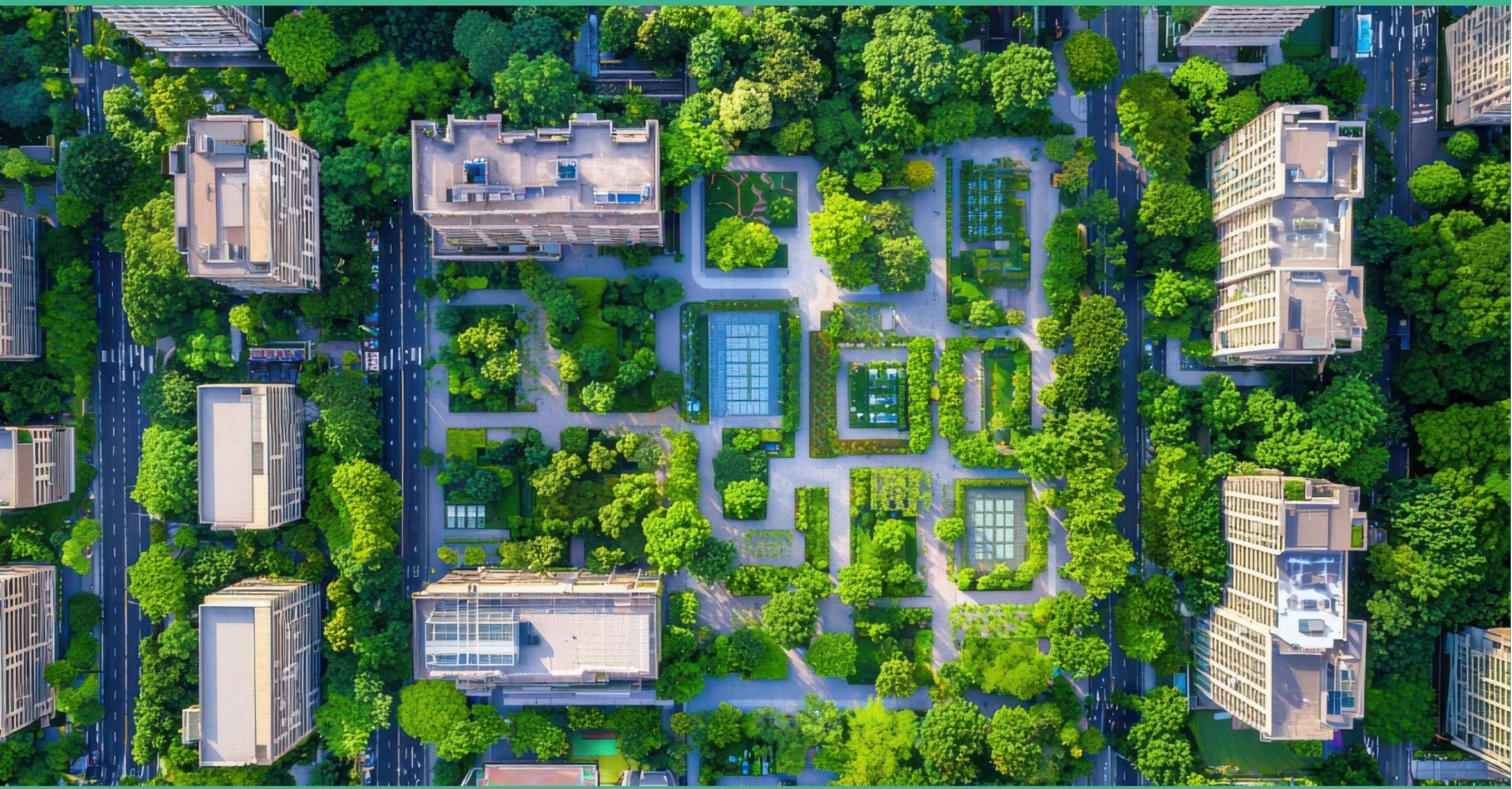
Stress Testing Urban Heat Adaptation and Greening Plans

A simulation model applied to the municipality of Vlaardingen, The Netherlands



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March 2026

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Executive Summary (English)

This study looks at how the city of Vlaardingen can stay cool during increasingly hot summers over the next twenty-five years. We know that urban areas, especially the city centre and the harbour districts, can become much hotter than the surrounding countryside because concrete and asphalt trap heat while a lack of shade prevents cooling. To tackle this, the city has plans to add more trees. Our research aims to stress-test these plans to see if they would hold up in the context of rising temperatures by the year 2050.

To do that, this research utilizes the Decision Making under Deep Uncertainty (DMDU) framework to move beyond traditional best-guess forecasting. Using a System Dynamics model and the DMDU framework, the study simulated thousands of potential futures for 11 specific neighborhoods in Vlaardingen. The model accounts for complex interactions between climate drivers, population growth, housing development, and the biological life cycle of urban green infrastructure. A diagnostic equation was adopted to calculate the maximum Urban Heat Island effect that integrated urban characteristics like the Sky-View Factor and vegetation fraction with climate projections. By looking at thousands of possible futures we tested where the current greening plans might fall short, and what is needed to keep the city liveable for everyone.

Our results show that in the hottest parts of the city, like the centre, temperatures can be up to four degrees higher than in rural areas during future heatwaves. While planting more greenery is a vital step, we found that simply putting trees in the ground is not enough. They must be regularly cared for and replaced immediately if they die. If the city neglects this maintenance or fails to replace dead trees, the cooling effect will quickly disappear. This will leave residents vulnerable to extreme heat.

To ensure long-term success, we recommend that the city treats its parks and trees with the same level of detailed planning and steady funding as it does for housing and roads. This means setting aside a reliable budget that can handle rising costs and ensuring that professional care for the greenery happens every few years without fail. We also suggest using new tools, like installing sensors that show real-time heat levels to help people stay safe during the hottest hours of the day. By working closely with health experts and regional partners, Vlaardingen can build a cool network of shaded paths and refreshing spaces that keep the community healthy and comfortable for decades to come.

Samenvatting (Nederlands)

Deze studie onderzoekt hoe de gemeente Vlaardingen koel kan blijven tijdens de steeds warmere zomers van de komende vijfentwintig jaar. We weten dat stedelijke gebieden, met name het stadscentrum en de havenwijken, veel warmer kunnen worden dan het omliggende platteland, omdat beton en asfalt warmte vasthouden en een gebrek aan schaduw afkoeling verhindert. Om dit aan te pakken, heeft de gemeente plannen om meer bomen aan te planten. Ons onderzoek heeft tot doel deze plannen aan een stresstest te onderwerpen om te zien of ze standhouden in de context van stijgende temperaturen tegen het jaar 2050.

Daartoe maakt dit onderzoek gebruik van het Decision Making under Deep Uncertainty (DMDU)-raamwerk om verder te gaan dan traditionele best-guess-prognoses. Met behulp van een System Dynamics-model en het DMDU-raamwerk heeft de studie duizenden mogelijke toekomsten voor 11 specifieke wijken in Vlaardingen gesimuleerd. Het model houdt rekening met complexe interacties tussen klimaatfactoren, bevolkingsgroei, woningbouw en de biologische levenscyclus van stedelijke groene infrastructuur. Er werd een diagnostische vergelijking gebruikt om het maximale stedelijke hitte-eilandeffect te berekenen, waarbij stedelijke kenmerken zoals de Sky-View Factor en de vegetatiefractie werden geïntegreerd met klimaatprognoses. Door te kijken naar duizenden mogelijke toekomstscenario's hebben we getest waar de huidige vergroeningsplannen tekortschieten en wat er nodig is om de gemeente leefbaar te houden voor iedereen.

Onze resultaten tonen aan dat in de warmste delen van de gemeente, zoals het centrum, de temperaturen tijdens toekomstige hittegolven tot vier graden hoger kunnen zijn dan in landelijke gebieden. Hoewel het aanplanten van meer groen een essentiële stap is, hebben we geconstateerd dat het niet voldoende is om alleen maar bomen te planten. Ze moeten regelmatig worden onderhouden en onmiddellijk worden vervangen als ze doodgaan. Als de gemeente dit onderhoud verwaarloost of dode bomen niet vervangt, zal het verkoelende effect snel verdwijnen. Hierdoor worden de inwoners kwetsbaar voor extreme hitte.

Om succes op lange termijn te garanderen, raden we de gemeente aan om haar parken en bomen met dezelfde gedetailleerde planning en stabiele financiering te behandelen als woningen en wegen. Dit betekent dat er een betrouwbaar budget moet worden gereserveerd om stijgende kosten op te vangen en ervoor te zorgen dat het groen om de paar jaar zonder mankeren professioneel wordt onderhouden. We stellen ook voor om nieuwe hulpmiddelen te gebruiken, zoals sensoren die de temperatuur in realtime weergeven, zodat mensen tijdens de warmste uren van de dag veilig kunnen blijven. Door nauw samen te werken met gezondheidsdeskundigen en regionale partners kan Vlaardingen een koel netwerk van schaduwrijke paden en verfrissende ruimtes opbouwen die de gemeenschap de komende decennia gezond en comfortabel houden.

1. Introduction

This report details the results from a research project funded by a Resilient Delta Initiative Kick-Starter Grant (€48k), entitled 'Building Heatwave Resilience: A Pathway for Equitable Urban (Re)Developments in Rotterdam'. The grant was awarded in June 2024 and the project lasted from 1 September 2024 to 31 August 2025. The co-applicants were Arka Bhattacharyya and Sylvia I. Bergh.

While the original proposal focused on the city of Rotterdam, this changed to the municipality of Vlaardingen during implementation, as we encountered difficulties to obtain the relevant data on Rotterdam, while Vlaardingen presented a similarly interesting and relevant case. In addition, so far, no academic study has been done on the topic of heatwaves and/or urban greening in Vlaardingen, whereas there are quite a few studies available for Rotterdam (see Ahmed et al 2025; van der Hoeven and Wandl 2018; and the various student theses and other reports on the Rotterdam Heatlab's website).

Through this project, we aimed to kick-start the journey of finding feasible and practical scientific solutions for making European cities resilient to extreme heatwaves, starting with Vlaardingen. While sea-level rise is often considered the dominant threat for Dutch cities posed by climate change, changing temperature patterns cannot be overlooked. History shows that hazards catching us off-guard can turn into disasters due to lack of preparedness, which further motivated our pursuit of this research project.

Apart from addressing an important policy issue, our study also addresses several gaps in the academic literature. While existing literature has extensively focused on modelling heatwaves and urban heat islands (UHI), studies on extreme heat planning and governance (with a focus on urban greening) are relatively rare (Keith et al., 2019). Additionally, while numerous studies have identified a link between heatwaves and social vulnerability conditions such as age, poverty, and racial and ethnic backgrounds, equitable solutions for heatwave resilience are not always stakeholder-centric and adaptive to future uncertainties. Thus, what is missing in the existing scientific literature is a Robust Decision-making Model (RDM) for creating stakeholder-centric and equitable pathways for adaptation plans aimed at urban heatwave resilience considering the deep uncertainties in the future. As we will detail in section 3, doing so was the objective of this research.

We very much hope that this report will be useful for the greening policy development of the municipality of Vlaardingen, as well as for other municipalities that are faced with the question of how best to allocate scarce land and resources for climate change adaptation. We also plan to utilize the findings from this study to pursue larger Dutch and/or European grants to research the potential application of our methodology and solutions to other Dutch and European cities and hereby invite interested partners to contact us.

The report is organized as follows. The next section gives a short background to heatwave trends and urban heat island effects. Section 3 then states the research questions and details the methodology. Section 4 presents the findings, and section 5 provides some policy recommendations.

2. Heatwave trends and urban heat islands effects

Climate change is rapidly altering temperature patterns in The Netherlands. The climate scenarios presented by the Royal Netherlands Meteorological Institute (KNMI) in 2014 and 2023, along with the 2021 Climate Report,[1] indicate a projected increase in both the frequency and intensity of heatwaves across the Netherlands. The KNMI defines a heatwave as a sequence of at least five summer days (with maximum temperature of 25.0 °C or higher) of which at least three are tropical (with a maximum temperature of 30.0 °C or higher).[2] The summers of 2003 and 2006 saw extreme heatwaves across Europe, and The Netherlands was not exempted from that. According to Garssen et al (2005), between 1400 and 2200 deaths in the summer of 2003 may have been heat-related (see also Huizinga and Kolen 2019 for a more historic perspective on heat-related mortality in The Netherlands). The findings from the 2024 Public Health Foresight Study (den Broeder et al 2024: 52) indicate that in the future, heat stress will have a bigger impact on our lives than it does now, and it will also occur more frequently. Heat stress is defined as the discomfort experienced from heat, for example during a heatwave. This will particularly affect the elderly, people with chronic heart disease, (very) young children and pregnant women. Symptoms include fatigue or headaches, developing a rash, feeling unwell, or even suffering a heat-induced stroke. Heatwaves and high temperatures lead to more premature deaths, especially among the over 75s and the chronically ill. In the KNMI's 'High greenhouse gas emissions' scenario, the increase in mortality due to heat is the greatest, meaning that in 2050, approximately 3,800 people will die prematurely, rising to 10,000 by 2100.

An aging population makes the Dutch society particularly vulnerable to heat, and urbanization. Due to Urban Heat Island (UHI) effect, urban areas experience more heat than surrounding rural areas. According to the UK's Royal Meteorological Society (and see also Figure 1 below), "the UHI effect is a phenomenon describing the elevated temperatures felt in towns and cities compared to rural surroundings. This is particularly felt at night-time as the heat retained by artificial surfaces is slowly released, keeping temperatures higher than in the countryside. The UHI effect also includes the reduced cooling effect of vegetation in urban areas, and the compounding effect of anthropogenic heat." [3] According to Ministeries van VWS, VRO en I&W (2025), the temperature difference with the surrounding area can reach 7 or 8 °C.[4]

A warmer built environment also limits the possibility of natural cooling in buildings. As part of the energy transition, the Netherlands is focusing on insulating homes, making them more difficult to keep cool in the summer once heat has entered. Especially in

[1] See https://www.knmiprojects.nl/projects/climate-scenarios (for the 2014 scenarios) and https://www.knmi.nl/kennis-en-datacentrum/achtergrond/knmi-23-klimaatscenario-s (for the 2023 scenarios); see https://www.knmi.nl/kennis-en-datacentrum/achtergrond/knmi-klimaatsignaal-21 for the 2021 climate report (all accessed on 21 January 2026).
[2] See https://www.knmi.nl/nederland-nu/klimatologie/lijsten/hittegolven (accessed on 20 January 2026)
[3] Cited from https://www.rmets.org/metmatters/urban-heat-islands (accessed on 18 January 2026).
[4] See also Mentaschi et al (2022) for a global long-term mapping of intra-city UHI extremes.

neighbourhoods with a low socio-economic status, homes, buildings, and residents are poorly equipped to withstand (persistent) heat. Residents often do not know how to prevent heat in their homes or are unable to do so. This may be because they are unable to make adjustments to the building themselves, as they are renting or live in a building with a homeowners' association (Ministeries van VWS, VRO en I&W, 2025).

Dutch cities such as Rotterdam are actively pursuing sustainability through urban greening and redevelopment projects, for examples as outlined in the "Rotterdam Climate Agreement"[5] to reduce greenhouse gas emissions. However, while urban resilience plans often acknowledge certain vulnerabilities, they often fail to integrate social dimensions such as age, gender, disabilities, racial and ethnic backgrounds, economic conditions, etc., pointing to the need for a holistic approach to urban development projects that consider both climate change adaptation and social resilience. The existing National Heatwave Plan,[6] which serves as a warning system to inform stakeholders about an impending heatwave, might also not be adequate to deal with extreme heatwave scenarios like 2003 or 2006 in absence of a stress-tested heat adaptation plan.

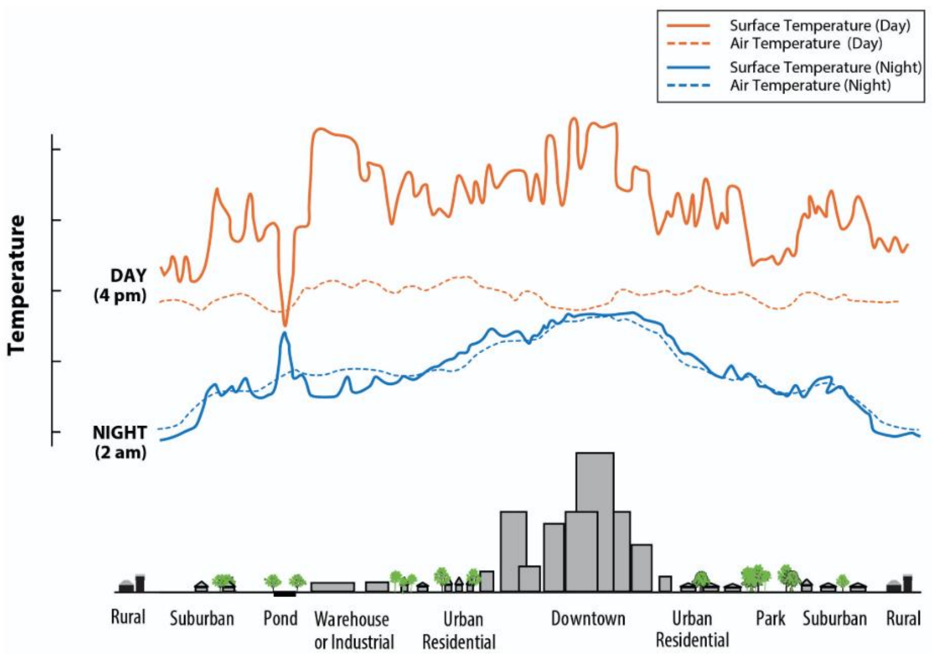

Figure 1 Heat Island Effect Diagram

Source: https://www.epa.gov/heatislands/what-are-heat-islands (accessed 21 January 2026).

[5] See https://rotterdamsklimaatakkoord.nl/ (accessed on 21 January 2026)

[6] https://www.rivm.nl/hitte/nationaal-hitteplan (accessed on 21 January 2026)

3. Research questions and methodology

Our research questions are:

- What is the effectiveness of current and planned urban greening projects in Vlaardingen in the year 2050, taking into account developments with regard to housing, changing population, land use patterns, and other related sectors?
- Will these projects lead to reduced heat exposure?
- What will be the associated costs of such greening projects, and are they sustainable for the municipal budget?

In other words, we seek to take a longer-term view (see Figure 2 below).

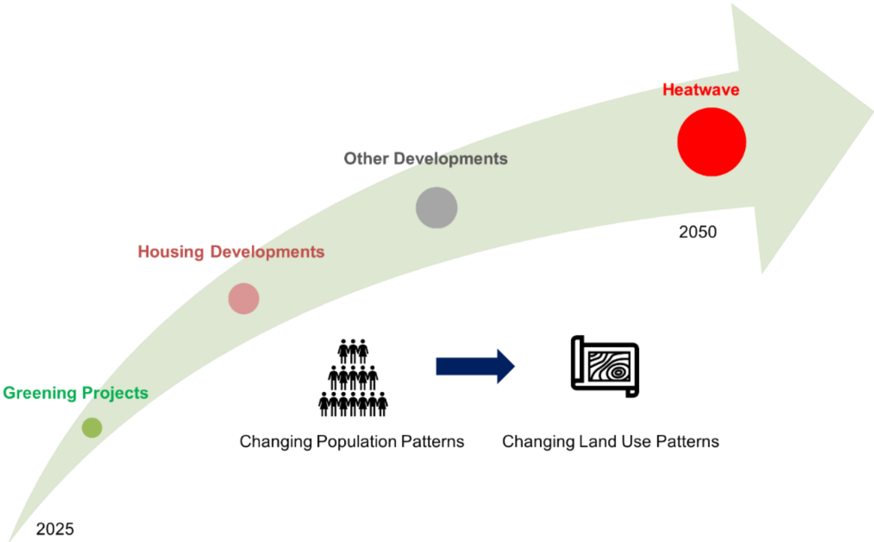

Figure 2 Long Term Approach in Estimating Effectiveness of Urban Greening against Heatwaves

Source: Authors' own construction

3.1 Study Area

Vlaardingen is located in South Holland province, to the West of Rotterdam and North of the Maas river. It had a population of 76,4k in 2024 and is expected to grow to 88,5k by 2050. It occupies an area of 26,7sq km, and the municipality is composed of 8 'wijken' and 40 'buurten'. A 'wijk' is a district or larger area within a city or town, while a 'buurt' can be translated as a neighbourhood, i.e. a smaller, more intimate part or neighbourhood of that district, often with strong social cohesion. A district is thus typically a larger area that may encompass multiple neighbourhoods. It is often defined by geographical or administrative boundaries, such as rivers, roads, or municipal divisions, may have its own council and/or specific facilities and infrastructure, such as schools and parks. This study focused on 11 neighbourhoods (see selection criteria in the next section). The climate challenges facing the municipality, as is the case for many if not all municipalities in The Netherlands, are floods, drought, heatwaves, biodiversity loss, and sea level rise. The municipality has planned 41 climate adaptation measures by 2034, of which nine are related to greening (Gemeente Vlaardingen: *Omgevingsprogramma Klimaatadaptatie 2025*).

3.2 UHI Calculation

Since the research is about calculating the Urban Heat Island (UHI) effect, we first had to establish a framework for calculating it. In The Netherlands, the framework developed by Theeuwes et al. (2017) and Dirksen et al. (2019) is widely used in academia and practice. In fact, the KNMI also adopted their framework for this UHI calculation (Van Dorland et al. 2023). The framework computes maximum UHI (UHI_{max}) value based on a combination of climatological and urban characteristics as shown in equation 1.

$$UHI_{max} = (2 - SVF - F_{veg}) \sqrt[4]{\frac{S(T_{max} - T_{min})^3}{U}} \qquad 1$$

This formula relies on three primary meteorological variables: the daily averaged incoming shortwave radiation (S), the diurnal temperature range (DTR) calculated as $(T_{max} - T_{min})$, and the diurnally averaged wind speed at a 10-meter height (U). The incoming radiation (S) represents the energy entering the system, which is stored in the urban fabric during the day and released at night. The DTR is positively correlated with the UHI_{max} because it reflects the atmospheric stability and cooling rates of the surrounding rural environment. Conversely, wind speed (U) acts as a mitigating factor; higher wind speeds facilitate better mixing and ventilation, which reduces the temperature difference between urban and rural areas.

The equation also incorporates specific urban morphological properties to adjust the heat island intensity based on a city's physical structure. The term (2-SVF-F_{veg}) quantifies these structural impacts using the sky-view factor (SVF) and the vegetation fraction (F_{veg}) within a 500-meter radius of the urban measurement site. The SVF measures the amount of open sky visible from the street level; lower SVF values indicate narrow street canyons that trap thermal radiation more effectively, thereby increasing the UHI_{max}. Similarly, the vegetation fraction (F_{veg}) accounts for the cooling benefits of urban greening, as higher levels of vegetation increase evapotranspiration and reduce overall heat storage compared to built-up surfaces. By combining these structural features with routine meteorological data, the equation provides a robust, physically based tool for UHI_{max} estimations. It should be noted that the equation is only applicable if $0< F_{veg}<0.4$ and $0.2<SVF<0.9$ (Dirksen 2019). Due to these two constraints, we only focused on 11 neighbourhoods within the municipality of Vlaardingen. These are: Babberspolder Oost, Babberspolder West, Centrum, De Vergulde Hand, Havengebied Oost, Maasboulevard, Oostneighbourhood, Vettenoordse Polder Oost, Vettenoordse Polder West, Vijfsluizen, Vogelneighbourhood Zuid. Figure 3 displays the current urban characteristics in Vlaardingen.

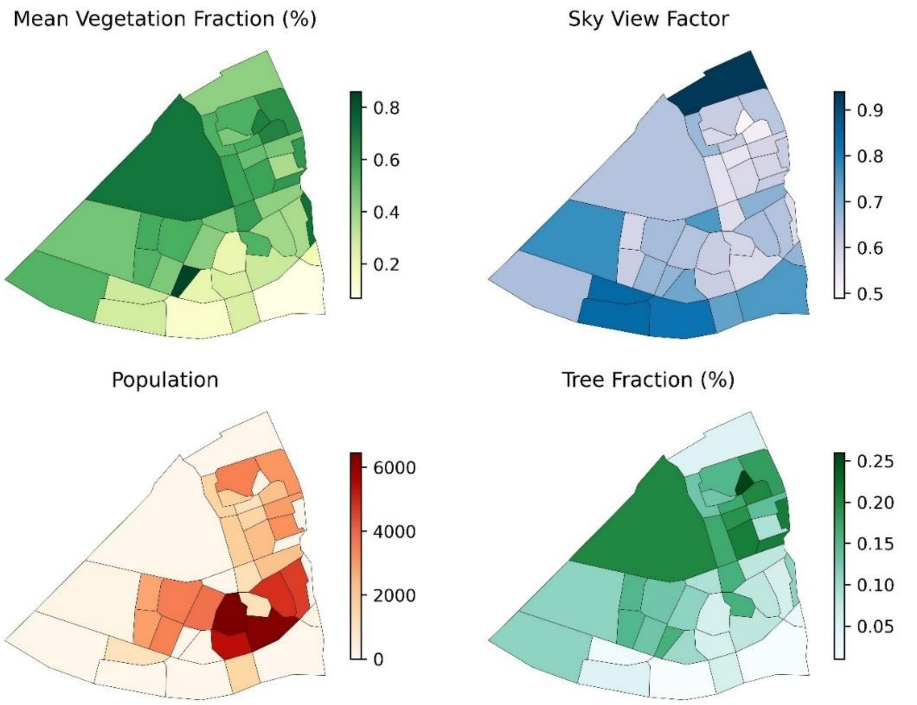

Figure 3 Urban Characteristics in Vlaardingen

Source: Authors' own construction with data from CBS[7], KNMI[8], and RIVM[9]

3.3 Decision Making under Deep Uncertainty

The methodology for this research is grounded in the principles of Decision Making under Deep Uncertainty (DMDU). This approach is specifically chosen to address the wicked problem of urban heat, where traditional probabilistic forecasting often fails due to the unpredictable nature of climate change, socio-economic shifts, and long-term urban development (Marchau et al., 2019).

The implementation follows a structured, iterative process designed to move from problem framing to the identification of robust strategies. The research begins by defining the system boundaries and the goals of the Vlaardingen municipality. Unlike traditional planning that seeks an optimal solution for a single predicted future, the DMDU approach acknowledges that the future is fundamentally uncertain (Walker et al., 2003). The system is framed using the XLRM framework, which serves as the conceptual map for the simulation model. This step ensures that all exogenous uncertainties (X), policy levers

[7] https://www.cbs.nl/nl-nl/maatwerk/2025/38/kerncijfers-wijken-en-buurten-2024 (accessed on 11 March 2026)

[8] https://dataplatform.knmi.nl/dataset/svf-nl-3 (accessed on 11 March 2026)

[9] https://www.atlasnatuurlijkkapitaal.nl/en/node/1761 (accessed on 11 March 2026) Mean Vegetation Fraction – Groenkaart van Nederland per buurt and Tree Fraction – Groenkaart van Nederland enkel bomen

(L), system relationships (R), and performance metrics (M) are explicitly accounted for before any simulations occur. The framework is shown in Figure 4 below.

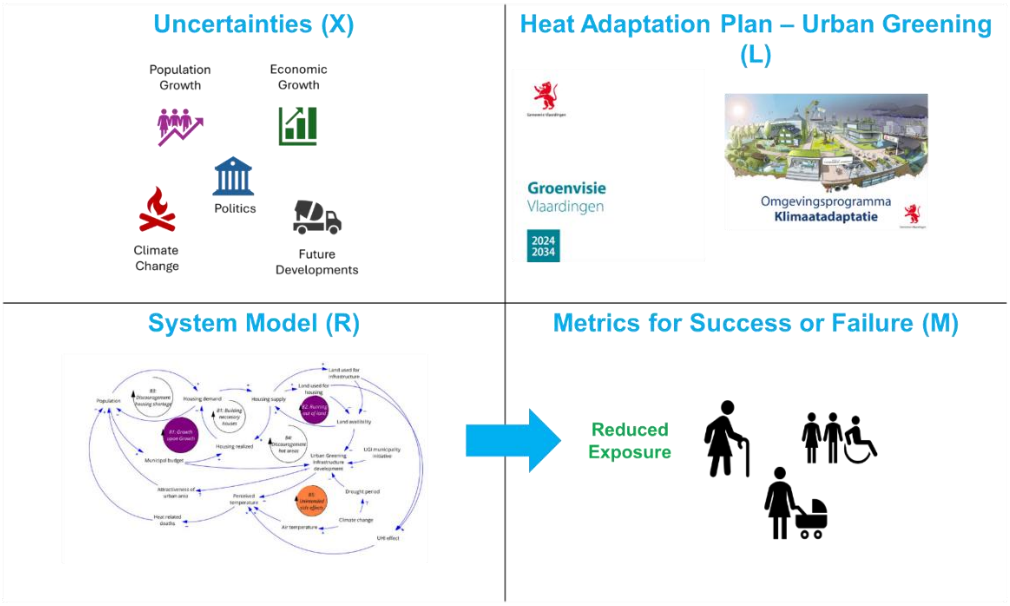

Figure 4 XLRM Framework

Source: Authors' own construction based on Lempert et al. (2003) and Vlaardingen policy documents

Rather than predicting a most-likely future, this methodology employs exploratory modelling (Lempert et al, 2003). A computational model is used to map the ensemble of possibilities by running thousands of simulations. Each simulation represents a different combination of the uncertainties identified in the XLRM matrix—such as varying KNMI '23 climate scenarios, fluctuating maintenance budgets, and different population growth rates. This process allows for the discovery of vulnerability regions, or conditions under which the current urban greening plans fail to meet the heat reduction targets.

The core of the methodology involves stress-testing the proposed greening initiatives. The performance of these levers is evaluated across the entire range of generated scenarios. A Robustness Analysis is then conducted to identify strategies that perform well enough across a vast array of futures, rather than performing perfectly in one and failing in others (Lempert et al, 2003). This is particularly vital for Vlaardingen, where the long-term health of green infrastructure is highly dependent on maintenance cycles that may be threatened by future economic shifts.

3.3.1 Uncertainties

The exogenous uncertainties within this research encompass a range of environmental, socio-political, and biophysical factors that are beyond the direct control of decision-makers but fundamentally impact the performance of adaptation plans. These include primary climate drivers, such as future temperature scenarios and their resulting heat island effects, as well as socio-economic variables like population growth and shifting political cycles that dictate the consistency of municipal greening budgets. Additionally, the model incorporates biophysical unknowns related to the mean lifetime of urban trees and the varying levels of impact that maintenance frequency has on tree health. Systemic constraints are also represented through land availability, where a saturation factor slows down planting and housing as land becomes scarce.

3.3.2 Policy Levers

The primary policy lever in the DMDU framework is the greening plan of the municipality. In 2050, one of the variables that is changing in equation 1 is the percentage of vegetation in each neighbourhood. That percentage is governed by Vlaardingen municipality's Green Vision plan, i.e., *Groenvisie Vlaardingen 2024 – 2034*,[10] which aims to ensure 30% tree shade in each district. We assumed that this vision translates into a target of 30% vegetation fraction in each neighbourhood within Vlaardingen.

Beyond initial planting, the policy levers include operational mandates for the long-term survival of the urban green spaces. The municipality controls the maintenance frequency, which determines how often green assets are inspected and cared for to extend their functional lifetime. A critical decision lever is the replanting fraction, which defines the commitment level for replacing trees that are lost to disease or climate stress. These operational choices are balanced against other municipal priorities, such as housing development plans. This requires a coordinated approach where greening initiatives are integrated into the broader land-use strategy, ensuring that adaptation goals are met even as the city's population and infrastructure grow.

3.3.3 System Model

The core of this research is a system model designed to simulate how Vlaardingen evolves from 2025 to 2050. Rather than looking at urban greening in isolation, the model views the city as a living network where housing, population, and nature are constantly interacting. It tracks the life cycle of urban greenery from the moment a tree is planted until it reaches maturity and begins providing shade while simultaneously accounting for the land needed for new homes and transportation. By simulating these processes over 25 years, the model helps us understand whether today's greening targets will actually be enough to keep the city cool under future climate conditions.

To visualize these complex interactions, we use a Causal Loop Diagram (CLD) shown in Figure 5. This diagram acts as a map of the cause-and-effect relationships within the city. For instance, it shows a balancing loop where an increase in population creates a higher demand for housing, which in turn reduces the land available for trees. Conversely, reinforcing loops illustrate how consistent maintenance extends the life of green spaces,

[10] https://www.vlaardingen.nl/Onderwerpen/Projecten_in_de_stad/Stadsprogramma_s_Vlaardingen/Stadsprogramma_Groen_Vlaardingen/Groenvisie_Vlaardingen_2024_2034 (accessed 5 February 2026)

ensuring they continue to provide cooling benefits. By mapping these feedback loops, the CLD reveals that urban heat is not just a weather problem, but a result of how our urban planning choices compete with environmental needs.

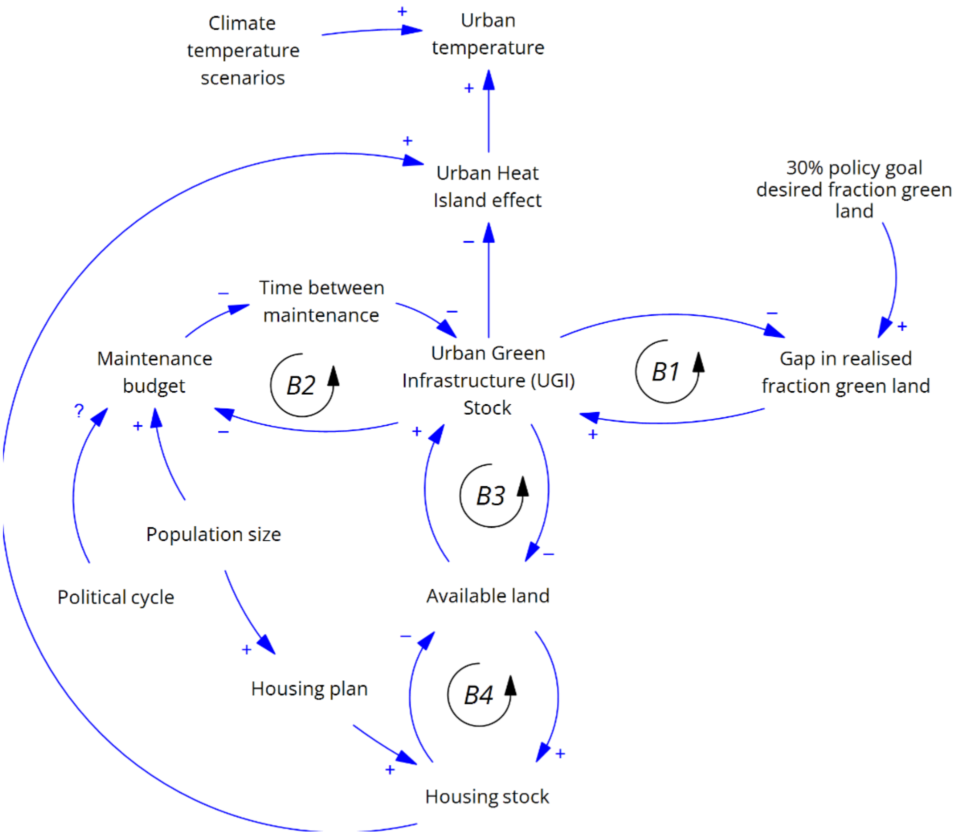

Figure 5 Causal Loop Diagram for System Dynamics Simulation

Source: Authors' own construction

Because we cannot predict the future with certainty, we employ Exploratory Analysis to test our plans. Instead of relying on a single best-guess forecast, we run 3,000 different simulations, each representing a unique combination of possibilities such as extreme heatwaves, varying budget levels, or unexpected population surges. This stress-testing approach allows us to see exactly where our plans are strong and where they might break. By exploring thousands of potential futures, we can identify which strategies are truly robust and will protect the residents of Vlaardingen regardless of which future actually unfolds.

It should be noted that the fabric of urban developments contain more than just housing and greening projects. Other dynamic developments like small business and retail, manufacturing, and water bodies were placed outside the scope of the model. Levers or uncertainties do not influence them, but their values still constrain the overall available land value. Also, the majority of the model was set to represent the detail at neighbourhood level. Increasing the resolution of the model was not deemed viable given the amount of data available. Future work could validate the chosen resolution by applying the model to other municipalities.

3.3.4 Metrics

The UHI calculation framework developed by Theeuwes et al. (2017) and Dirksen et al. (2019) that is shown in equation 1 forms the basis for measuring the effectiveness of urban greening in Vlaardingen. As discussed previously, there are two parts to the equation. The first part relates to meteorological parameters, which were collected from KNMI. Since the research is about understanding the extent of UHI in 2050, we used KNMI projections for the year 2050 as shown in Figure 6. The KNMI’23 climate scenarios provide an updated outlook for the Netherlands based on the 2021 IPCC report, detailing four potential paths (Ld, Ln, Hd, and Hn) for the years 2050. These scenarios are categorized by two main drivers: the level of global greenhouse gas emissions (Low or High) and the degree of change in regional precipitation patterns ('d' for dry-trending and 'n' for wet-trending). Across all scenarios, The Netherlands is projected to experience rising temperatures, accelerating sea-level rise, wetter winters, and more intense summer downpours. The dry variants specifically project significantly drier summers, while wet variants indicate a more substantial increase in winter rainfall.

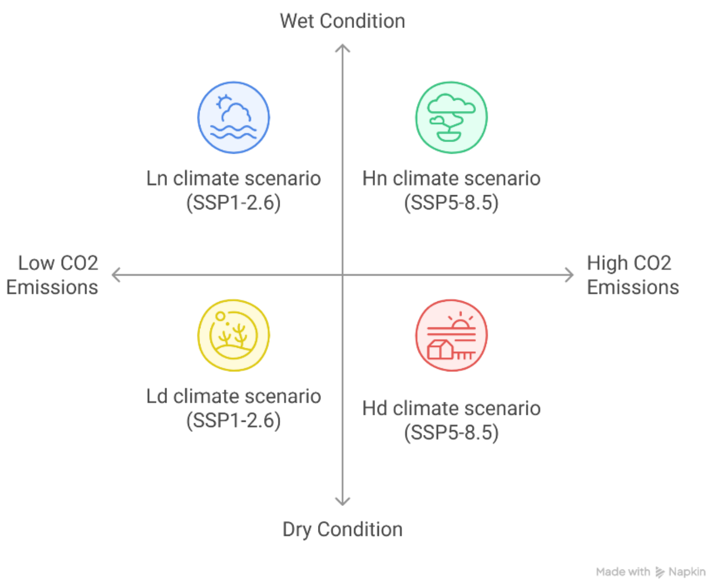

Figure 6 KNMI Climate Scenarios for 2050

Source: Developed with Napkin AI based on van Dorland et al (2023)

The second part of the equation relates to urban dynamics. Here, the sky view factor data was also obtained from KNMI. The percentage of vegetation, i.e., F_{veg} determines the effectiveness of greening projects in reducing UHI. To do that, first, we calculated the maximum UHI values for each neighbourhood within Vlaardingen using the climate variables for 2050 and existing urban characteristics (F_{veg} and SVF). The existing percentage of vegetation was collected from Atlas Natuurlijk Kapitaal’s data portal, which processed the original data from RIVM. The portal summarizes vegetation fraction for each neighbourhood. With all these data, we calculated neighbourhood level max UHI under current urban characteristics and future climate projections.

This max UHI data was additionally utilized to come up with a heat exposure measure. For that, we identified three population groups that are the most vulnerable to heat stress – elderly, children, and poor sections of the community. For each neighbourhood, we multiplied the number of residents of Vlaardingen that belonged to these three groups together with the max UHI value to derive our baseline exposure metric. The cumulative exposure for Vlaardingen was calculated as the sum of exposure of the 11 neighbourhoods of interest. This is the baseline exposure metric. Against this metric, we measured the effectiveness of urban greening projects.

With the urban greening plans, in 2050, the only variable that is changing in equation 1 is the percentage of vegetation in each neighbourhood. The system model yields the percentage of vegetation in the 11 neighbourhoods of interest in Vlaardingen. This percentage vegetation was used to calculate the max UHI under each of the 3,000 iterations. Similarly, future population growth of the vulnerable groups was also computed through the system model and 3,000 possible population scenarios corresponding to the max UHI were derived. Finally, these two variables, i.e., max UHI and vulnerable populations in each of the 11 neighbourhoods in 2050 were used to calculate the cumulative heat exposure of Vlaardingen in 2050. It is worth noting that 3,000 such values were derived, where each corresponds to one iteration reflecting one possible future scenario. In each of these 3,000 scenarios, we calculated the percentage increase or decrease of the exposure metric from its baseline value. Evidently, low or negative change in exposure is more desirable than high positive change.

3.3.5 Data Sources and Stakeholder Consultations for Model Development

In order to map the uncertainties and develop the system dynamics model, we held several informal interviews with experts in academia, the municipalities of Rotterdam and Vlaardingen, the municipal health services of the Rotterdam-Rijnmond region, the Safety Region of Rotterdam-Rijnmond (VRR), as well as The Royal Netherlands Meteorological Institute (KNMI). We also received unpublished and published reports, maps and data sets which were necessary inputs for the model. The data included CBS population data files, district zoning data, KNMI climate scenarios 2023 data, QGIS files, urban greening cost estimates, the Vlaardingen municipality's *groenvisie* (green vision) document and other policy documents such as on housing plans, greening budget, and guidance documents, etc. We also regularly participated in webinars on heat organized by the Klimaatverbond[11] as well as watched the recording of a session on heat stress of

[11] See https://klimaatverbond.nl/ons-werk/hitte/ (accessed on 21 January 2026)

the National Deltaprogram Congress in 2020[12] in order to ensure that we included all relevant variables in our model.

As input to the model development, we held a workshop with the relevant members of the team in charge of managing public and green space at the municipality of Vlaardingen on 4 June 2025. Apart from yielding useful information as to the available policy documents and data sets, it also brought up a number of interesting points. These included details about the ecological mowing policy which increases the surface of green spaces along the streets, aids with biodiversity, retaining rainwater, and infiltration. However, this is a more costly policy than mowing everything short.

Another example of a successful urban greening was an experiment with 15 trees in mobile containers on the central square. Benches and other outdoor furniture were put around them, which made it very attractive for people to come and sit there under the trees when it was warm. The food and drink establishments located there welcomed this initiative, as there were more people consuming food and drinks, and the square was being used more. In the workshop, there was agreement that this is a good alternative to planting permanent trees which is not possible in the centre due to other events taking place there (and for which the space is needed), as well as underground cables & pipes, and logistical movements such as delivery trucks which need space to manoeuvre to offload goods for the businesses.

Workshop participants also pointed out some disadvantages of planting trees in an urban setting. These include the fact that the roots can 'lift' the sidewalks which can become dangerous for residents due to the risk of tripping, and the municipality has to flatten them again. Roots are also an issue for the new underground installations to do with the energy transition, sewerage, and glass fiber cables. More importantly, the ground level is sinking in the Netherlands, but the trees are not. This means that every 30 to 35 years, trees have to be renewed because they are no longer at the right level. We also discussed signs of climate change such as some trees losing their leaves in the summer already (rather than autumn) because of drought. The municipality's response is to plant Mediterranean trees like the Holm Oak (Quercus ilex, *steeneik* in Dutch), but they cannot tolerate too much rain. In other words, it's difficult to find an adapted tree species.

Other challenges we discussed was the water needed for irrigation, and in general the financing for green spaces. Greening is coming after other priorities in the municipal budget, but the *omgevingsprogramma* (urban planning policy) helps to claim a dedicated budget for greening. And incomes from housing taxes also increase if the house values increase, which is the case for those that have more green around them. There are some programs like the NK Tegelwippen[13] (a national competition where residents can get rid of their garden tiles/bricks for free) which the municipality participates in, and subsidies for green roofs. Another initiative is a subsidy for residents which allows them to replace the wooden separation fences between private gardens to be replaced by a hedge.

[12] See https://youtu.be/su59dTWB2gQ?si=NOGjAbJwQV7L3izY (accessed on 21 January 2026)
[13] See https://www.nk-tegelwippen.nl/ (accessed 22 January 2026)

Vlaardingen also has district-level initiatives, so-called *wijkdeals* where people can adopt a space of green which they manage (resulting in savings by the municipality). For this, the residents sign a small contract with the municipality.

The workshop also included a discussion on the decision-making framework or *afweegingskader* that is used to decide where new housing projects will be sited. For example, what does *zwaarwegend maatschappelijke belang* (significant societal interest) mean, which could justify building in the green area, such as a GP's office and health clinics? We also learnt that vulnerable groups get priority for greening projects. For example, the municipality tries to place green spaces around elderly care homes.

Designers of new building projects take the *groenvisie* policy document into account and encourage the developers to include green roofs and facades. In addition, the urban planners try to preserve green spaces by adding higher buildings on existing sites instead of building on new land. When deciding about parking spots and norms, public transport routes are considered and less spots are allocated along those routes. The team is also considering constructing permeable ‘green’ parking spots.

We ended the workshop by discussing the organisational governance implications of urban greening. Having a holistic approach to urban greening means that the municipality needs to work in an integrated way and across different departments, including between the ‘desk’ staff and those actually doing the planting and maintenance.

Once we had developed our preliminary findings and recommendations, we visited Vlaardingen again on 9 October 2025 to present them to the municipality team involved in this research. Their feedback was taken into account as much as possible in this report.

4. Findings

4.1 Assessment of Maximum Urban Heat Island (UHI_{max}) Effects

The spatial analysis of the 11 neighbourhoods in Vlaardingen reveals a significant variation in heat intensity across the municipality as shown in Figure 7. The maximum Urban Heat Island (UHI_{max}) values highlight a clear heat gradient between the densely built urban core and the more permeable residential areas. Specifically, the Centrum and Havengebied Oost areas exhibit the highest thermal stress, with temperature differences reaching up to 4°C higher than the surrounding rural reference points. These areas are characterized by a high fraction of impervious surfaces and a low sky-view factor, which prevents the effective release of stored thermal energy during the night, thereby exacerbating the daily maximum heat levels.

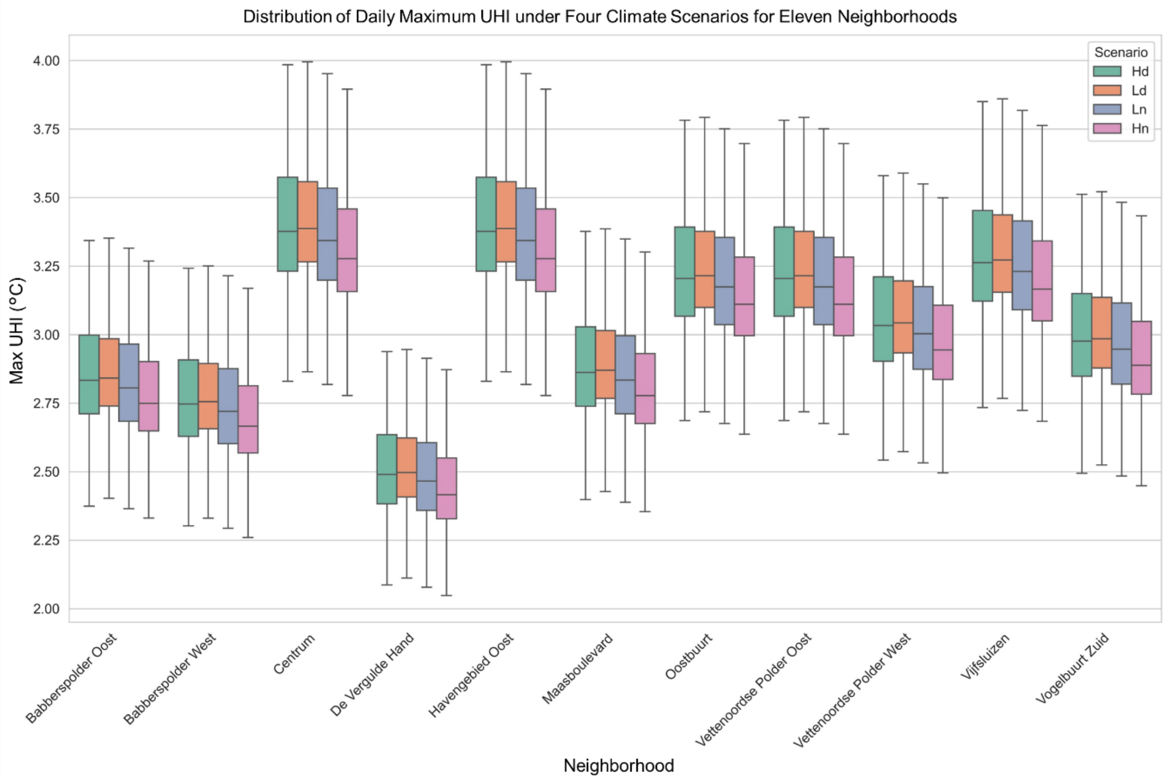

Figure 7 Max UHI Values under 4 Climate Conditions

Source: Authors' own construction

The findings indicate that the current vegetation levels in several neighbourhoods are insufficient to counteract the intensifying heat projected for 2050. While more residential neighbourhoods show moderate UHI_{max} values, the cumulative effect of housing development and increased population density poses a risk of heat trapping. In the absence of expanded greening, these neighbourhoods are expected to see a rise in baseline temperatures. The analysis confirms that the intensity of the heat island effect is not uniform; rather, it is concentrated in zones with the least vegetation fraction, making these the highest priority for the municipality's proposed shade and cooling interventions. In Figure 8, the average max UHI values per day between the months of June and August based on the KNMI's transformed time series are shown for the average of the four climate scenarios. The transformed time series indicate as accurately as possible how the observations fit the climate in the future according to the KNMI climate scenarios. They thus give an impression of what the weather in the future may look like from day to day. They are not a prediction of the weather in the future on a certain day or in a certain year.[14]

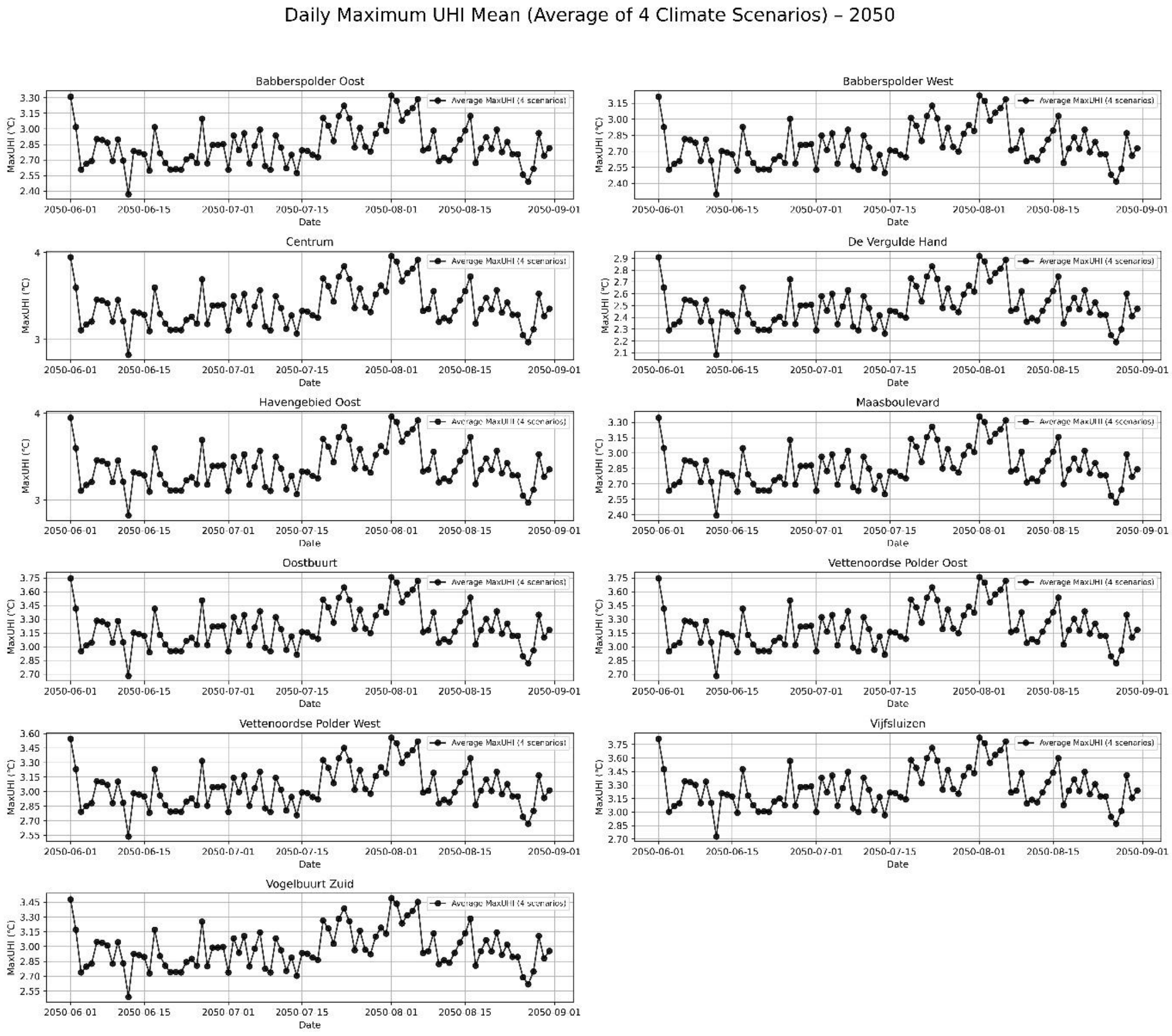

Figure 8 Average Max UHI Variation across 11 Neighbourhoods

Source: Authors' own construction

[14] https://www.klimaatscenarios-data.knmi.nl/kerncijfers (accessed 18 February 2026)

4.2. Vulnerability maps and success/failure zones

Based on the sensitivity analysis, the generated vulnerability maps are shown in Figure 9. In the absence of a clearly defined threshold by the municipality, we decided that if the percentage increase in exposure is within the 25th percentile, this was considered a success. Similarly, if the cumulative cost, i.e., total of tree plantation and maintenance across 25 years adjusted for annual inflation between 1% and 3% falls within the 25th percentile, it was assumed as a success. Figure 9 shows the distribution of these two metrics. The 25th percentiles are shown as dotted black lines.

The results highlight a clear threshold between the success and failure of Vlaardingen's heat adaptation strategy. The performance of the greening plan is primarily dictated by the balance between urban growth and ecological maintenance. As shown in the Success and Failure regions of the analysis, a plan is considered successful only if it maintains the proposed heat exposure metric within safe limits while remaining financially viable. The Success zone represents scenarios where the city remains resilient, while the Failure zone identifies conditions where the urban heat island effect becomes unmanageable or maintenance costs exceed municipal capacities.

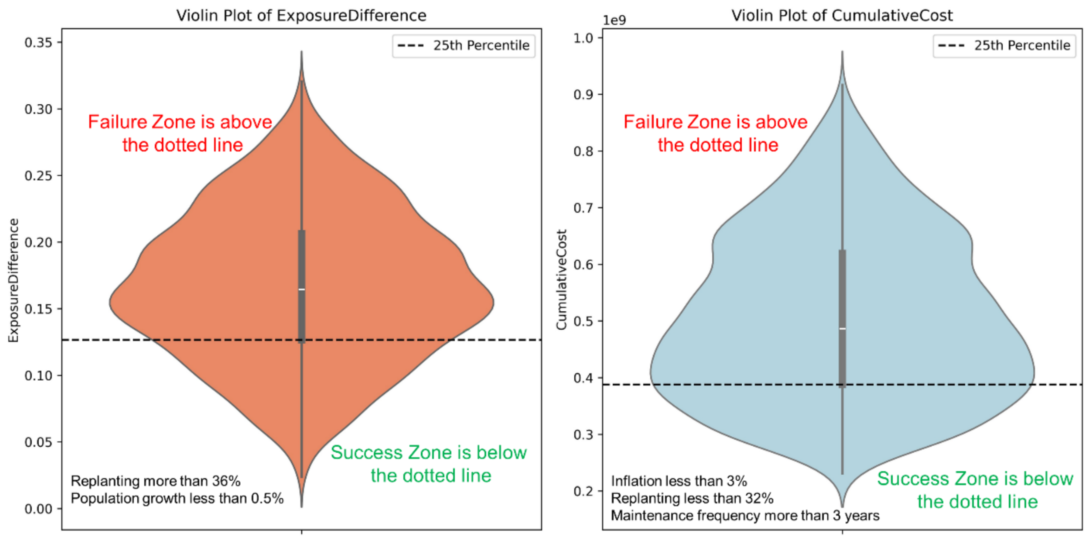

Figure 9 Distribution of Performance Metrics across 3000 Iterations

Source: Authors' own construction

Specifically, the exploratory analysis identifies critical tipping points that decision-makers must monitor. For the greening vision to remain effective through 2050, the replanting rate must stay above 36% and population growth should ideally remain below 0.5%. If the replanting rate drops below 32% or if maintenance is neglected for more than three years, the system enters a failure state regardless of how many trees were initially planted. Furthermore, an inflation rate of more than 3% poses a significant threat to the financial sustainability of the plan. These results demonstrate that planting trees is only half the battle; the long-term robustness of the strategy depends almost entirely on the commitment to consistent maintenance and the replacement of lost green infrastructure.

5. Policy Recommendations

Based on the insights gathered from our research and the failure conditions identified during the stress testing, we are able to offer the following policy recommendations for Vlaardingen municipality.

1. Adopt a Comprehensive Green Master Plan

Vlaardingen is highly susceptible to the **Urban Heat Island (UHI)** effect, particularly in the ***Centrum* and *Havengebied Oost*** areas, where temperature differences can reach up to **4°C** compared to rural surroundings. It is recommended that the municipality transitions from viewing greening as a secondary aesthetic project to a primary infrastructure priority. Much like housing development, urban greening should have a detailed, **long-term master plan** that maps out specific planting locations, species diversity, and spatial connectivity to ensure the **3-30-300 rule** is met across all neighbourhoods.

2. Institutionalize Maintenance and Replanting Mandates

The success of the "Green Vision" is largely reliant on the survival of green infrastructure over its intended lifetime. Our findings indicates that the adaptation plan is likely to fail if the **replanting rate falls below 32%** or if maintenance cycles are delayed beyond **three years**.

- **Guaranteed Replanting**: Establish a policy mandate to **replace 100%** of dead or diseased trees within 12 months to maintain canopy continuity.
- **Frequency over Fixes**: Shift from reactive maintenance to a periodic, **preventative assessment of tree health**. High-frequency maintenance, while more costly, significantly extends the cooling lifespan of the urban green spaces and is more cost-effective than frequent mass-replanting.

3. Integrated Land-Use and Heat Monitoring

Greening should not exist in a vacuum. The municipality should integrate heat mitigation targets directly into housing and transportation development plans.

- **Heat Island Monitoring**: Install a network of **local temperature sensors** in high-risk zones (*Centrum* and *Havengebied Oost*) to monitor the real-time effectiveness of cooling interventions.
- **Multi-Strategy Adaptation**: While greening is effective, it should be **combined with other measures** such as using heat-resistant or high-reflectivity materials in new constructions, sun shade sails etc., to buffer against the most extreme KNMI '23 climate scenarios.

4. Ensure Financial and Data Sustainability

A robust plan requires both funding and information. The municipality must account for the impact of **inflation** and changing **population patterns** on maintenance budgets.

- **Dynamic Budgeting**: Conduct **periodic assessments of maintenance cost** requirements, adjusting for projected inflation to avoid funding gaps that lead to tree mortality.
- **Cross-Institutional Collaboration**: Formalize **data-sharing agreements** with regional partners like RIVM, KNMI, and the Safety Region Rotterdam-Rijnmond (VRR). Maintaining a shared database of urban heat metrics and maintenance records is essential for the iterative evaluation and adjustment of the adaptation strategy through 2050.

5. Quantify Public Health and Economic Benefits

While this study focused on temperature reduction and maintenance costs, the direct financial impact on healthcare is a significant factor. Calculating the benefits of urban greening in terms of **healthcare cost savings** for the specific case of Vlaardingen was beyond the scope of this study.[15] Hence, we would recommend this as an area for future research, perhaps by students of the Rotterdam Heat Lab.

6. Integrate Advanced Heat Stress Metrics

In terms of outlook, there are a few interesting developments taking place which may help us and the municipality of Vlaardingen (and others) to further improve the model and apply our findings. In terms of climate data, the KNMI, together with other partners, is developing a heat stress (*hittekracht*) index to better assess how stressful heat is for humans. This new index is based on the Wet Bulb Globe Temperature (WBGT) and combines temperature, humidity, solar radiation, and wind. It takes into account that a dry summer day with a temperature of 30 degrees and a breeze feels very different from a humid day with a temperature of 25 degrees and no wind. From summer 2026, the index is expected to be available via the KNMI app, so that everyone can see how intense the heat feels at that moment, and can adapt their behaviour accordingly.[16] Our findings might also be relevant for the EU-funded project COOL CITIES which aims to develop a methodology to determine where and how to realise a cool network (shaded outdoor routes and cool places), and the municipality of Vlaardingen might want to connect with this project to learn more.[17]

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[15] See studies such as Iungman et al (2023), Lee and Maheswaran (2011), Willis and Crabtree (2011),
[16] See https://www.knmi.nl/kennis-en-datacentrum/uitleg/hittekracht (accessed on 18 January 2026)
[17] See www.interregnorthsea.eu/cool-cities (accessed on 18 January 2026)

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Colophon

Title	Stress Testing Urban Heat Adaptation and Greening Plans: A simulation model applied to the municipality of Vlaardingen, The Netherlands
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Publication date	March 2026
Acknowledgements	Apart from the Resilient Delta Initiative (and Jelle Burger in particular), we would like to thank the municipality of Vlaardingen (and especially Julia van der Weijde, Climate and Sustainability Advisor to the team in charge of managing public space, and the members in her team) for all their assistance and encouragement. The research would not have been possible without their participation in our research activities, as well as help with data collection. We are also grateful to Rick Heikoop at the Rotterdam University of Applied Sciences and his team at the Rotterdam Heatlab[18] for his support, as well as Danny van Duijn at the Safety Region Rotterdam-Rijnmond and colleagues at the Municipal Health Services GGD & GHOR in the same region, i.e. Yvonne van Duijnhoven, Esther Wienese and Josine van den Bogaard. We are also thankful to Janette Bessembinder and Leon van Voorst at the Dutch Meteorological Institute KNMI for sharing climate forecast related data and resources. We are grateful to Stephanie Erwin (Amsterdam University of Applied Sciences) and Lisette Klok (Climate Adaptation Services) for sharing insightful resources on urban heat islanding with us. We would also like to thank the participants at the various workshops and conferences in which we participated and/or presented our research design and preliminary findings for their useful

[18] See https://convergence.nl/resilient-delta-heatlab/

feedback and the opportunity to network.[19] Finally, we thank Laura van Gelder for her help with formatting this report.

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ISBN/EAN 978-94-6518-301-5

ISBN: 978-9-46518-301-5

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This project was funded and supported by the Resilient Delta initiative, a collaboration between Erasmus University Rotterdam, Erasmus Medical Center and TU Delft (jointly known as Convergence).

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[19] Among others, we participated in and/or presented our work at The Hague Humanitarian Studies Centre (HSC) (based at the International Institute of Social Studies, Erasmus University Rotterdam) annual conference on 13 September 2024, the Kick-off Meeting of the Rotterdam Heat Lab on 7 November 2024, the ZonMw and Samen Klimaatbestendig werkbijeenkomst hitteadaptatie on 27 January 2025, the HOPE - Responding to Heatwaves in the Older People Ecosystem project final conference in Brussels on 3 March 2025, the first National Heat Action Day in Rotterdam on 2 June 2025, the joint conference by the European Safety and Reliability Association (ESREL) and Society for Risk Analysis Europe (SRA-E), Stavanger, Norway, from 15-19 June 2025, and the IHS Urban Research Day in Rotterdam on 14 October 2025. Our abstract for the ICONHIC International Conference on Natural Hazards & Infrastructure, to be held from 29 June to 2 July 2026 in Chania, Greece has been accepted.

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