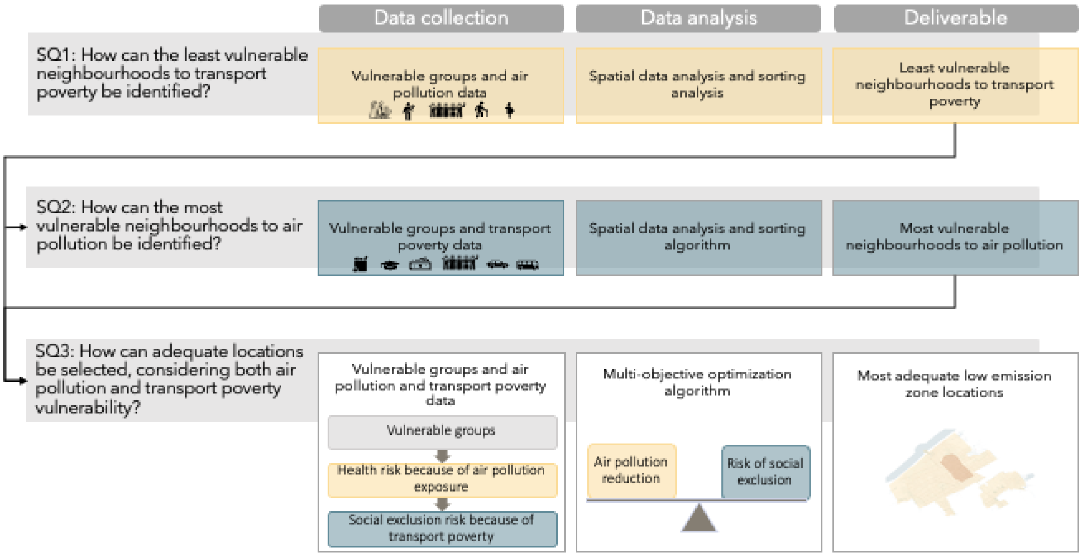



**Figure 2.5:** Research flow diagram

## 2.6. Scene Setting: the Hague

In the Netherlands, only four cities have implemented low emission zones (LEZs) that also target private transport, besides freight transport and havy duty vehicles (LEZ, 2022). These cities are Amsterdam, Arnhem, Den Haag and Utrecht. This private transport is important, as it captures that people doing their everyday needs, can be prohibited to enter into an area because of their polluting car. The Hague is one of these four cities and was therefore considered in the application for this research.

With more than half a million inhabitants, the Hague is the third biggest city in Netherlands, after Rotterdam and Amsterdam (CBS, 2022). The Dutch parliament is located in the Hague, as well as international judicial bodies, such as the International Court of Justice and the International Criminal Court. And with the presence of the peace palace, The Hague serves as the international city of peace and justice (DenHaag, 2017). This makes the Hague an interesting case for assessing just low emission zones.

Additionally, data-availability and quality is high for the municipality of the Hague. The Hague in numbers is a free open-access database that is managed by the municipality itself and offers a lot of data on neighbourhood-level.

### 2.6.1. Current Low Emission zone Policy

Currently, the Hague has a low emission zone that prohibits vehicles that run on diesel, whether private or freight transport, to enter the zone. However, it is dependent on the emission class. Emission classes indicate how polluting the vehicle is, and the higher the emission class, the lower the pollution of that vehicle. If the vehicle has an emission class of 4 or higher, it is allowed to enter the LEZ in the Hague. If the vehicle has an emission class of 3 or lower, it is not allowed to enter. The LEZ is visualised in Figure 2.6. When people do enter the LEZ with their polluting car, they are fined with 100 Euro (LEZ, 2022).

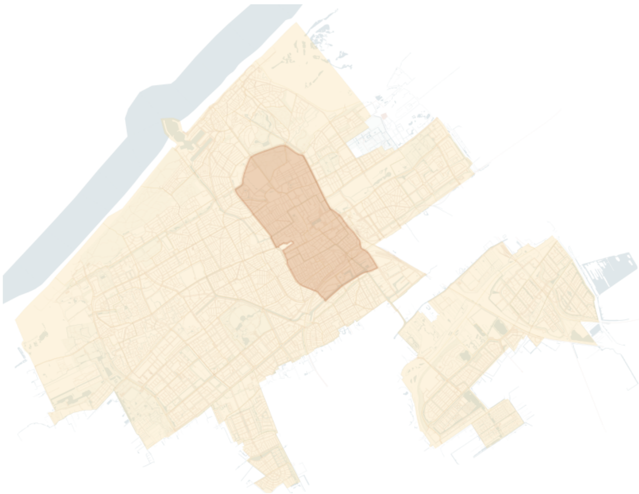


**Figure 2.6:** Current Low Emission Zone location in the Hague

In some cases, you are allowed to apply for an exemption, so that you can still enter the zone. Some vehicles that are exempt from not entering the zone are:

1. Diesel oldtimers that are older than 40 years old
2. Old diesel campervans whose owners live in the LEZ
3. Diesel cars with facilities to transport wheelchairs (wheelchair accessible vehicles)

### 2.6.2. Future Low Emission Zone Policy

In February 2022, the council passed a motion requesting to make plans to expand the current low emission zone by 2023 to reduce nitrogen deposition and improve air quality. In response, the municipality has commissioned more insight into the effect of an expansion of the existing low emission zone and/or zero-emission zone for city logistics on nitrogen deposition in Natura-2000 areas. In addition to reducing nitrogen emissions, environmental zones also have an effect on the overall air quality and the health of residents, entrepreneurs and visitors. Several scenario's for the expansion of the current low emission zone have been identified, among which the possibility to expand the low emission zone towards Scheveningen and to make the whole of the Hague a low emission zone. Concrete plans have yet to be established.

**Table 2.3:** Identified factors and corresponding metrics to transport poverty in literature

| **Socio-demographic vulnerable groups** | **Metrics** | **Source** |
|---|---|---|
| Women | Number of women | Simcock et al. (2021); Lucas et al. (2016, 2019); Pojani et al. (2017) |
| Households with children | Number of people younger than 19 years | Simcock et al. (2021); Lowans et al. (2021); Lucas et al. (2016, 2019) |
| People with health conditions | Number of people with one or more long-term illnesses or conditions | Simcock et al. (2021); Lowans et al. (2021); Lucas et al. (2016, 2019) |
| People with mobility impairments | Number of people with one or more physical impairments | Simcock et al. (2021); Lowans et al. (2021); Lucas et al. (2016, 2019) |
| Elderly | Number of people older than 65 years | Simcock et al. (2021); Lucas et al. (2016, 2019) |
| Ethnic minorities | Number of ethnic minorities | Simcock et al. (2021); Lowans et al. (2021); Lucas et al. (2016, 2019) |
| Low income | Number of low income households | Simcock et al. (2021); Lucas et al. (2019) |
| **Mobility poverty indicators** | | |
| Car ownership | Number of cars per address | Lucas et al. (2016, 2019); Groth (2019) |
| Bike ownership | Number of bikes per inhabitants | Martens (2013); Groth (2019); Lucas et al. (2016) |
| Access to public transport | Distance to nearest public transport stop | Lucas et al. (2016, 2019); Groth (2019) |
| **Accessibility poverty indicators** | | |
| Access to jobs | Number of accessible jobs | Lucas et al. (2016, 2019) |
| Access to health care | Distance to general practitioner | Lucas et al. (2016, 2019) |
| Access to local parks | Distance to local green | Lucas et al. (2016, 2019) |
| Access to secondary schools | Distance to secondary school | Lucas et al. (2016, 2019) |
| **Transport affordability indicators** | | |
| Travel expenses | Percentage of income spent on travel | Simcock et al. (2021); Lowans et al. (2021) |
| **Exposure to transport externalities metrics** | | |
| Air pollution | NOx concentration | Lucas et al. (2016, 2019) |
| Noise pollution | | Lucas et al. (2016, 2019) |
| Traffic accidents | Number of traffic accidents | Lucas et al. (2016, 2019) |

# 3

# Research Approach and Methods

## 3.1. Research Approach

In this chapter, the general approach will be established. Additionally, the sub-questions and their corresponding research method will be formulated, that in combination can answer the research question as formulated in the previous chapter. Finally, a research flow diagram will give insight into the whole research process.

This research aims to select a set of optimal LEZ locations for different scenario's, taking into account the air pollution vulnerability and transport poverty vulnerability. Additionally the air pollution and transport poverty will also be looked at in combination. Where the output will be an algorithm that can optimise LEZ locations. The research approach that is chosen to achieve this is the quantitative research approach. Creswell and Creswell (1994) describe that quantitative research is best suited in research that asks for the evaluation of the effectiveness of an intervention, in this case that is the air pollution and transport poverty. In combination with the research question that has been formulated correspondingly, this asks for a quantification both vulnerability to air pollution and transport poverty, combining it into a geo-spatial analysis. From the analysis, conclusions can be drawn on the impact and relations of the selected variables. A common limitation of the quantitative research approach is that it cannot indicate a clear cause and effect, it merely yields correlation (Queirós et al., 2017).

Furthermore, a single case-study approach will be taken in this research. As mentioned before, LEZ implementations and results are city-specific. For this research, the case will be used to generate a new optimisation model, both using and testing the conceptual theories of vulnerability to air pollution and transport poverty as described earlier. As Crowe et al. (2011) mention about case studies: 'it allows in-depth, multi-faceted explorations of complex issues in their real-life settings'. the Hague will be used as the case in this research, as a lot of spatial data is available, and they also announced an extension on the already implemented LEZ in the city centre, planning to make the restricted area bigger.

## 3.2. Research Methods

In this research, several methods are employed to answer the main research question. This section will outline the different phases. The process in this research is two-fold. First a spatial analysis will be carried out to explore air pollution vulnerability and transport vulnerability in the Hague. Subsequently, data used in this spatial analysis will be used in the spatial optimisation in an extensive experimental setup to get adequate neighbourhoods where an LEZ implementation is desired. The overall research flow diagram is depicted in 3.1.

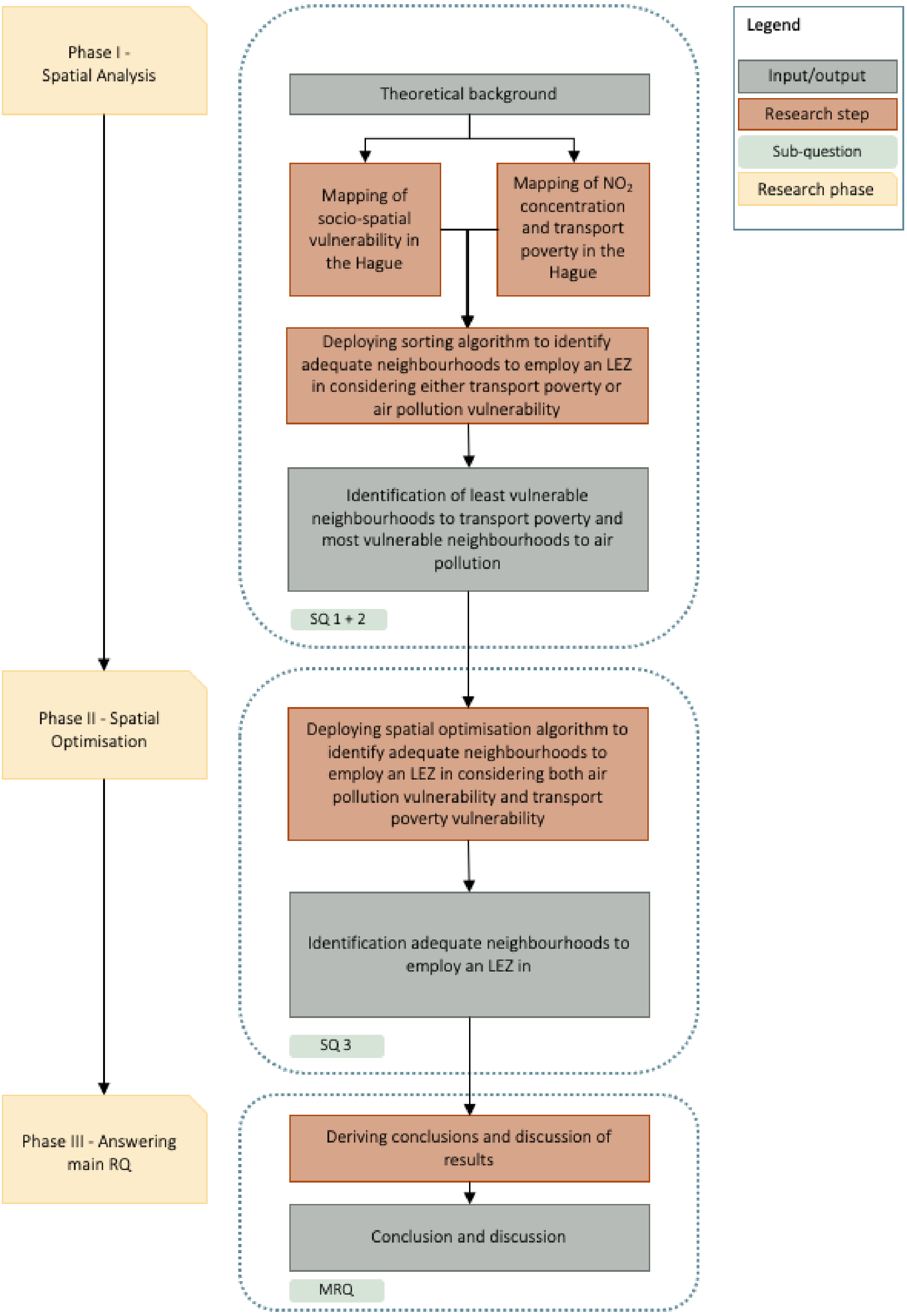



**Figure 3.1:** Research flow diagram

### 3.2.1. Spatial analysis

A spatial analysis will be conducted to gain insight in the geographical distribution of vulnerable groups to air pollution and transport poverty,as well as to air pollution and transport poverty itself. In order to perform the socio-spatial analysis, data needs to be retrieved and pre-processed. First, the air pollution and transport poverty vulnerability will be elaborated on, after which the operationalisation of transport poverty will discussed.

#### Air pollution and transport poverty vulnerability

As discussed in Chapter 2, vulnerable groups to air pollution and transport poverty are well defined in literature. These groups are the starting point of this research and will be used to identify the socio-spatial vulnerabilities to air pollution and transport poverty in the Hague. The operationalised vulnerable groups, as well as their corresponding data sources are listed in Figure 3.1. The identification of the different vulnerable groups suggests that many dimensionalities in inequalities exist when relating them to either air pollution vulnerability or transport poverty vulnerability, also implying that people might face them cumulatively. After all, someone can be an old women, indicating that they might be of more risk because of age and gender. Therefore, when combining the pre-identified vulnerable groups in relation to air pollution and transport poverty into two total vulnerable groups in relation to air pollution and transport poverty, the sum will be taken, possibly double counting some people might change the gravity of vulnerability towards this possible accumulation of vulnerabilities.

**Table 3.1:** Operationalisation of Socio-Demographic Vulnerable groups to air pollution and transport poverty

| Socio-demographic vulnerable groups | Metric | Data Source |
|---|---|---|
| (pregnant) Women | Number of women | Den Haag in Cijfers |
| Children | Number of people younger than 19 years | Den Haag in Cijfers |
| Elderly | Number of people older than 65 years | Den Haag in Cijfers |
| Ethnic Minorities (African American, Hispanic and Asian) | Number of ethnic minorities | Den Haag in Cijfers |
| Low income | Number of low income households | Den Haag in Cijfers |
| Low education | Number of low educated people | CBS |
| People in bad health | Number of people with one or more long-term illnesses or conditions | Den Haag in Cijfers |
| People with mobility impairments | Number of people with one or more physical impairments | Den Haag in Cijfers |

#### Transport poverty operationalisation

As discussed before, Lucas et al. (2016) introduces 4 subsets of transport poverty and underlines the notion that transport poverty is multi-dimensional concept. Additionally, the quantification of transport poverty has been done before. Often these measures are used that cover only an aspect one of the four subsets of transport poverty as discussed by Lucas et al. (2016). Kamruzzaman et al. (2016) discuss neighbourhood mobility-based measures that indicate the concept of transport poverty that explicitly relate to social exclusion. As social exclusion is one of the main burdens that is experienced by vulnerable groups in relation to LEZ implementation, this measure is taken as the starting point in the operationalisation of transport poverty. Neighbourhood mobility-based measures identify neighbourhoods where mobility options are limited by examining car-ownership and public transport accessibility. Car-ownership is a more dominant indicator for mobility and subsequently, a person's ability to participate in society. However, the indicator of car ownership has also been critiqued as the sole indicator for a mobility-based measure, the absence of a car does not need to lead to social exclusion when good public transport is also available in the area (Kamruzzaman et al., 2016). So, the combination of using car-ownership and public transport accessibility are an appropriate set of indicators for transport poverty. But this mobility-based indicator does not take into account the opportunities available in their area. People without access to a car may still have good mobility when considering good accessibility to key services (Kamruzzaman et al., 2016). Therefore, in this research, the transport poverty will be a composite indicator of car-ownership, public transport accessibility and accessibility to key services. Composite indicators are often used in supporting decision-makers, as they can summarise complex and multi-dimensional realities, such as transport poverty.

As described above, in this research a neighbourhood-based mobility measure composed of car-ownership and the public transport accessibility, that is corrected for proximity of services will be used. This section will describe in more detail how this indicator is composed. The first step in calculating the transport poverty indicator is to normalise the data of *average cars per address* and *public transport accessibility index*, so that the mean of these two metrics can be calculated, in order to say something about the mobility potential of the neighbourhoods. Now, there is a neighbourhood mobility level. The next step is to take the metrics about proximity of key services and to do the same, normalise them and take the mean. The metrics that are used are: *distance to supermarket*, *distance to practitioner*, *distance to secondary school* and *number of accessible jobs*. The inverse of first three was used so that all proximity measures move in the same direction. So a higher value indicates good proximity and thus good accessibility. The two key aspects of the neighbourhood-based mobility measure that is corrected for proximity of services are now calculated. Subsequently, the weighted average of the proximity measure is calculated for each neighbourhood by taking the neighbourhood value and dividing it by the sum of the proximity value for all neighbourhoods. Finally, this weighted average of the proximity is multiplied by the mobility level of each neighbourhood in order to achieve the final transport poverty indicator that will be used in this research. For the transport poverty value, the higher the value, the less transport poor a neighbourhood is.

**Table 3.2:** Operationalisation of transport poverty and air pollution

| Indicators | Metric | Data source |
|---|---|---|
| Car ownership | Number of cars per address | Den Haag in Cijfers |
| Access to public transport | Public transport accessibility index | Deltametropool |
| Access to jobs | Number of accessible jobs | Hans Voerknecht |
| Access to grocery stores | Distance to grocery store | CBS |
| Access to health care | Distance to general practitioner | CBS |
| Access to secondary schools | Distance to secondary school | CBS |
| Air pollution | NO2 concentration | Open data van de overheid |

### 3.2.2. Data retrieval

The spatial analysis and optimisation will be carried out using neighbourhood-level data. As described above, data is needed in for both the identification of vulnerable groups, as well as for the air pollution and transport poverty itself. This data needs to be collected from different data sources. First, general data sources will be discussed. In Table 3.1 and 3.2, the factors and their corresponding data sources are listed. The data sources that are used are the following:

1. National bureau of statistics (CBS)
2. Den Haag in Cijfers (DHc, 2022)
3. Open data van de Overheid
4. Job Accessibility data (Voerknecht, 2021)

### 3.2.3. Data pre-processing

In order to use the raw data as, the data needs to be processed. This involves data cleaning. Some issues arose when using the data from the aforementioned data sources. In some cases, missing values were indicated using an 'x', which caused the entire column to be interpreted as an object. In other cases, missing data, or null-data was depicted by a simple dot. Therefore, these 'x's' and dots were replaced by a 0, and subsequently, the column was converted to a float in order do other operations and analyses on the data. Additionally, some neighbourhoods are non-residential areas, such as parks, values for demographic data was 0 here. After cleaning, some data could be directly used in further steps of the data analysis. Some variables needed to be calculated using different metrics. These calculations are discussed below.

#### Air pollution

Den Haag monitors its air pollution, NO2 concentration, on 29 places in the city. It does not cover all neighbourhoods, therefore the NO2 concentration was inter- and extrapolated for the whole of den Haag. For this, the radial inter- and extrapolation was used. This resulted in a grid of the Hague, capturing a value for air pollution (NO2) in a grid of 50 by 50 meters. This air pollution was averaged per neighbourhood and saved.

#### Number of of low educated people

The number of low educated people was not directly available and needed to be calculated. This was done using data on how many people per neighbourhood per age category were low educated, and summing this to achieve the total number of low-educated people per neighbourhood.

#### Public transport accessibility index

For the access to public transport, the public transport accessibility index (PTAI) was used. This assessment of public transport accessibility was developed by Transport for London. It does not only take into account the distance to public transportation stops, but also the quality of these stops. PTAI scores are also computed for the Netherlands using a grid of 500 by 500 meters (Deltametropool, 2019). This data is used in combination with neighbourhood shapefiles of den Haag to aggregate this data on neighbourhood level, taking the mean of different PTAI values when necessary. The higher the value of PTAI, the better the public transport accessbility in the corresponding area.

### 3.2.4. Spatial optimisation

Building upon the data used in the socio-spatial analysis, a spatial optimisation algorithm was used. Spatial optimisation algorithms can result in optimal arrangement or allocation of infrastructures (Tong and Murray, 2012). Typically, the spatial optimisation approach entails a geographical problem as a specific objective. Common spatial optimisation problems are, for example, maximising the population covered or minimising the distance to a facility, often accompanied by a set of constraints that are implied by the decision-making process (Robinson et al., 2022). Spatial optimisation problems are common and different spatial features can be the focus herein. Focus can lie on distance, adjacency, connectivity, containment, intersection, shape, districts, and patterns (Tong and Murray, 2012). In the case of just LEZ allocation, two objectives are put in place that cover either the transport poverty or air pollution aspect, in relation to the socio-demographic vulnerability aspect. In this research, a genetic algorithm is used to generate optimal sets of neighbourhoods that considers these multiple objectives. Below, more information on approach for the single- and multiple-objective problem formulations will be discussed, as well as the formulation of the LEZ allocation problem will be discussed in more detail.

#### Single objective approach

For the single-objective approach, a simple sorting algorithm was employed that selects the desired number of neighbourhoods that maximises one of the two objectives. As the values for air pollution and transport poverty are static, a greedy algorithm did not need to be employed as the values of the air pollution or transport poverty did not need recalculation after selecting the LEZ location that yields the biggest gain when considering one of the objectives. The resulting neighbourhoods are neighbourhoods where either the air pollution vulnerability is highest or transport poverty vulnerability is the lowest. For the sake of this research only the top five of the neighbourhoods will be analysed.

#### Multi objective approach - genetic algorithm

For the multi-objective approach, a genetic algorithm is used to yield the optimal set of neighbourhoods. A genetic algorithm is a heuristic algorithm. Heuristic algorithms are frequently used algorithms that yield good solutions to either optimisations or search problems. They are based on biological evolutionary processes, such as crossover and mutations and selections. Genetic algorithms are commonly used in spatial optimisation and perform well when a Pareto optimum needs to established in order to deal with conflicting objectives, as is the case in this research (Tong and Murray, 2012). In this research the Non-Sorting Genetic Algorithm II (NSGA-II) is used for the multi-objective optimisation problem using the pygmo package in python. This algorithm is widely used for multi-objective optimisation problems. It also finds many application in spatial planning, such as optimal sensor placements or forest planning (Tong and Murray, 2012). NSGA-II yields a set of non-dominant results, where each set of solutions represents a compromise between the multiple selected objectives. Solution sets are a Pareto optimum, where a neighbourhood cannot be interchanged by another neighbourhood, as it will decrease one of the objectives. Any solution that is not in the Pareto optimum, is an inferior solution that can be substituted by another solution that performs better when considering the multiple objectives Tong and Murray (2012).

### Problem formulation

The approach that is taken in this research is based on that of Robinson et al. (2022). In that research, an optimal set of sensors was placed, maximising the coverage of different vulnerable groups, as well as a combination of them. This approach can be translated to the case of LEZ allocation by some minor adjustments. Similar as in the study of Robinson et al. (2022), the weighted average of the objectives are calculated, to focus on the benefits for the given demographic population of each possible LEZ location. The different demographics that are considered are listed in Table 3.1 In this case, two different problem formulations, considering the two different objectives need to be formulated. These formulas are deployed in both the single-objective as the multi-objective problem formulations:

$$APgain = \frac{\sum_{i \in I} w_i AP_i}{\sum_{i \in I} w_i} \tag{3.1}$$

$$TPgain = \frac{\sum_{i \in I} w_i TP_i}{\sum_{i \in I} w_i} \tag{3.2}$$

$APgain$ = weighted normalised value of air pollution in given neighbourhood
$TPgain$ = weighted normalised value of transport poverty in given neighbourhood
$AP_i$ = value of air pollution in given neighbourhood
$TP_i$ = value of transport poverty in given neighbourhood
$w_i$ = number of people (of vulnerable demographic) in given neighbourhood

Where the w is the the number of people in that neighbourhood for a given demographic. So, in neighbourhoods that have a higher weighted average for a given demographic end up with a higher value for both APgain and TPgain. So the benefit for the given demographic will be greater when the number of people of that given demographic is higher in a neighbourhood. Similarly, neighbourhoods with a lower number of a given demographic when compared to the total sum for that demographic over the whole of the Hague, are given a lower value for either AP- or TPgain. APgain indicates the weighted normalised air pollution, TPgain indicates the weighted normalised indicator for transport poverty. The conceptualisations for APgain is formulated as maximising the air pollution, assuming that when the air pollution is higher, the gain of air pollution reduction will also be greater. To achieve comparable values of the gain within air pollution and transport poverty values, the values for air pollution and transport poverty are normalised before calculating the APgain and TPgain. In this research, different contrasting conceptualisations of the LEZ allocation will be estimated and analysed for both the air pollution and the transport poverty objective, as well as a combination of them, that is the multi-objective problem formulation. Multi-objective problem formulation was run for 1e6 iterations, and for 10 times. Subsequently, unique solution sets were saved and analysed, as will be discussed in Chapter 5.

### Experimental setup

This section is attributed to what kind of scenario's were run, for both the single-objective as the multi-objective approach. For both single-objective problem formulations, different problem formulations are run, yielding a single solution set of 5 neighbourhoods that prioritises either the total population, each of the vulnerable demographic groups, as well as a combination of them. This results in nine different solution sets for the air pollution objective, as well as for the transport poverty objective, each one prioritising a different group. For the multi-objective problem formulations, two scenarios will be run, yielding solution sets that either prioritise the total population or the total vulnerable population. An overview of the experimental setup can be viewed in Table 3.3.

**Table 3.3:** Experimental setup: the objective, corresponding demographic that the objective is prioritised for, and the number of unique solutions for solution set sizes of 1, 3 and 5 neighbourhoods

| **Objective** | **Demographic** | **Number of unique solutions 1 neighbourhood** | **Number of unique solutions 3 neighbourhood** | **Number of unique solutions 5 neighbour-hoods** |
|---|---|---|---|---|
| Transport poverty vulnerability | Total population | - | - | 1 solution set |
| | Women | - | - | 1 solution set |
| | Children | - | - | 1 solution set |
| | Elderly | - | - | 1 solution set |
| | Ethnic minorities | - | - | 1 solution set |
| | Low-income people | - | - | 1 solution set |
| | People in bad health | - | - | 1 solution set |
| | People with physical impairment | - | - | 1 solution set |
| | Total vulnerable population | - | - | 1 solution set |
| Air pollution vulnerability | Total population | - | - | 1 solution set |
| | Women | - | - | 1 solution set |
| | Children | - | - | 1 solution set |
| | Elderly | - | - | 1 solution set |
| | Ethnic minorities | - | - | 1 solution set |
| | Low-educated people | - | - | 1 solution set |
| | Low-income people | - | - | 1 solution set |
| | People in bad health | - | - | 1 solution set |
| | Total vulnerable population | - | - | 1 solution set |
| Transport poverty and air pollution vulnerability | Total population | 2 solution sets | 29 solution sets | 55 solution sets |
| | Total vulnerable population | 2 solution sets | 22 solution sets | 49 solution sets |

# 4

# Spatial Data Analysis

In this chapter, the spatial data analysis will be performed. First, the analysis on the socio-demographic vulnerability will be done, thereafter, the analysis for the transport poverty will be done, as well as an analysis on the relation between transport poverty and vulnerability.

## 4.1. Air pollution

Figure 4.1 shows the distribution of the NO2 concentration. The values per neighbourhood are the averaged values for that neighbourhood. The lowest averaged neighbourhood value for NO2 concentration is 16.56 µg/m3 and the highest averaged neighbourhood value is 31.71 µg/m3. As can be seen, there are 3 more dominant areas that have a higher air pollution. These are situated near Scheveningen beach, Holland Spoor and the central station. The value of NO2 concentration is lower for more eastern and western located neighbourhoods.

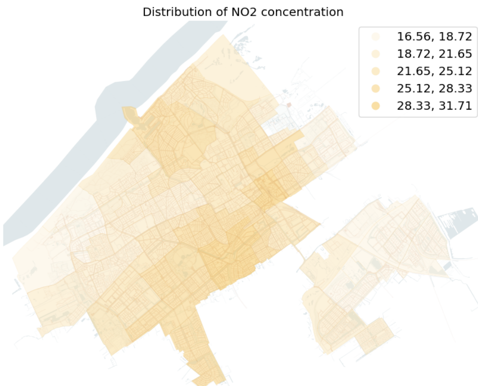
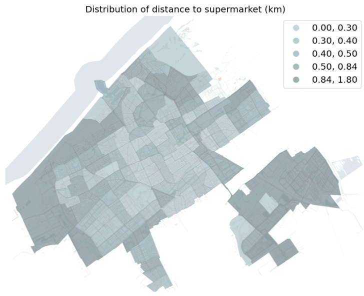



**Figure 4.1:** Distribution of NO2 concentration in the Hague

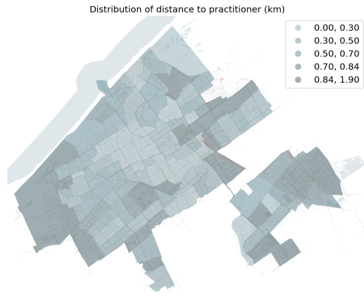
## 4.2. Transport poverty

Figure 4.2 shows the distribution of all the indicators that are taken into account in the neighbourhood-based mobility measure, that is corrected for the accessibility. This value is used for the operationalisation of transport poverty in the Hague.

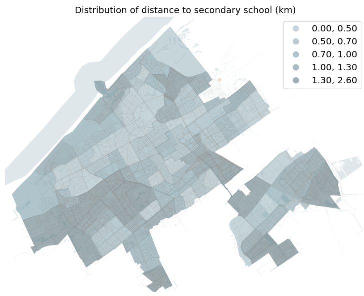
In Figure 4.2a, the distribution of distance to the supermarket is mapped. Noticeable is that the value for distance to the supermarket increases when moving away from the centre and increases to a maximum of 1.80 km.



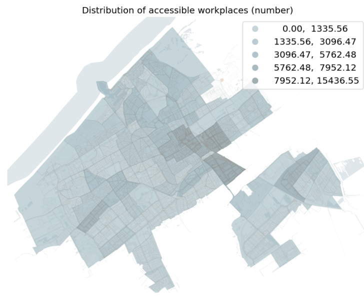

**(a)** Distribution of distance to supermarket (km)



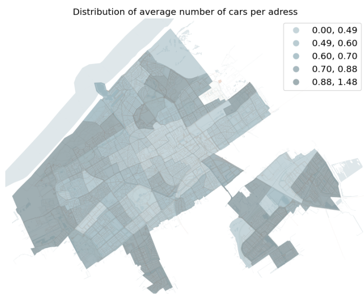

**(b)** Distribution of distance to practitioner (km)



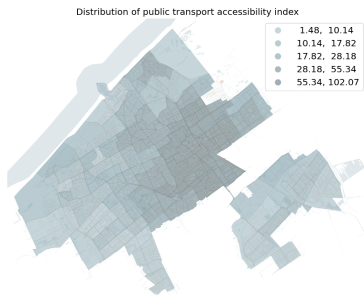

**(c)** Distribution of distance to secondary school (km)




**(d)** Distribution of accessible working places




**(e)** Distribution of average number of cars per address




**(f)** Distribution of public transport accessibility index

**Figure 4.2:** Figures showing the distribution of all transport poverty indicators

Figure 4.2b shows the distribution of distance to practitioner. Noticeable is that the values are dominantly low in the centre of the city and increase towards the outsides of the centre, with a dominantly higher distance in the south-west of the city.

Similarly, Figure 4.2c shows the distance distribution to secondary school. When looking at the distribution of distances to the supermarket, practitioner and secondary school, what stands out is that the maximum value of the distance to secondary school is significantly higher than that of the distance to practitioner and supermarket. Respectively 2.60 km compared to 1.80 and 1.90 km.

The distribution of accessible working places is mapped out in Figure 4.2d. Values range from 1335 accessible work places to 15436 work places. This is a significant increase in workplaces when relating neighbourhoods. The neighbourhoods with a higher number of accessible workplaces are located near the central station and lower values are more dominantly present in neighbourhoods located towards the outer edges of the city. Indicating less work places being available from the more outer edges of the city.

Figure 4.2e shows the distribution of average number of cars per address. Values range from 0 average cars per address to 1.48 average cars per address. Noticeable is that the values are lower in neighbourhoods located in the centre of the city and increase when going to neighbourhoods located at the outer edge of the city.

Another mobility-based indicator that is the distribution of the transport accessibility index, is depicted in Figure 4.2f. Values range from 1.48 to 102.07. Lower values are more dominantly present in neighbourhoods located at the outer edges of the city. Higher values are concentrated in neighbourhoods in the centre of the city. Noticeable is that the 4.2e and 4.2f are an inverse of each other, places where car-ownership is lower, public transport accessibility is higher, and vice versa.

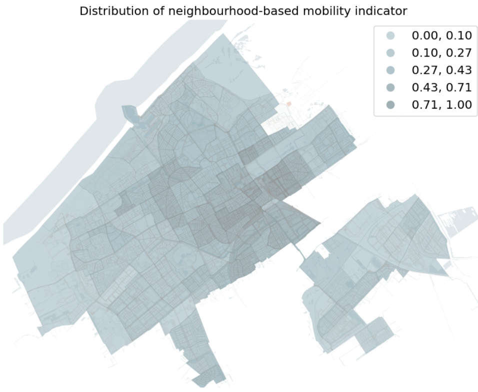



**Figure 4.3:** Distribution of transport poverty indicator in the Hague

Figure 4.3 shows how the pre-defined neighbourhood-based mobility that relates to social exclusion is distributed over the Hague. Note that a higher value for the transport poverty indicator means that a neighbourhood is less transport poor. As can be seen, the higher values are located near the centre, indicating the least transport poor neighbourhoods. Lower values are more situated towards the outer edges of the city.

## 4.3. Demographic distributions

This section will report on the spatial distributions of the pre-identified vulnerable groups to transport poverty and air pollution, as well as the total population and the total vulnerable populations.

### 4.3.1. Total population

The distribution of the total population over the Hague is mapped out in Figure 4.4. Values range from 0, indicating non-residential areas such as parks, to 16300 people. Neighbourhoods with a higher and lower population are fragmented over the city.

### 4.3.2. Vulnerable groups in relation to air pollution and transport poverty

Figure 4.5 shows the distribution of overlapping identified groups that are more at risk when considering transport poverty and air pollution health effects.

The distribution of the number of females over the Hague is shown in Figure 4.5a. The maximum number of females living in a neighbourhood is 8327. In general, neighbourhoods that have a higher number of total population also have a higher number of female population.

Figure 4.5b shows the distribution of number of children over the Hague. The maximum value of number of children in a neighbourhood is found to be 3595. Similarly as for the distribution of females, the distribution of children also largely follow the distribution of total population. Neighbourhoods that have a higher number of total population also tend to have a higher number of children.

The distribution of the number of elderly over the Hague is shown in Figure 4.5c. The neighbourhood with the highest number of elderly has 2822 number of elderly. Also here, the neighbourhoods that have a higher number of total population also tend to have a higher number of elderly.

Figure 4.5d shows the distribution of number of low-income people over the Hague. The neighbourhood with the highest number of low-income people has up to 8475 number of low-income people.

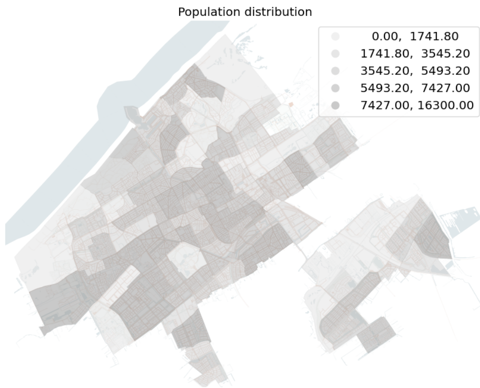



**Figure 4.4:** Distribution of total population

Noticeable is that unlike the other distributions of vulnerable people over the Hague, the distribution of low-income people follows the total population distribution in a lesser extend. Neighbourhoods that have a high number of total population do not always indicate a neighbourhood with a higher number of low-income people. The other way seems to be true, a neighbourhood with a higher number of low-income people does tend to indicate a higher number of total population for that same neighbourhood.

The last distribution for overlapping vulnerable groups is depicted in Figure 4.5e. In this figure, the distribution of the number of ethnic minorities is mapped out in the Hague. The neighbourhood with the maximum number of ethnic minorities has 13152 number of minorities. This number stands out when comparing it to the other maximum number of a given vulnerable group. Similarly to the distribution of number of low-income people, neighbourhoods with a higher number of minorities also tend to have a higher number of total population, but the reverse is not true. A higher number of total population does not indicate a higher number of minorities.

### 4.3.3. Vulnerable groups in relation to air pollution

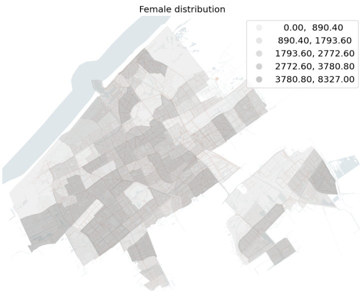
Besides the overlapping vulnerable groups in relation to transport poverty and air pollution, there is also also an additional vulnerable group for transport poverty. This group is the group of low educated people. The distribution of the this group over the Hague is visible in Figure B.2a. As can be seen, some neighbourhoods that have a higher value for the total number of people also have a higher value for low educated people. But this relationship does not always hold. Looking at the more northern-located neighbourhoods at the shore, some neighbourhoods have a higher number of total people, but these neighbourhoods do not light up from the number of low-educated distribution. Additionally, the maximum value for the number of low-educated people is 5960.

Figure 4.6 shows the summed value of all vulnerable groups in the Hague. Here, the value is only indicative of how the neighbourhoods will be weighted in the single- and multi-objective problem formulations.

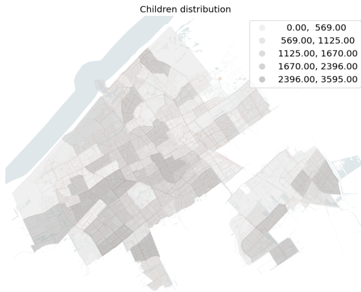
### 4.3.4. Vulnerable groups in relation to transport poverty

Similarly as mentioned above, there is also also an additional vulnerable group for transport poverty. This group is the mobility impaired. The distribution of the number of mobility impaired people over the Hague is visible in Figure 4.7a.

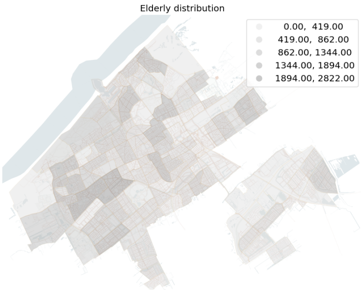
Figure 4.7 shows the summed value of all vulnerable groups in the Hague. Here, the value is only indicative of how the neighbourhoods will be weighted in the single- and multi-objective problem formulations.



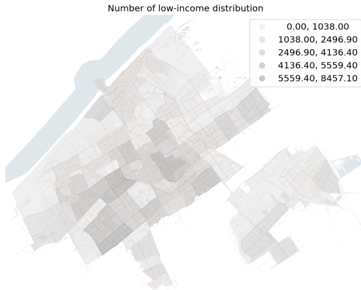

**(a)** Distribution of number of females



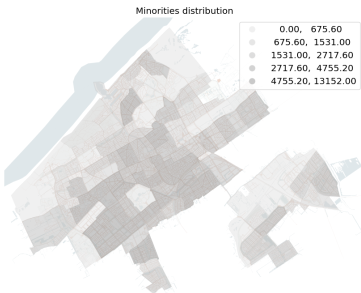

**(b)** Distribution of number of children




**(c)** Distribution number of elderly

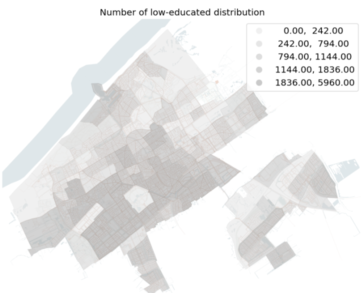



**(d)** Distribution of number of low-income people

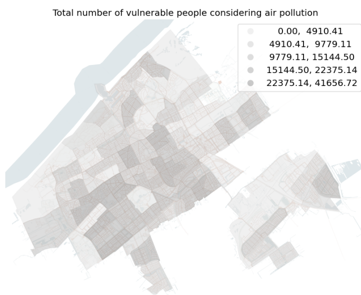



**(e)** Distribution of number of minorities

**Figure 4.5:** Figures showing the distribution of all overlapping vulnerable groups for air pollution and transport poverty

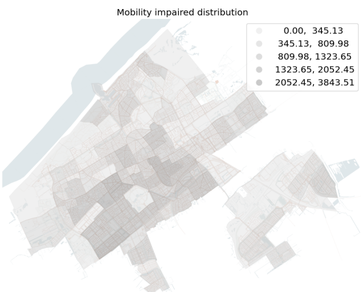



**(a)** Distribution of number of low educated people

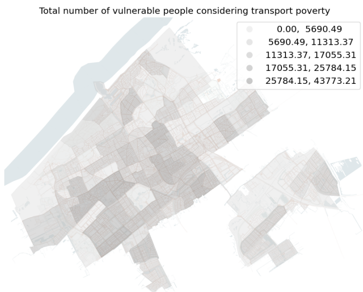



**(b)** Distribution of total number of vulnerable people considering air pollution

**Figure 4.6:** Figures showing the distribution of unique group for air pollution and all groups combined for air pollution




**(a)** Distribution of number of mobility-impaired




**(b)** Distribution of total number of vulnerable people considering transport poverty

**Figure 4.7:** Figures showing the distribution of unique group for transport poverty and all groups combined for transport poverty

# 5

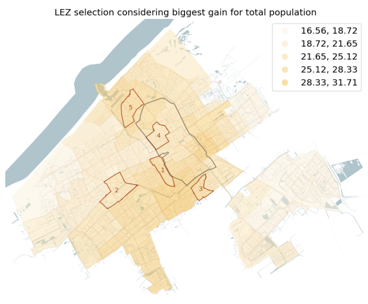
# Single and Multi-Objective Problem Formulations: an Analysis and Evaluation of LEZ allocation

In this chapter, the results of the single- and multi objective problem formulations will be discussed. First, the single-objective problem formulations will be discussed, shedding light on either optimising for air pollution and their vulnerable groups, or optimising for transport poverty and their vulnerable groups. A detailed experimental setup and the operationalisation of both transport poverty and air pollution are described in Chapter 3. The results will be discussed in the sections below. The results of both the single- and multi- objective problem formulations are supported using parallel plots. These parallel plots

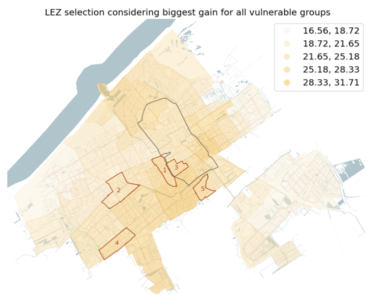
## 5.1. Single-Objective Problem Formulation

For the single-objective problem formulation, two single objectives are considered, as described in the earlier chapter. The problem is being optimised to prioritise (a combination of) vulnerable demographic groups in relation to the air pollution or transport poverty aspect. Additionally, the problems will also be optimised for the total population to evaluate the shift in LEZ allocation when not prioritising different demographic groups, but to take a utilitarian approach where the majority of the demographic will be prioritised. First, the results of air pollution objective will be discussed, after which the results for the transport poverty objective will be discussed.

### 5.1.1. Air pollution objective




**(a)** LEZ selection for air pollution objective, considering total population




**(b)** LEZ selection for air pollution objective, considering total vulnerable population

**Figure 5.1:** Figures showing the LEZ selection for all total population and total vulnerable population

Figure 5.1 shows two scenarios for the LEZ allocation with respect to the air pollution objective. Figure 5.1a shows the 5 best neighbourhoods to assign an LEZ, considering the biggest benefit for the total number of people living in that neighbourhood. The numbers indicate the biggest benefit, so 1 will yield the biggest benefit for the most people, after that number 2 etc. Similarly, Figure 5.1b shows the best LEZ locations considering the biggest benefit for the total number of vulnerable people. Noticeable is that for both the total population as the total vulnerable population, the neighbourhoods that yield the two biggest gains overlap. Additionally for both the solution for prioritising the total population, as well as for the solution set for prioritising the total vulnerable population, one neighbourhood that is in the solution set is also already in the current LEZ as situated in the Hague.

Results also vary when only prioritising a subgroup in the vulnerable population. In Appendix B, the results of prioritising each vulnerable demographic separately can be found.

For the selection of LEZ neighbourhoods that prioritise the total vulnerable population, Figure 5.2 shows numbers of vulnerable demographic in all the neighbourhoods, as well as the total population. The selected neighbourhoods are depicted by bright colours, with their corresponding name in the legend. All other neighbourhoods are depicted in grey and offers a view on how the selected neighbourhoods perform in covering the vulnerable demographic groups, as well as the total population. Additionally, the value of NO2 gain is also mapped out in the parallel plot. The parallel plots are plotted in such a way that the direction of preference is the same for all. Noticeable from this figure is that the selected neighbourhoods, when prioritising air pollution for the vulnerable population, do not have the highest value for the NO2 gain. Additionally, Leyenburg and Schildersbuurt-West are neighbourhoods that have, besides the highest total number of vulnerable people, the highest number for the total population. Schildersbuurt-Noord is a neighbourhood that has a lower total population in comparison to the other neighbourhoods in the solution set as well as some other neighbourhoods, but does have a high number of total number of vulnerable people. But overall, for the selected neighbourhoods, values for NO2, population, as well as the total vulnerable population are significantly higher when relating them to all the other neighbourhoods in the Hague.

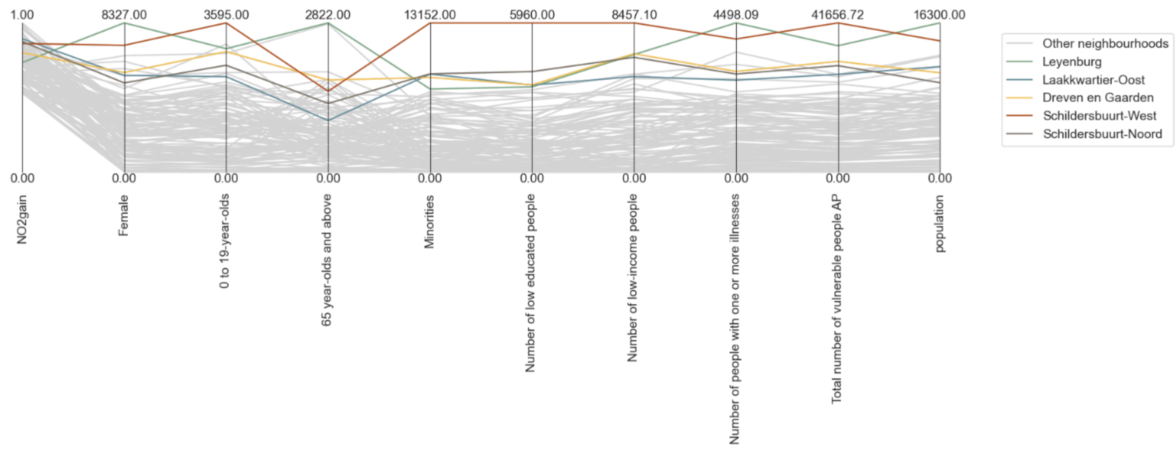



**Figure 5.2:** Parallel plot for the air pollution objective considering total vulnerable population. Extremes are positioned such that the higher values are always more desirable for each indicator.

### 5.1.2. Transport poverty objective

Similarly as described above, Figure 5.3 shows two scenarios for the LEZ allocation with respect to the transport poverty objective. Figure 5.3a shows the 5 best neighbourhoods to assign an LEZ, considering the biggest benefit for the total number of people living in that neighbourhood. The numbers indicate the biggest benefit, so 1 will yield the biggest benefit for the most people, after that number 2 etc. Similarly, Figure 5.3b shows the best LEZ locations considering the biggest benefit for the total number of vulnerable people. Noticeable is that for both the total population as the total vulnerable population, the solution set largely overlaps. Only the fourth neighbourhood is different, Indicating that the first three neighbourhoods are the same when prioritising either the total population or the total vulnerable population. When comparing these figures to those of the air pollution objective solution sets, the first thing that stands out is that the solution sets are more clustered together, and less fragmented


**(a)** LEZ selection for transport poverty objective, considering total population

**(b)** LEZ selection for transport poverty objective, considering total vulnerable population

**Figure 5.3:** Figures showing the LEZ selection for all total population and total vulnerable population

over the Hague.

Figure 5.4 depicts the parallel plot for the transport poverty objective prioritising the total vulnerable population. The selected neighbourhoods are depicted by bright colours, with their corresponding name in the legend. All other neighbourhoods are depicted in grey and offers a view on how the selected neighbourhoods perform in covering the vulnerable demographic groups, as well as the total population and the transport poverty for each neighbourhood. The parallel plots are plotted in such a way that the direction of preference is the same for all. Schildersbuurt-Noord is a neighbourhood that has has a more average value for the transport poverty indicator, indicating that this is not per se a neighbourhood that would be most transport poor in relation to other neighbourhoods in the Hague, but because this neighbourhood has the most vulnerable people living here, it is part of the solution set.

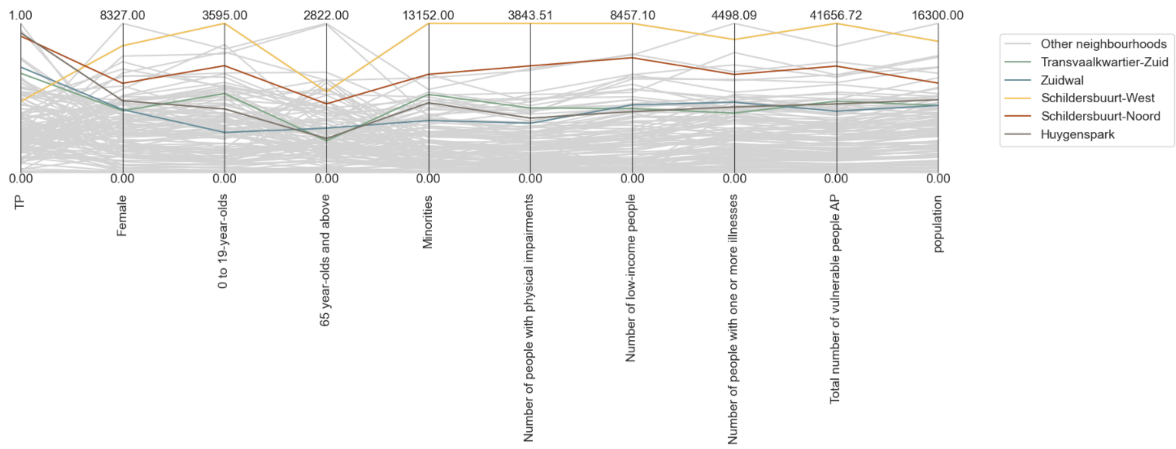


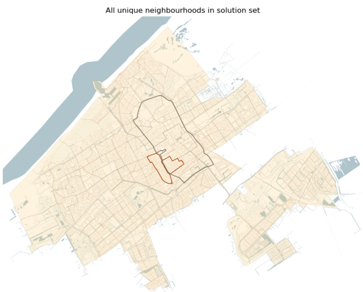

**Figure 5.4:** Parallel plot for the transport poverty objective considering total vulnerable population. Extremes are positioned such that the higher values are always more desirable for each indicator.

## 5.2. Multi-Objective Problem Formulation

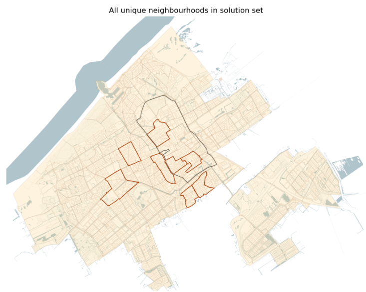
This section will elaborate on the results coming from the multi-objective problem formulation, where the objectives of air pollution and transport poverty will be combined, prioritising the vulnerable population or the total population, in the search for an adequate solution set that balances these objectives. The results were generated with a NSGA-II algorithm and different scenarios are selected to also vary the solution set size between a solution set of one, three and five neighbourhoods. The NSGA-II was run for 1e6 iterations, based on trial and error and a visual evaluation of the (unique) solution sets. The number of unique solutions in the Pareto optimum solution set increases with the desired number of neighbourhoods in the solution set, as will be discussed. First, the multi-objective problem formulation prioritising the total population will be discussed for a solution set of one, three and five neighbourhoods, after which the shift to prioritising the total vulnerable population will be discussed for the same solution set sizes.

Figure 5.5a shows what unique neighbourhoods come forward from the multi-objective problem formulation when prioritising the total population. The unique neighbourhoods that come forward for the different sizes of solution sets increase exponentially. For a solution set of only one neighbourhood, the algorithm has a Pareto solution set of only two neighbourhoods, as can be seen in Figure 5.5a. When shifting to a solution set of three and five neighbourhoods the number of unique neighbourhoods in the solution sets increase to 20 and 55 neighbourhoods correspondingly. This indicates that when the desired number of LEZs in a solution set increases, the problem becomes more ambiguous. What stands out as well is that the unique neighbourhoods, especially when looking at the solution set of one and three neighbourhoods, are mostly located in the centre of the city. When looking to the unique neighbourhoods in the solution set of five neighbourhoods, the neighbourhoods become much more spread over the city.

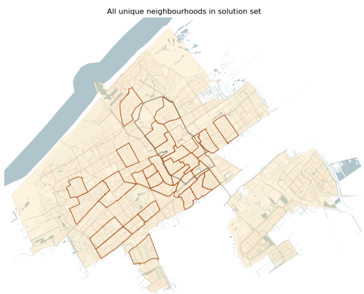
Additionally, when comparing the neighbourhoods to the current LEZ, there is only a small overlap between the allocated LEZs and the LEZ as currently situated in the Hague. This is especially the case for the solutions sets of one and three neighbourhoods.




**(a)** Unique neighbourhoods in solution sets for set of 1 neighbourhood considering total population




**(b)** Unique neighbourhoods in solution sets for set of 3 neighbourhoods considering total population



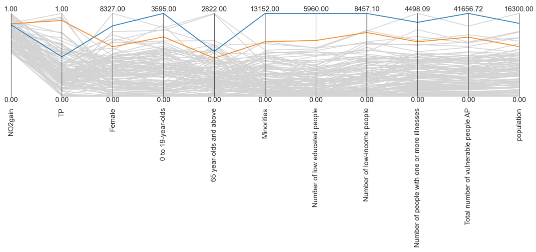

**(c)** Unique neighbourhoods in solution sets for set of 5 neighbourhoods considering total population

**Figure 5.5:** Figures showing the unique neighbourhoods in the solution sets for 1, 3 and 5 neighbourhoods considering total population

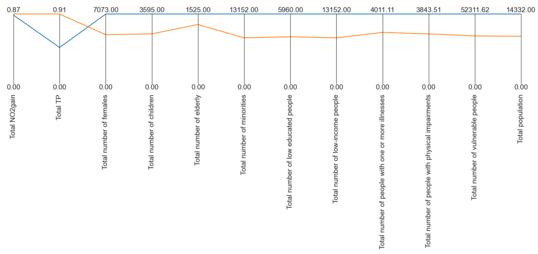
A similar trend as described above is visible when shifting to prioritising the total vulnerable population and can be seen in Appendix B.1. When going from a solution set of one neighbourhood to that of three and five neighbourhoods, the unique neighbourhoods in the solutions set increase exponentially.

### 5.2.1. Solution set 1 neighbourhood

Figure 5.6 shows two figures that give insight into the outcomes of prioritising the total population for both air pollution and transport poverty. As described above, only 2 neighbourhoods are present in the solution set: Schildersbuurt-Noord and Schildersbuurt-West. Figure 5.6 shows two parallel plots, on the left all the unique neighbourhoods in the solution set are plotted against all other neighbourhoods in the Hague to see how the selected neighbourhoods perform. On the right, the performance of the unique solution sets are plotted to compare the performance between the solution sets. When looking at the parallel plot of the air pollution values and transport poverty values, as well as the number of (vulnerable) people in the neighbourhoods, some things stand out. Both neighbourhoods are not the worst off when looking at the air pollution and transport poverty, but do have a higher number of (vulnerable) population. Additionally, When shifting from prioritising the total population to only prioritising the vulnerable population, the LEZ allocated neighbourhoods do not change. Indicating that the weight for the total population and total vulnerable population do not have an influence on the result when looking at both the transport poverty as the air pollution aspect. Therefore, the parallel plots for the total vulnerable population can be seen in the Appendix Figure 5.6b depicts the performance of the solution set. As the solution set size is only one neighbourhood. Here, it stands out more that one neighbourhood has a higher number of vulnerable people in comparison to the other, but a lower value for the transport poverty indicator, so this neighbourhood is considered more transport poor.



**(a)** Parallel plot of each neighbourhood in the Hague. Coloured lines indicate the unique neighbourhoods in the solution sets that consider the total population. Extremes are positioned such that the higher values are always more desirable for each indicator.

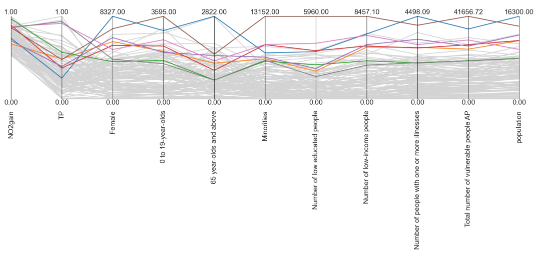


**(b)** Parallel plot of the solution sets of one neighbourhood considering total population. Extremes are positioned such that the higher values are always more desirable for each indicator.

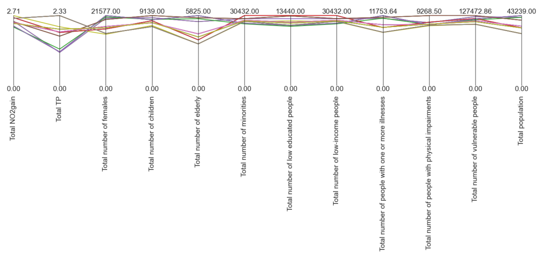
**Figure 5.6:** Figures showing trade-off plot for solution set of 1 neighbourhood considering total population

### 5.2.2. Solution set 3 neighbourhoods

When going from a solution set size of one neighbourhood to a solution set size of three neighbourhoods, there is an increase in unique solutions. Figure 5.7 shows both the performance of all the unique neighbourhoods in the solution set, as well as the overall performance of the unique solution sets. As can be seen in Figure 5.7a. What stands out is that the same neighbourhoods that come forward from the solutions sets of one neighbourhood, are also present in the unique neighbourhoods as resulted from the solution set of three neighbourhoods. Furthermore, when looking at the overall performance of the solution sets, the differences are less distinct than for the solution sets of only one neighbourhood. Air pollution values are around the same for each solution set. Contradictory, the values for the transport poverty aspect vary more. Noticeable is that the value for the total number of vulnerable people is the same for each neighbourhood. Indicating that for each solution set, the number of vulnerable people covered in the resulting neighbourhoods is the same. On the same note, the number of total people covered in the solution sets vary more.

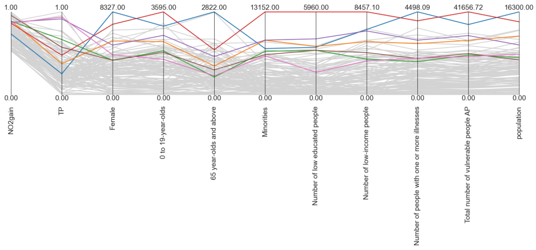


**(a)** Parallel plot of each neighbourhood in the Hague. Coloured lines indicate the unique neighbourhoods in the solution sets of three neighbourhoods that consider the total population. Extremes are positioned such that the higher values are always more desirable for each indicator.

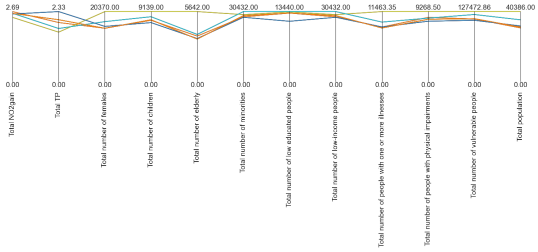


**(b)** Parallel plot of the solution sets of three neighbourhoods, considering total population. Extremes are positioned such that the higher values are always more desirable for each indicator.

**Figure 5.7:** Figures showing parallel plot for solution set of three neighbourhoods considering total population




**(a)** Parallel plot of each neighbourhood in the Hague. Coloured lines indicate the unique neighbourhoods in the solution sets of three neighbourhoods that consider the total vulnerable population. Extremes are positioned such that the higher values are always more desirable for each indicator.

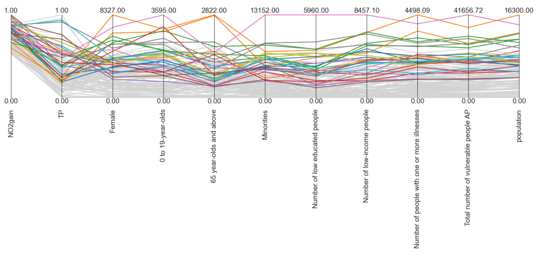



**(b)** Parallel plot of the solution sets of three neighbourhoods, considering total vulnerable population. Extremes are positioned such that the higher values are always more desirable for each indicator.

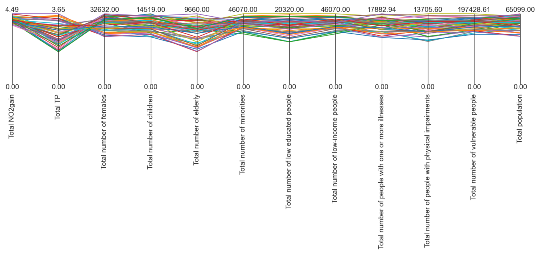
**Figure 5.8:** Figures showing parallel plot for solution set of three neighbourhoods considering total vulnerable population

## 5.2.3. Solution set 5 neighbourhoods

This section will go into detail in analysing the results for the multi-objective problem formulation regarding a solution set of 5 neighbourhoods. Figure 5.9 shows both the performance of all the unique neighbourhoods in the solution set, as well as the overall performance of the unique solution sets when prioritising the total population. Also here, unique neighbourhoods in the solution set do dominantly have higher values for the number of vulnerable people, as well as the total population. Noticeable is that the range of air pollution values almost span the entire range of possible NO2 values. Trade-offs in the number of vulnerable people of different vulnerable groups are less distinct. Overall, a higher number of total vulnerable people in a neighbourhood also correspond to a higher number of total population in the same neighbourhood, as can be seen in Figure 5.7a. The same trend is visible for the unique neighbourhoods in the solution set when prioritising the total vulnerable population as visualised in Figure 5.8a When comparing the overall performance of the solution sets, prioritising either the total vulnerable population or the total population, they are very similar. The only visible difference that can be seen when comparing Figure 5.9b and 5.10b is that the solution sets that prioritise the total population seems to dominantly cover more elderly people.

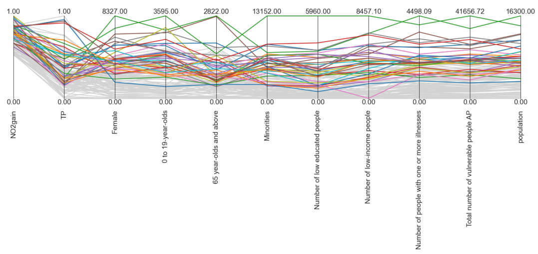



**(a)** Parallel plot of each neighbourhood in the Hague. Coloured lines indicate the unique neighbourhoods in the solution sets of five neighbourhoods that consider the total population. Extremes are positioned such that the higher values are always more desirable for each indicator.

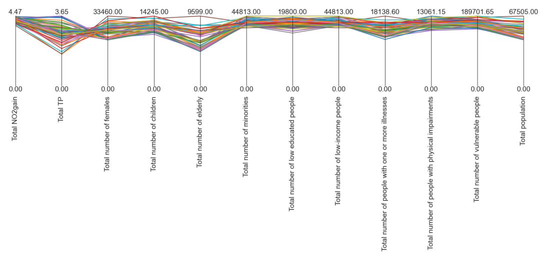



**(b)** Parallel plot of the solution sets of five neighbourhoods, considering total population. Extremes are positioned such that the higher values are always more desirable for each indicator.

**Figure 5.9:** Figures showing parallel plot for solution set of five neighbourhood considering total population




(a) Parallel plot of each neighbourhood in the Hague. Coloured lines indicate the unique neighbourhoods in the solution sets of five neighbourhoods that consider the total vulnerable population. Extremes are positioned such that the higher values are always more desirable for each indicator.




(b) Parallel plot of the solution sets of five neighbourhoods, considering total vulnerable population. Extremes are positioned such that the higher values are always more desirable for each indicator.

**Figure 5.10:** Figures showing parallel plot for solution set of five neighbourhood considering total vulnerable population

# 6 Discussion

The findings from the analysis carried out for this study are clarified in this chapter. The important findings will be briefly discussed, along with how they add to our understanding of the research question that was posed at the start of the research. As a result, it goes into detail about how and where the research fits into the body of literature. It will also discuss the study's limitations before commenting on how the research may be useful for formulating policies and how the results of this investigation may advance future research.

## 6.1. Main findings

As stated in Chapter 3, the main research question of this study is formulated as follows: *How can the combination of social-spatial vulnerability to transport poverty and air pollution guide possible LEZ locations and evaluation of existing ones?* To answer this research question, several steps were undertaken that provide more insight in the key topics, that of air pollution vulnerability and transport poverty vulnerability, in particular in relation to the Hague. First, air pollution and transport poverty were operationalised on neighbourhood-level and their relationship with low emission zones were established. Transport poverty was operationalised using a neighbourhood-based mobility measure that is corrected for accessibility of key services to indicate risk of social exclusion. Additionally, the vulnerable groups in relation to air pollution and transport poverty were identified. The aim of this study was to introduce a multi-objective problem formulation that takes into account the air pollution and transport poverty vulnerability in order to identify neighbourhoods that perform well on both these aspects. To be able to analyse and compare these results, an intermediate step was also taken: that of the single-objective problem formulations. Where neighbourhoods were selected on their performance on only one of the objectives in relation to the total population and total vulnerable population. Resulting in neighbourhoods that will prioritise air pollution reduction for the most vulnerable groups in society and similarly, the transport poverty aspect for the corresponding vulnerable groups as well. Additionally, also neighbourhoods that prioritise the same objectives for the total population are established to analyse the differences.

From the spatial analysis, some things come forward. In general, the distributions of the vulnerable populations largely follow that of the total population, indicating that neighbourhoods where the total population is higher, the vulnerable population is also higher. This is the case for all vulnerable subgroups, except for the distribution of low-income people. Neighbourhoods that have a high number of total population do not always indicate a neighbourhood with a higher number of low-income people.

Shifting between the single objective problem formulations for the total and total vulnerable population, there is a significant change in neighbourhoods that come forward from the analysis. When looking at the air pollution objective, neighbourhoods are more fragmented over the city of the Hague. When considering the transport poverty aspect, resulting neighbourhoods are grouped together, not surprisingly, around the important train station Den Haag HS. This is to be expected, as neighbourhoods that are around this station have a good accessibility to public transport, as one of the main train stations is so close-by. Car-ownership, that is also taken into account in the neighbourhood-based mobility measure that is used to identify the transport poverty in the Hague, is relatively lower then when comparing this value to neighbourhoods located towards the outer edges. Together with the high proximity of services and high number of total and total vulnerable population in these areas, it is logical that these neighbourhoods come forward when looking at the transport poverty aspect. This indicates that using different objectives significantly changes the outcomes of the analysis.

When relating the multi-objective problem formulation results with the current low emission zone as put in place in the Hague, there is only a slight overlap, especially for the solution sets that only have one or three neighbourhoods. It is more difficult to compare the solution sets of five solutions with the current LEZ because of the higher number of unique solutions. But when looking at the unique neighbourhoods that are present in the solution sets, there is a large overlap visible with the current LEZ. But still, this does not indicate whether the solution sets are actually composed of only neighbourhoods that are already located in the current LEZ. Thus commenting on the justness of the current LEZ location in the Hague and relating in to air pollution vulnerability as well as transport poverty vulnerability is difficult in this analysis. However, as policy-makers in the Hague underline, the values used for air pollution come from 2020, from when the current LEZ was already in place. Policy-makers find it striking that there is an overlap in neighbourhoods that come out of the analysis and that are already in the current LEZ. Even with the reduction of air pollution after the implementation of the LEZ, these neighbourhoods still occur in the solution sets, and stricter measures might be necessary here to stimulate the reduction in air pollution even more. Noteworthy is that the current LEZ will be converted into a zero-emission zone, also for the freight transport, so this reduction is considered to be enforced.

When exploring the multi-objective problem formulation results several things stand out. First, the results of the multi-objective problem formulation yields results where there is an optimal value of air pollution and transport poverty, ideally neighbourhoods where the air pollution is high, and the transport poverty is low. Air pollution and transport poverty values are either prioritised for the total population, so looking at the absolute number of people living in a neighbourhood, or for the total vulnerable population. For the case of the Hague, when considering the results of the multi-objective problem formulation, prioritising the total population does not yield significantly different results then when prioritising total vulnerable population. This might have to do something with the big difference in absolute numbers of total and vulnerable population of neighbourhoods in the Hague. It can be traced back to the distributions of the total and total vulnerable populations, as neighbourhoods with the highest total population often also have a dominantly higher number of total vulnerable population. This indicates that for the Hague, by prioritising the total vulnerable population, the total vulnerable population is also prioritised indirectly.

When looking at the shift from single - to multi-objective problem formulations, some dominant neighbourhoods can be identified. This indicates that these neighbourhoods are, regarding what objectives you consider, always part of the solution set. These neighbourhoods are Schildersbuurt-Noord and Schildersbuurt-West. Relating these neighbourhoods back to the spatial distributions of air pollution, transport poverty and the corresponding total and total vulnerable population, this is not a surprising result. These neighbourhoods have bad air pollution when relating them to other neighbourhoods in the Hague, and a good score for transport poverty, indicating these neighbourhoods are not considered transport poor when relating them to other neighbourhoods in the Hague. Additionally, these neighbourhoods have relatively high number of total and vulnerable population. So it is logical that these neighbourhoods are dominantly present in both the single and multi-objective problem formulations, whether prioritising the total or total vulnerable populations. When talking to policy-makers in the Hague, they underline this outcome, in these neighbourhoods, the car is also often used for short distance trips and car ownership is a bit higher than other surrounding neighbourhoods, also resulting from the spatial analysis. But in these neighbourhoods, there is simply limited support from inhabitants to policy implementations. Policy makers also underline that the sentiment towards the government and local policy makers in this neighbourhood is a dominant factor in whether or not to implement an LEZ. They describe that a lot of people in this neighbourhood already feel marginalised. Commenting on the fact that policy makers think they also deserve clean air, the inhabitants of this neighbourhood much prefer the access to their car. This is in line with results of a recent study of Walker et al. (2022), where their analysis shows an in-built acceptance of burdens of from motor vehicles, also relating to the pollution. This is also referred to as motonormatity, the notion of biases due to cultural assumptions about the role of private cars. This motonormativity, that is also evident in these neighbourhoods implies that key public health and sustainability issues are being neglected by policy makers and in the case of Schildersbuurt, being trivialised by inhabitants. Strikingly, whilst the Schildersbuurten come forward in this analysis as neighbourhoods were the risk of social exclusion is low, because of high proximity to key services and the combination with good public transport accessibility. The sentiment in this neighbourhood is that they are more socially excluded and being burdened by policy implementations.

## 6.2. Positioning in literature

The work, as presented in this study aims to facilitate a transition to just decision making related to transport or infrastructural issues. This is done for low-emission zone applications, where socio-spatial vulnerabilities to air pollution and transport poverty are combined. Over the years, transport poverty, and correspondingly, transport justice, has been an emerging field of research and academics have made a call to actively include this in policy-making. This is also underlined by policy-makers in the Hague, where over the years, transport poverty has come more to their attention and has been a field of research in the municipality of the Hague. The multi-dimensionallity of transport poverty makes this topic more complex. Lucas et al. (2016) has made a large contribution to this topic, introducing a definition that tries to cover all the aspects of transport poverty, accompanied by ways how to operationalise these different aspects of transport poverty. This work adds to the call of academics by also using transport poverty as an objective in LEZ allocation. As discussed in literature, the identification of vulnerable groups in relation to transport poverty is also crucial. Furthermore, this research goes further than trying to include socio-spatial vulnerabilities to transport poverty in the decision making process. When looking at LEZs in particular, air pollution is a strong determinant in the allocation, as air pollution reduction is the ultimate goal. But air pollution can also have negative effects on the health of people. And also for air pollution, more vulnerable groups in society can be identified. This research aims to include both vulnerabilities in order to try to contribute to shift the approach to a vulnerability-based one, to facilitate just decision making processes.

So, the outcomes of this study can facilitate the debate on the need for effective and just policies relating to, in this case, low emission zone applications. This work provides insights in how to improve policy implementations, that enable local decision-makers to identify vulnerable groups and include justice in the decision making process for LEZ implementation, considering the socio-spatial vulnerability to both air pollution and transport poverty. This work offers a quantitative approach using optimisation tools in order to facilitate including justice. Additionally, similarly to the study of Robinson et al. (2022), this work adds to the notion of how simple optimisation tools can be useful in explaining spatial inequalities in relation to air pollution and transport poverty and can be useful in communicating how relating the notions of air pollution and transport poverty to the corresponding (vulnerable) population might shift the decision-making process of LEZ implementations.

## 6.3. Limitations and recommendations

In this study, a quantitative approach was taken, using static data, to operationalise the air pollution, transport poverty as well as the socio-spatial vulnerability. This research has some limitations that will be elaborated on in this section.

By taking a quantitative approach in the inclusion of transport justice in the LEZ allocation, this work heavily relies on available data. To truly grasp the notion of transport poverty in relation to low emission zones, car data would ideally be broken down to pollution label that would subsequently be included in the transport poverty indicator. Where not the number of cars will be a determinant in whether a neighbourhoods would be more or less transport poor in relation to low emission zones, but the fraction of electric cars in relation to the total number of cars. In light of this, the view on transport poverty in the Hague could also be investigated, using a more qualitative approach, by for example structured interviews, surveys or focus groups to clarify the relationship definition of transport poverty in relation to social exclusion. Moreover, the data-scale of this research is neighbourhood-level. As all the data was only available on neighbourhood level. This also makes comparability between neighbourhoods more difficult, neighbourhoods not only vary in size but also composition. When using a finer grid, for example using 100 by 100 meter data, comparability would be easier. But in the same light, applicability of LEZs on neighbourhood level would be easier than on a finer grid. One another note, an example that was given by a mobility-expert in the Hague, low emission zones also tend to impact the self-employed, who drive a polluting van. This can subsequently also be added in order to tailor the transport poverty aspect to the decision-makers wishes, taking into account aspects they find important when considering transport poverty in the Hague .

In mapping out socio-spatial vulnerabilities to air pollution and transport poverty an important comment must be made. Not all people who are covered by these vulnerable groups will actually be vulnerable in real life. The vulnerable groups rather indicate people who are more likely to experience transport poverty or adverse health effects because of exposure to air pollutants. Additionally, in identifying the socio-spatial vulnerability, this work only takes into account the actual inhabitants of the neighbourhoods. Failing to also include other possible aspects that decision-makers might find important, such as how many workers are located in the area, indicating that people travel and spend their day somewhere else. In light of this, combining travel data would also gain insight in where people spend most of their time, rather then only using their home location. This mobility data will not only give insight in where people go and spend their day, but also will give insight in the transport poverty notion. Some people are reliant on their car to access their job, as their jobs might be located in areas that are simply not accessible by public transport. Additionally, this research also fails to consider practicalities regarding low emission zone implementation. For example where low emission zones can actually be employed. Additionally the fragmentation of neighbourhoods over the Hague in solution sets also adds another impracticality, that of the effectiveness and application of fragmented low emission zones.

Furthermore, in this work, static indicators are used in order to assess LEZ implementations. As research already shows, results of LEZ implementations are ambiguous, in some cases air pollution reduction is insignificant, in other cases there is a significant reduction. Additionally, the implementation of LEZs can also imply a shift in traffic to surrounding neighbourhoods. This influences the effectiveness of the LEZs. Ideally, more research on this topic would be done and the addition of a more comprehensive simulation model would be of benefit here, where air pollution will be attributed to polluting vehicles, and the shift and/or reduction in polluting vehicles will determine the effectiveness of the low emission zone. In this research to relate the air pollution heavily to car-related traffic, the NO2 concentration was used, which is a dominant air pollutant of cars, in order to account for the potential reduction in air pollution when a low emission zone is implemented. Additionally, the NO2 concentration that is used in this research is an important indicator, as discussed by policy-makers in the Hague. The NO2 concentration has been up for a lot of debate in politics and policy making over the past years and the reduction of it is incredibly important and also in more urban areas, such as the Hague.

Additionally, results of this analysis are useful for policy-making in relation to Low Emission Zone implementation. For the case of the Hague, a Low Emission Zone is currently already in place. In this analysis, the neighbourhoods that are dominantly present in the results are neighbourhoods where the sentiment is a more driving factor in whether or not to implement an LEZ. Mitigating measures can be a solution here. For example incentives that give the inhabitants the feeling that they are not solely loosing the access to their pollution car, or applying time frames on the implementation of the LEZ. Additionally, subsidies for use of public transport or bike-plans could be considered for the compensation of losing their car. Another option would be to inform people better on the consequences of air pollution exposure and the adverse health effects. Subsequently, more research can also be done on the mitigating measures that will soften the feeling of car loss in these marginalised neighbourhood. Additionally, neighbourhoods that are already in the current LEZ also come forward from the analysis, alternative measures need to be taken here to reduce the air pollution. Creating significantly more green places might reduce the air pollution here.

On a last note, the application of identification of socio-spatial vulnerabilities transcends to that of only LEZ allocation. In particular, the single-objective transport poverty objective can be used to identify neighbourhoods that are transport poor. This is can then also be used in a more elaborated research on transport poverty in the Hague, where possible policy levers can be suggested in order to diminish these existing discrepancies in transport poverty. Additionally, the single-objective air pollution objective also offers more applications. This can be related to the state of insulation in homes in order to evaluate the exposure of vulnerable groups to air pollution even more and to come up with policy levers in order to diminish this exposure.

# 7 Conclusion

## SQ1: How can the least vulnerable neighbourhoods to transport poverty be identified?

Using existing literature on transport poverty vulnerability, a complete overview of a all vulnerable groups in relation was established. This is the first step in identifying vulnerable neighbourhoods to transport poverty. For the operationalisation of transport poverty, a neighbourhood-based mobility measure was used that was corrected for by accessibility. The mobility measure used car-ownership and public transport accessibility. Accessibility was determined by proximity of key services, using distance to practitioner, supermarkets and secondary school, as well as the number of accessible jobs. The transport poverty indicator was also weighted by the total (vulnerable) population in order to prioritise these groups in society when considering transport poverty. Subsequently, the least vulnerable neighbourhoods to transport poverty can be identified.

## SQ2: How can the most vulnerable neighbourhoods to air pollution be identified?

Similarly as SQ1, here the approach is two-fold. First the air pollution in the Hague needs to be established. Nitrogen dioxide was used as an indicator for the air pollution. Secondly, a spatial analysis in relation to where vulnerable groups are distributed over the Hague needs to be performed. By calculating the weighted average for the different vulnerable groups, as well as a combination of them, accounting for the whole vulnerable population, the more vulnerable neighbourhoods can be established in relation to air pollution. These neighbourhoods are well fit to be a Low Emission Zone when solely considering the air pollution.

## SQ3: How can adequate LEZ locations be selected, considering both air pollution and transport poverty vulnerability?

This research employs a multi-objective optimisation algorithm that selects appropriate LEZ locations, taking into account air pollution and transport poverty. Giving priority to either the total population or the total vulnerable population.

By employing this quantitative approach on including justice in LEZ allocation, the transition to including transport justice in policy-making can be facilitated.

So, in order to consider air pollution vulnerability and transport vulnerability in LEZ allocation, several steps need to be undertaken. First, the vulnerable groups need to be identified, after which the air pollution and transport poverty need to be quantified. Subsequently, the air pollution and transport poverty values can be adjusted to prioritise these pre-identified vulnerable groups. A non dominated sorting algorithm (NSGA-II) was employed and tailored to the given objectives in order to result in a solution set of neighbourhoods that have an optimal value for both air pollution and transport poverty.

## MQ: How can the combination of social-spatial vulnerability to transport poverty and air pollution guide LEZ evaluation and implementation?

The combination of social-spatial vulnerabilities to transport poverty and air pollution can LEZ implementation and evaluation. For the case of the Hague, the following conclusions were drawn after analysing the results. First, there are some dominant neighbourhoods coming forward from the analysis, indicating great potential to implement a just LEZ, when relating it to transport poverty and air pollution vulnerability. Additionally, results of the analysis include neighbourhoods that are present in the current LEZ, indicating that the whilst the current LEZ is in place, the air pollution and vulnerability to air pollution is still high here. Stricter measures are necessary here to reduce the air pollution vulnerability further.

Results from the Hague also point out that it is still very important to keep the human-in-the-loop. Results may indicate that these neighbourhoods are just LEZ locations, but policy-makers can tell otherwise, by addressing important issues regarding these neighbourhoods that this approach fails to grasp. But results can still be supportive in their decision-making.

But overall, results from the analysis are two-fold. On one hand they can identify neighbourhoods that are adequate places to introduce LEZs. Simultaneously, the analysis gives the opportunity to reflect on the current LEZ.

# Bibliography


(2022). Den haag in cijfers.

(2022). Locaties milieuzones.

(2022). Luchtkwaliteit Den Haag.

and European Environment Agency (2022). *Decarbonising road transport : the role of vehicles, fuels and transport demand*. Publications Office of the European Union.

Anderson, J. O., Thundiyil, J. G., and Stolbach, A. (2012). Clearing the air: A review of the effects of particulate matter air pollution on human health. *Journal of Medical Toxicology*, 8(2):166 – 175.

Bernardo, V., Fageda, X., and Flores-Fillol, R. (2021). Pollution and congestion in urban areas: The effects of low emission zones. *Economics of Transportation*, 26-27:100221.

Borsboom, J., Haindlmaier, G., Dinges, M., Gualdi, M., and Heinonen, S. (2021). *Mission area : climate-neutral and smart cities : foresight on demand brief in support of the Horizon Europe mission board*.

Brunekreef, B. and Holgate, S. T. (2002). Air pollution and health. *The Lancet*, 360(9341):1233–1242.

Börjesson, M., Bastian, A., and Eliasson, J. (2021). The economics of low emission zones. *Transportation Research Part A: Policy and Practice*, 153:99–114.

CBS (2022). Dashboard bevolking.

Cesaroni, G., Boogaard, H., Jonkers, S., Porta, D., Badaloni, C., Cattani, G., Forastiere, F., and Hoek, G. (2012). Health benefits of traffic-related air pollution reduction in different socioeconomic groups: The effect of low-emission zoning in rome. *Occupational and Environmental Medicine*, 69(2):133 – 139.

Creswell, J. W. and Creswell, J. D. (1994). Research design.

Crowe, S., Cresswell, K., Robertson, A., Huby, G., Avery, A., and Sheikh, A. (2011). The case study approach. *BMC medical research methodology*, 11(1):1–9.

De Vrij, E. and Vanoutrive, T. (2022). 'no-one visits me anymore': Low emission zones and social exclusion via sustainable transport policy. *Journal of Environmental Policy and Planning*.

Deltametropool (2019). Keuzevrijheid van vervoer voor iedereen.

DenHaag (2017). International city of peace and justice.

di Milano, C. (2015). Milan's area c reduces traffic pollution and transforms the city center.

D'Amato, G., Bergmann, K. C., Cecchi, L., Annesi-Maesano, I., Sanduzzi, A., Liccardi, G., Vitale, C., Stanziola, A., and D'Amato, M. (2014). Climate change and air pollution. *Allergo Journal*, 23(1):32–38.

EEA (2021). Air quality in europe 2021.

Ellison, R. B., Greaves, S. P., and Hensher, D. A. (2013). Five years of london's low emission zone: Effects on vehicle fleet composition and air quality. *Transportation Research Part D: Transport and Environment*, 23:25–33.

EU (2022). A european green deal.

Franco, V., Kousoulidou, M., Muntean, M., Ntziachristos, L., Hausberger, S., and Dilara, P. (2013). Road vehicle emission factors development: A review. *Atmospheric Environment*, 70:84–97.

Gordon, S. B., Bruce, N. G., Grigg, J., Hibberd, P. L., Kurmi, O. P., bong Hubert Lam, K., Mortimer, K., Asante, K. P., Balakrishnan, K., Balmes, J., Bar-Zeev, N., Bates, M. N., Breysse, P. N., Buist, S., Chen, Z., Havens, D., Jack, D., Jindal, S., Kan, H., Mehta, S., Moschovis, P., Naeher, L., Patel, A., Perez-Padilla, R., Pope, D., Rylance, J., Semple, S., and Martin, W. J. (2014). Respiratory risks from household air pollution in low and middle income countries. *The Lancet Respiratory Medicine*, 2(10):823–860.

Gronkiewicz-Waltz, H., Larsson, A., Boni, A., Krogh Andersen, K., Ferrao, P., Forest, E., Jordan, R., Lenz, B., Lumbreras, J., Nicolaides, C., Reiter, J., Russ, M., Sulling, A., Termont, D., and Vassilakou, M. (2020). *100 climate-neutral cities by 2030 - by and for the citizens : report of the mission board for climate-neutral and smart cities*. Publications Office.

Groth, S. (2019). Multimodal divide: Reproduction of transport poverty in smart mobility trends. *Transportation Research Part A: Policy and Practice*, 125:56–71.

Gössling, S. (2016). Urban transport justice. *Journal of Transport Geography*, 54:1–9.

Holman, C., Harrison, R., and Querol, X. (2015). Review of the efficacy of low emission zones to improve urban air quality in european cities. *Atmospheric Environment*, 111:161–169.

Invernizzi, G., Ruprecht, A., Mazza, R., De Marco, C., Močnik, G., Sioutas, C., and Westerdahl, D. (2011). Measurement of black carbon concentration as an indicator of air quality benefits of traffic restriction policies within the ecopass zone in milan, italy. *Atmospheric Environment*, 45(21):3522–3527.

Kampa, M. and Castanas, E. (2008). Human health effects of air pollution. *Environmental Pollution*, 151(2):362–367. Proceedings of the 4th International Workshop on Biomonitoring of Atmospheric Pollution (With Emphasis on Trace Elements).

Kamruzzaman, M., Yigitcanlar, T., Yang, J., and Mohamed, M. A. (2016). Measures of transport-related social exclusion: A critical review of the literature. *Sustainability*, 8(7):696.

Künzli, N., Kaiser, R., Medina, S., Studnicka, M., Chanel, O., Filliger, P., Herry, M., Horak, F., Puybonnieux-Texier, V., Quénel, P., Schneider, J., Seethaler, R., Vergnaud, J.-C., and Sommer, H. (2000). Public-health impact of outdoor and traffic-related air pollution: a european assessment. *The Lancet*, 356(9232):795–801.

Liang, Z., Yang, Y., Li, J., Zhu, X., Ruan, Z., Chen, S., Huang, G., Lin, H., Zhou, J.-Y., and Zhao, Q. (2019). Migrant population is more vulnerable to the effect of air pollution on preterm birth: Results from a birth cohort study in seven chinese cities. *International Journal of Hygiene and Environmental Health*, 222(7):1047–1053.

Lowans, C., Furszyfer Del Rio, D., Sovacool, B. K., Rooney, D., and Foley, A. M. (2021). What is the state of the art in energy and transport poverty metrics? a critical and comprehensive review. *Energy Economics*, 101:105360.

Lucas, K., Martens, K., Di Ciommo, F., and Dupont-Kieffer, A. (2019). *Measuring transport equity*. Elsevier.

Lucas, K., Mattioli, G., Verlinghieri, E., and Guzman, A. (2016). Transport poverty and its adverse social consequences. In *Proceedings of the institution of civil engineers-transport*, volume 169, pages 353–365. Thomas Telford Ltd.

Ma, L., Graham, D. J., and Stettler, M. E. (2021). Has the ultra low emission zone in london improved air quality? *Environmental Research Letters*, 16(12).

Makri, A. and Stilianakis, N. I. (2008). Vulnerability to air pollution health effects. *International Journal of Hygiene and Environmental Health*, 211(3):326–336.

Martens, K. (2013). Role of the bicycle in the limitation of transport poverty in the netherlands. *Transportation research record*, 2387(1):20–25.

Martens, K. (2017). *Transport Justice: Designing Fair Transportation Systems*.

Marttunen, M., Lienert, J., and Belton, V. (2017). Structuring problems for multi-criteria decision analysis in practice: A literature review of method combinations. *European journal of operational research*, 263(1):1–17.

Medina-Ramon, M. and Schwartz, J. (2008). Who is more vulnerable to die from ozone air pollution? *Epidemiology*, pages 672–679.

Moore, F. (2021). Low emission zones: Challenges and solutions.

Orru, H., Ebi, K., and Forsberg, B. (2017). The interplay of climate change and air pollution on health. *Current environmental health reports*, 4(4):504–513.

Panteliadis, P., Strak, M., Hoek, G., Weijers, E., van der Zee, S., and Dijkema, M. (2014). Implementation of a low emission zone and evaluation of effects on air quality by long-term monitoring. *Atmospheric Environment*, 86:113–119.

Pereira, R. H. M., Schwanen, T., and Banister, D. (2017). Distributive justice and equity in transportation. *Transport Reviews*, 37(2):170 – 191.

Pojani, E., Boussauw, K., and Pojani, D. (2017). Reexamining transport poverty, job access, and gender issues in central and eastern europe. *Gender, Place & Culture*, 24(9):1323–1345.

Porter, J. (2022). Parisian car ban now planned for 2024.

Poulhès, A. and Proulhac, L. (2021). The paris region low emission zone, a benefit shared with residents outside the zone. *Transportation Research Part D: Transport and Environment*, 98:102977.

Qadir, R., Abbaszade, G., Schnelle-Kreis, J., Chow, J., and Zimmermann, R. (2013). Concentrations and source contributions of particulate organic matter before and after implementation of a low emission zone in munich, germany. *Environmental Pollution*, 175:158–167.

Queirós, A., Faria, D., and Almeida, F. (2017). Strengths and limitations of qualitative and quantitative research methods. *European journal of education studies*.

Rawls, J. (2004). A theory of justice. In *Ethics*, pages 229–234. Routledge.

Robinson, C., Franklin, R. S., and Roberts, J. (2022). Optimizing for equity: Sensor coverage, networks, and the responsive city. *Annals of the American Association of Geographers*, 112(8):2152–2173.

Rybarczyk, G. and Wu, C. (2010). Bicycle facility planning using gis and multi-criteria decision analysis. *Applied Geography*, 30(2):282–293.

Seaton, A., Godden, D., MacNee, W., and Donaldson, K. (1995). Particulate air pollution and acute health effects. *The Lancet*, 345(8943):176–178.

Sicard, P., Agathokleous, E., Paoletti, E., and Calatayud, V. (2020). *Urban Population Exposure to Air Pollution in Europe Over the Last Decades*.

Simcock, N., Jenkins, K., Lacey-Barnacle, M., Martiskainen, M., Mattioli, G., and Hopkins, D. (2021). Identifying double energy vulnerability: A systematic and narrative review of groups at-risk of energy and transport poverty in the global north. *Energy Research & Social Science*.

Tibuakuu, M., Michos, E. D., Navas-Acien, A., and Jones, M. R. (2018). Air pollution and cardiovascular disease: a focus on vulnerable populations worldwide. *Current epidemiology reports*, 5(4):370–378.

Tong, D. and Murray, A. T. (2012). Spatial optimization in geography. *Annals of the Association of American Geographers*, 102(6):1290–1309.

Valdivia, A. G. (2020). Barcelona opens one of europe's largest low emissions zones.

Verbeek, T. and Hincks, S. (2022). The 'just' management of urban air pollution? a geospatial analysis of low emission zones in brussels and london. *Applied Geography*, 140:102642.

Verlinghieri, E. and Schwanen, T. (2020). Transport and mobility justice: Evolving discussions. *Journal of Transport Geography*, 87.

Voerknecht, H. (2021). De integrale kijk op bereikbaarheid voor sturen op brede welvaart. *CVS-congres*.

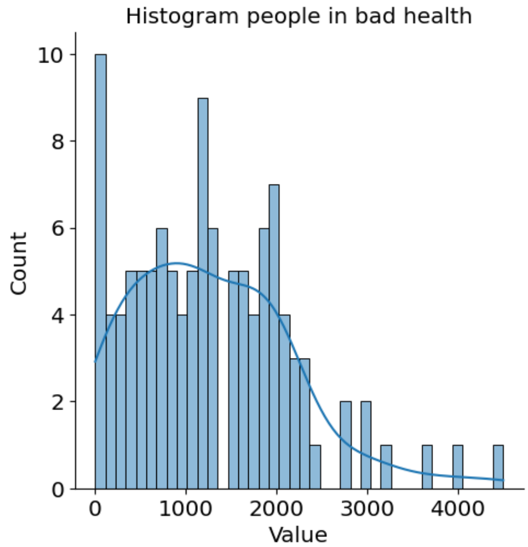
Vrij, E. D. and Vanoutrive, T. (2022). 'no-one visits me anymore': Low emission zones and social exclusion via sustainable transport policy. *Journal of Environmental Policy & Planning*, 0(0):1–13.

Walker, I., Tapp, A., and Davis, A. (2022). Motornomativity: How social norms hide a major public health hazard.

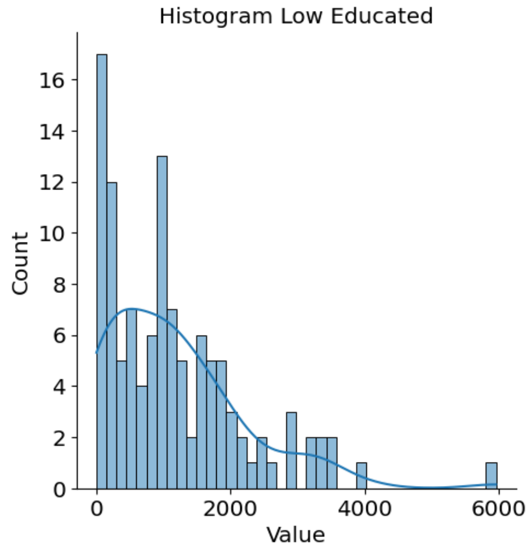
Yannis, G., Kopsacheili, A., Dragomanovits, A., and Petraki, V. (2020). State-of-the-art review on multi-criteria decision-making in the transport sector. *Journal of Traffic and Transportation Engineering (English Edition)*, 7(4):413–431.

# A

# Data

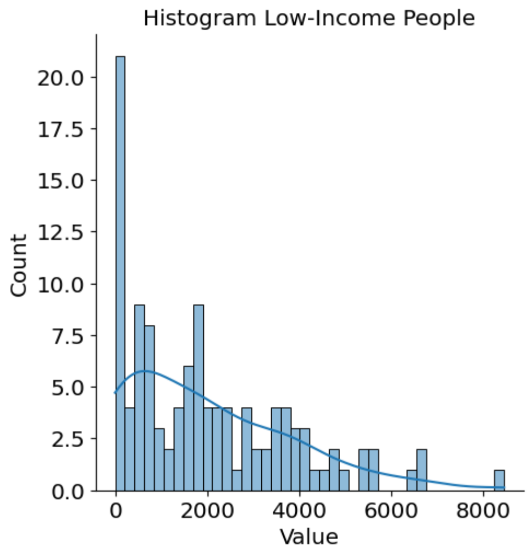



**(a)** Histogram of distribution of number of people in bad health

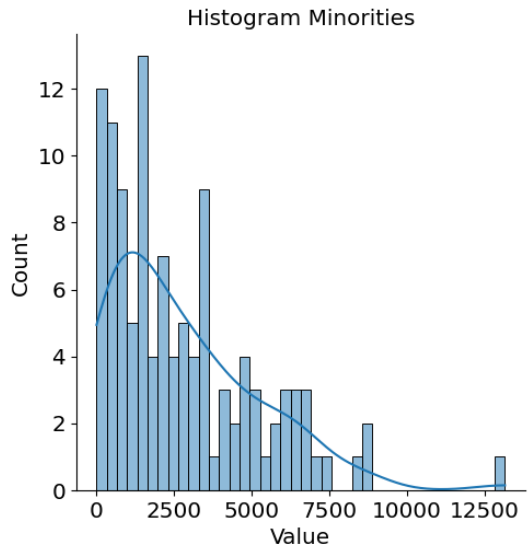



**(b)** Histogram of distribution of number of low-educated people

**Figure A.1:** Histograms of number of people in bad health and number of low-educated people

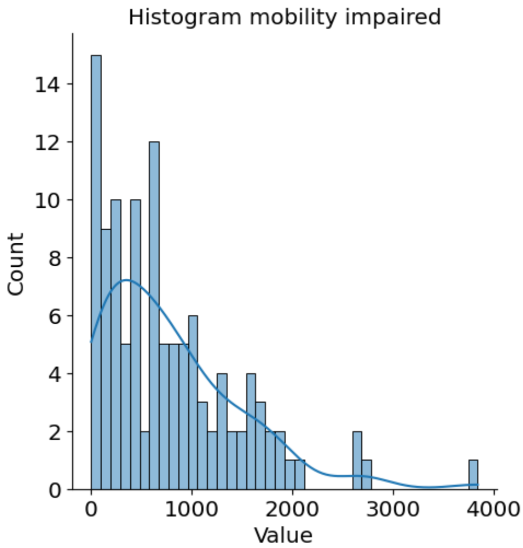



**(a)** Histogram of distribution of number of low-income people

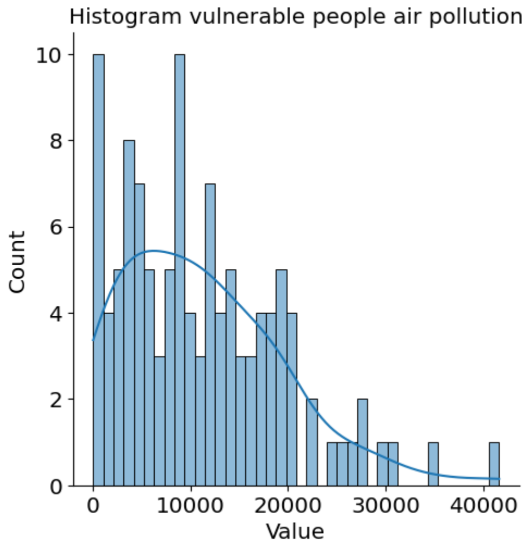



**(b)** Histogram of distribution of number of ethnic minorities

**Figure A.2:** Histograms of number of low-income people and number of ethnic minorities




**(a)** Histogram of number of physically impaired people




**(b)** Histogram of aggragated total number of people vulnerable to air pollution

**Figure A.3:** Histogrm of number of number physically impaired and total number of people vulnerable to air pollution

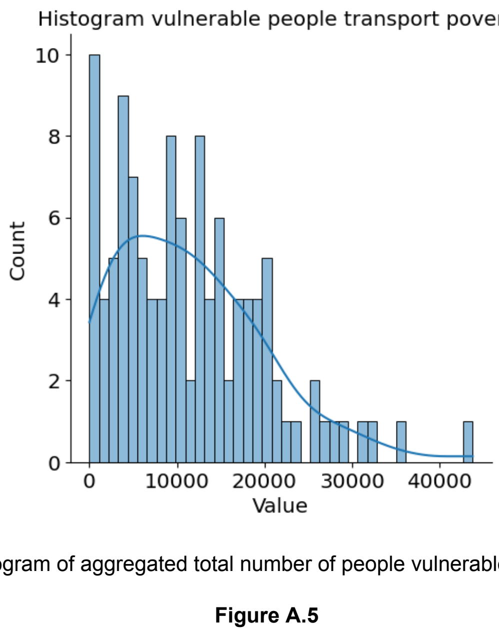
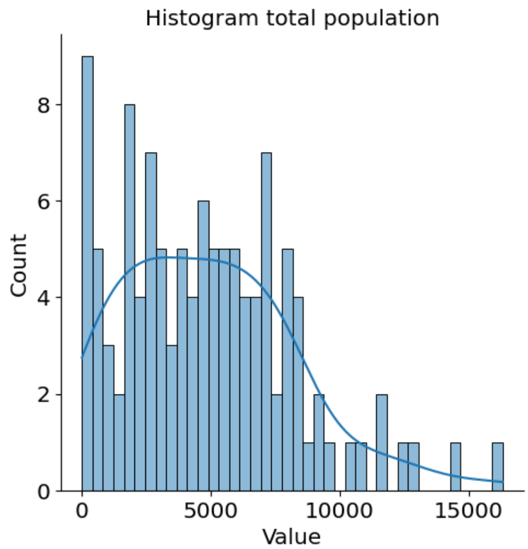
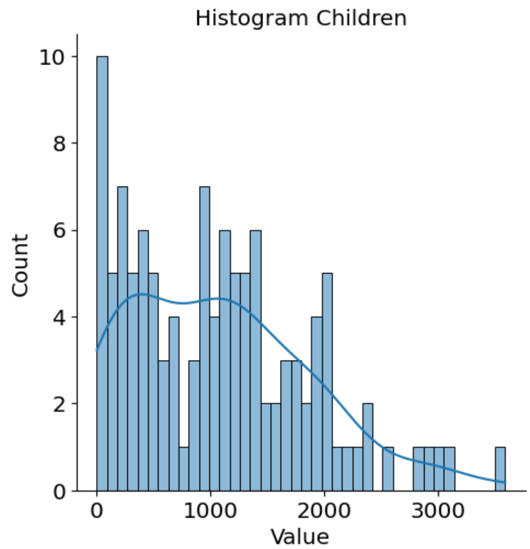



**Figure A.4:** Histogram of aggregated total number of people vulnerable to transport poverty

**Figure A.5**

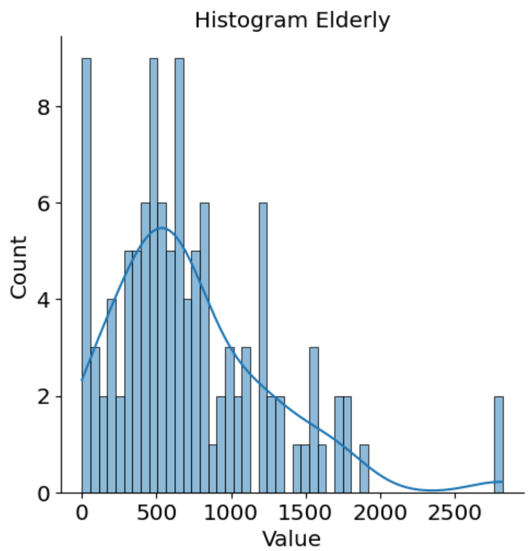



**(a)** Histogram of number of total population

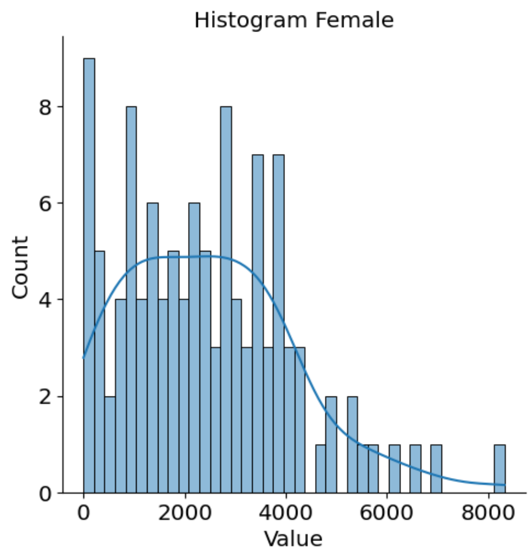



**(b)** Histogram of number of children

**Figure A.6:** Histograms of number of total population and number of children

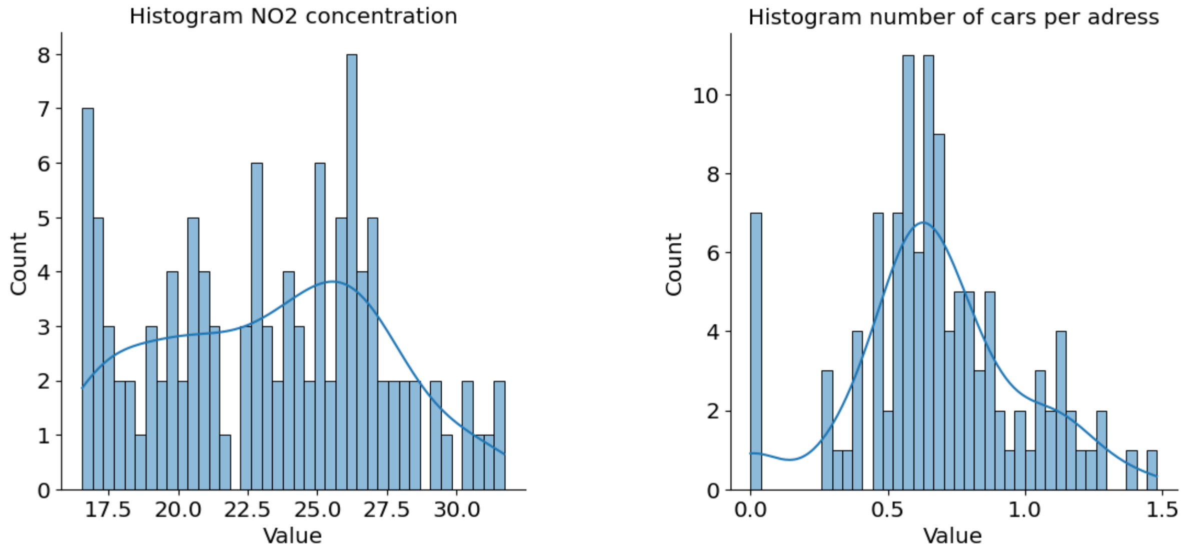



**(a)** Histogram of number of elderly




**(b)** Histogram of number of female population

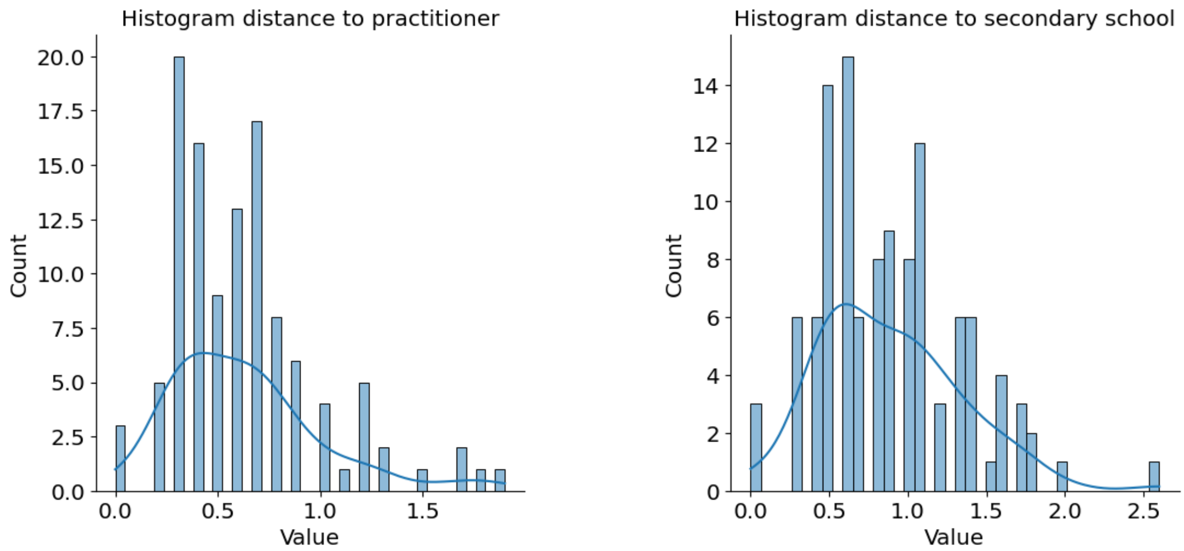
**Figure A.7:** Histograms of total number of elderly and number of female population




**(a)** Histogram of NO2 concentration

**(b)** Histogram of number of cars

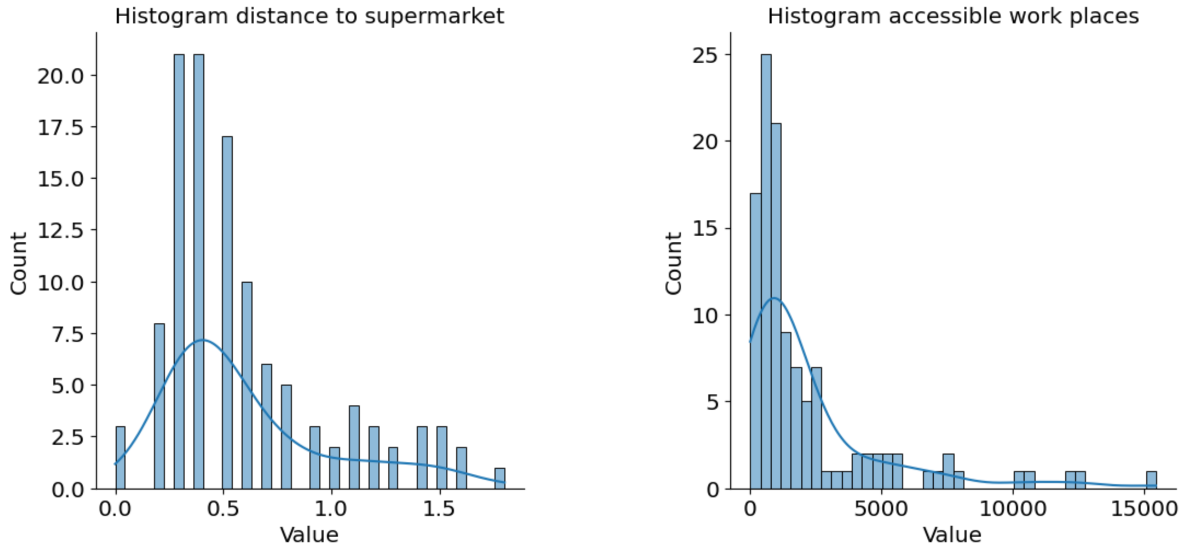
**Figure A.8:** Histograms of NO2 concentration and the number of cars per adress




**(a)** Histogram of distance to practitioner

**(b)** Histogram of distance to secondary school

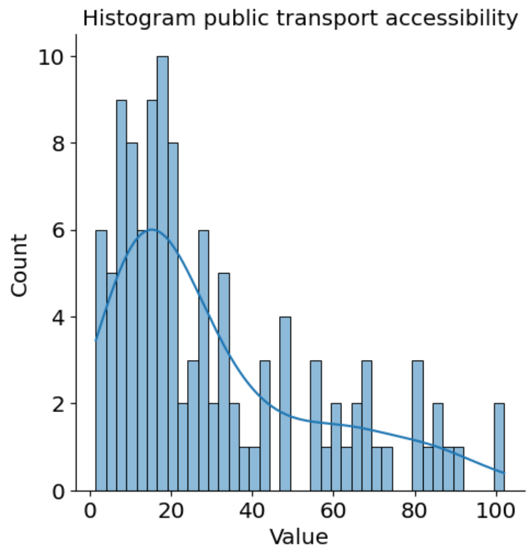
**Figure A.9:** Histograms of distance to practitioner and distance to secondary school




**(a)** Histogram of distance to supermarket

**(b)** Histogram of number of accessible workplaces

**Figure A.10:** Histograms of distance to supermarket and number of accessible workplaces

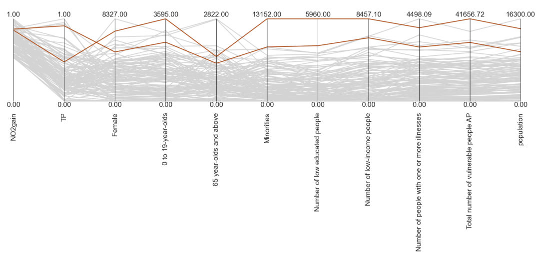



**(a)** Histogram of public transport accessibility index

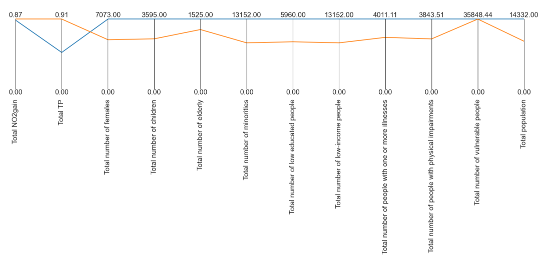
**Figure A.11:** Histogram of public transport accesibility index

# B

# Single-objective problem formulation results prioritising different demographics in relation to air pollution

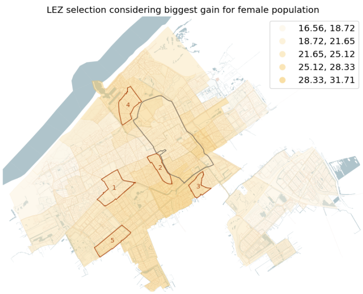


**(a)** Trade-off plot of the benefit of air pollution and transport poverty, as well as the number of people in each unique neighbourhood in relation to all neighbourhoods

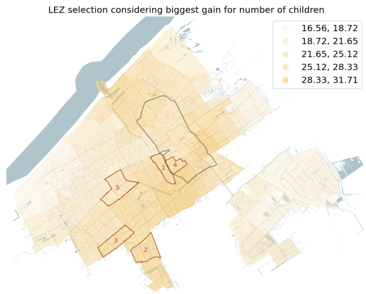


**(b)** Trade-off plot of the total benefit of air pollution and transport poverty, as well as the number of people 2 solution sets for 1 LEZ

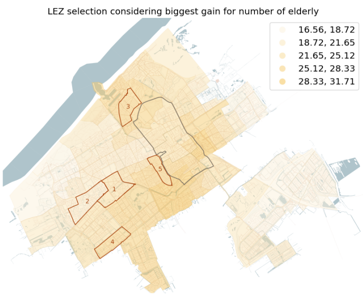
**Figure B.1:** Figures showing trade-off plot for solution set of 1 neighbourhood considering total vulnerable population



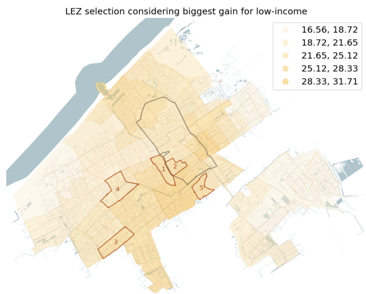

**(a)** Selection of best neighbourhoods for air pollution objective with respect to number of females



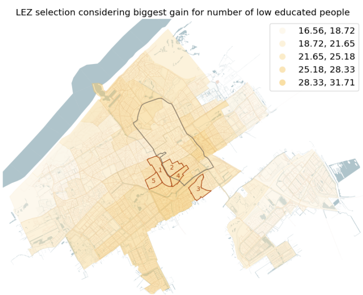

**(b)** Selection of best neighbourhoods for air pollution objective with respect to number of children



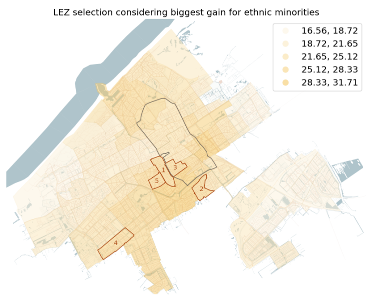

**(c)** Selection of best neighbourhoods for air pollution objective with respect to number of elderly



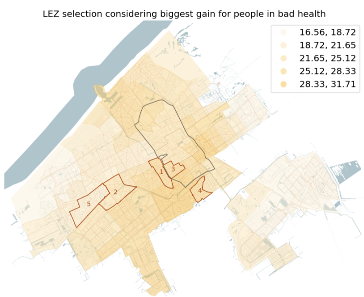

**(d)** Selection of best neighbourhoods for air pollution objective with respect to number of low-income people




**(e)** Selection of best neighbourhoods for air pollution objective with respect to number of low educated people




**(f)** Selection of best neighbourhoods for air pollution objective with respect to number ethnic minorities




**(g)** Selection of best neighbourhoods for air pollution objective with respect to number people in bad health

**Figure B.2:** Figures showing best LEZ locations considering the biggest benefit in air pollution for the corresponding vulnerable groups.

# C

# Multi-Objective Optimisation Algorithm

```
class MultiObjective(Problem):
    def __init__(self):
        super().__init__(5, 2) # select on how many neighbourhoods to select in the set
        self.types[:] = Real(0,114)
        self.directions[:] = Problem.MAXIMIZE
        self.constraints[:] = "==0"
        self.neighbourhoods = 5 # select on how many neighbourhoods to select in the set

    def evaluate(self, solution):
        y = []
        while len(y) < self.neighbourhoods:
            n = random.randint(0,113)
            if n not in y:
                y.append(n)
        weights = datasetDH.wtotpop.values
        solution.variables[:] = y
        pollution = weights*datasetDH.NO2gain.values.tolist()
        pol = sum([pollution[(y[i])] for i in range(0, (self.nvars))])
        transportpoverty = weights*datasetDH.TP.values.tolist()
        tp = sum([transportpoverty[(y[i])] for i in range(0, (self.nvars))])
        buurten = datasetDH.buurten.values.tolist()
        solution.objectives[:] = [pol, tp]
        # if len(duplicates) > 0:
        #     print(duplicates)
        # duplicates = [number for number in solution.variables if solution.variables.count(
            number) > 1]
        solution.constraints[:] = [len([item for item, count in collections.Counter(solution.
            variables[:]).items() if count > 1])]
        solution.neighbourhoods = []
        for i in range (0, self.nvars):
            b = (y[i])
            solution.neighbourhoods.append(buurten[b])
```