Planning Support System Development for analysing environmental performance of form-based design decisions: Case Study of Enschede

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Abstract

The environmental performance of urban neighbourhoods is a crucial indicator to measure the sustainability of the built urban form, especially as cities face increased urbanisation and densified development. With new construction contributing significantly to global carbon emissions, there is a need to understand how modifications in the urban form can affect its environmental performance at the scale of the neighbourhood. This research addresses this need by developing a Planning Support System workflow to aid decision-making in urban planning in order to analyse environmental performance, focusing on thermal comfort and solar energy potential. It explores the relationship between urban form and the selected environmental performance indicators while utilising freely available 3D geoinformation data of the Netherlands. It develops simplified workflows using established plug-ins and open-source 3D software that can be replicated by smaller municipalities with resource constraints, thus removing barriers to 3D-data based data-driven decision making for sustainable and informed urban planning.

1. Introduction

The built form of urban area significantly affects the environmental performance at the scale of the neighbourhood (Mussawar et al., 2023). Given that construction contributes approximately 40% of the total global carbon emissions, and urbanisation and densification of cities continue unabated, it is necessary to understand the impact of urban form-based decisions on its environmental performance (van Oostrom, 2022). As the scale of action shifts from policy at global level to action at a local level, municipalities are now obliged to create action plans within the realms of the national and international policy (Salter et al., 2020). Acknowledging the critical role of early-stage decision-making in influencing urban form (Méndez Echenagucia et al., 2015), there is a requirement for a Planning Support System workflow that facilitates informed decision-making in planning projects with the objective of analysing environmental performance, as a contribution to sustainability at a local scale.

To derive comprehensive insights into the environmental performance of neighbourhood-scale projects, a 3D perspective is important as buildings exist under the influence of their surroundings. It enables understanding spatial relations from a volumetric viewpoint, highlighting the influence of morphology in immediate surroundings. Thus, this research intends to make use of the freely available 3D geoinformation of the Netherlands to model existing and future scenarios to examine to what extent does change in urban form effect the environmental performance of a neighbourhood.

The environmental performance of buildings and neighbourhoods together contribute to urban liveability as the immediate outdoors are seen as an extension of the living space (Lau et al., 2018). As the research delves into the components and contributors to environmental performance and its measurement, it is crucial to clarify the terminology. Indicators describe the state of the environment and are used to assess performance (European Environment Agency, n.d.). They are often made of a combination of parameters and serve as an estimate of a system, such as PET (thermal comfort indicator) or Solar Potential estimate derived from solar irradiation (in KWh/m^2). Variables are any modifiable factors within a system, such as building orientation, or roof area. They may be dependent or independent in nature and can be measurable or qualitative. Parameters are measurable variables, such air temperature, or percentage of shadowing of roof surfaces.

While multiple performance indicators exist, such as thermal performance, energy consumption, greenery, daylighting, carbon emissions etc, in the context of this research, environmental performance is narrowed down to two performance indicators – the indicator of thermal comfort due to urban built form (estimated using Physiological Equivalent Temperature) and the indicator of solar rooftop energy harvest (using pixel-based Solar Energy Potential suitability analysis). These are selected as both indicators are very dependent on location and morphology and have differing morphological requirements for improvement – as is illustrated further in Table 1.

UHI	Source	Solar Potential	Source
Average building height: street width ratio - urban canyon	(Deng and Wong, 2020; Nasrollahi et al., 2021; Siu et al., 2021)	Available roof area (not too small, without major obstructions)	(Li-Lian, 2022)
Shadowing from neighboring buildings – height ratio between adjacent buildings	(Nasrollahi et al., 2021; Siu et al., 2021)	Shadowing from neighboring buildings – height ratio between adjacent buildings	(Bardhan et al., 2020; Li-Lian, 2022)
Building orientation – long side towards south	(Nakata-Osaki et al., 2018)	Roof angle/orientation – long side towards south	(Bardhan et al., 2020; Li-Lian, 2022)

Airflow blocking due to building arrangement	(Stewart and Oke, 2012)	Obstruction to roof e.g., trees	(Li-Lian, 2022)

Table 1 - Morphological parameters affecting solar potential and thermal comfort, derived from literature review.

The causal effect of urban form on environmental performance have been widely studied in the past few decades (Boccalatte et al., 2020; Li et al., 2020; Poon et al., 2020; Siu et al., 2021; Zhou et al., 2017). Studies focusing on analysing block types for solar potential consistently show that Floor-Area Ratio, building density and building height and spacing between adjacent buildings influence solar potential in residential zones (Liu et al., 2023).

In a similar vein, the relationship between urban morphology and Urban heat Island effect (UHI) has been studied using different indicators such as Physiological Equivalent Temperature (PET), and also through multiple numerical models (Karimimoshaver et al., 2021; Li et al., 2020; Xu et al., 2019). PET considers the air temperature, relative humidity and wind speed, along with surface albedo on the human body (Matzarakis et al., 1999). Based on the Munich Energy-balance Model for Individuals (MEMI), it is a holistic indicator of thermal comfort and describes the thermal perception and grade of physiological stress (Table *2*).

PET/°C	Thermal perception	Grade of physiological stress
≤4.0	Very cold	Extreme cold stress
4.1–8.0	Cold	Strong cold stress
8.1–13.0	Cool	Moderate cold stress
13.1–18.0	Slightly cool	Slight cold stress
18.1–23.0	Comfortable/Neutral	No thermal stress
23.1–29.0	Slightly warm	Slight heat stress
29.1–35.0	Warm	Moderate heat stress
35.1–41.0	Hot	Strong heat stress
41.1≤	Very hot	Extreme heat stress

Source: Matzarakis and Mayer (1997)

Table 2 - Estimated PET, its thermal perception, and the Grade of Physiological Stress

Environmental performance can be measured at different scales. While the most common is that of building scale, i.e., to check whether an individual building is performing in an acceptable manner, the effect of introducing new built forms on its neighbours and their metrics is rarely measured. Easement rights protect individual homeowners from poor design decisions of neighbours. One such easement is solar easement, which allows property users access to their share of sunshine onto their plots (Thoubboron, 2021). These are necessary as increased shade due to taller neighbouring buildings or tall trees can hinder solar energy generation through rooftop panels. Similarly, change in urban form and building material can affect the perception of thermal comfort in its immediate neighbourhood (Elkhazindar et al., 2022) as it can result in changed sky view factor, albedo and shadowing.

The aim of this research is to develop a Planning Support System workflow which can analyse and visualise the environmental performance of existing urban built forms to aid further form-based design decisions at the neighbourhood scale by identifying critical patterns, if any. It also attempts to develop it in a defined and simplified manner so as to allow it to be replicated by smaller resource-constrained municipalities, which should not be deprived of data-based decision making.

The research uses LIDAR data of the Netherlands, available as the AHN-4 dataset as the primary information of the built form. Using Typical Meteorological Year TMY5.2 EPW dataset for the meteorological variables, it attempts to develop a workflow to analyse and visualise the environmental indicators in a 3D environment using free and open-source software.

2. Materials and methods

A part of the administrative neighbourhood of Twekkelerveld in Enschede, the Netherlands is selected as the study area due to availability of data and the plans of the local municipality to redevelop the zone in the near future.

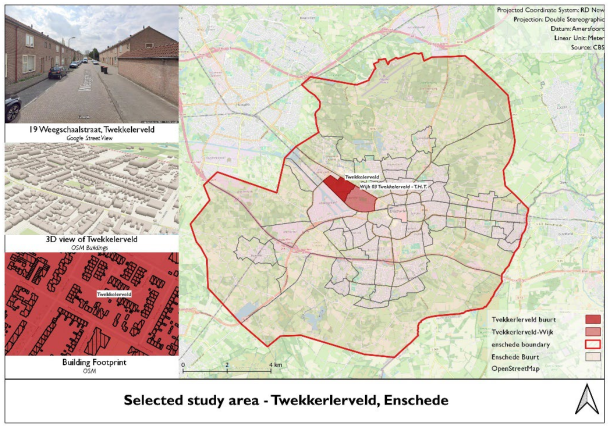

Figure 1 - Location of the study area.

The research is divided into two phases, where the workflow is developed and tested, and result is visualised in a 3D web interface.

Phase 1 estimates the solar energy potential of rooftops and the outdoor human thermal comfort of the streets. The methodological processes to approximate the environmental indicators are intentionally kept simple and easy to replicate, so that they may be adopted by local government departments with ease. Once the method is formalized, it is simplified for other users using Graphic Modeler. Utilising elevation raster (DSM, DEM) derived from the AHN-4 LIDAR data also ensures that future built form scenarios can also be tested in the same methodology by converting to elevation rasters and compared with existing built forms.

Phase 2 develops the workflow for importing 3D information as CityJSON and .obj from the 3DBAG dataset of the Netherlands, and modifying it on the freely available 3D modelling software Blender, and focuses on developing the workflow to visualise the results in a 3D web interface using Cesium Ion.

2.1 Analysing solar potential using open-source methods

To analyse solar potential, data regarding building information such as roof size, building orientation and roof slope are required. These can be collected from the Dutch information portal top10NL (via PDOK, Kadaster), and the DTM and DSM can be derived from AHN-4 (LIDAR data) at the desired pixel size, which is selected as 0.5m in this research. Weather information is collected from an EPW file of the location (meteorological information in an Energy Plus Weather file format). This includes information on Global irradiation as well as direct and diffuse shortwave radiation (EU-JRC, n.d.).

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S.No.	*Topic*	*Dataset*	*Source/ Owner*	*Data form*	*More information*
1	LIDAR/point cloud data	AHN4 dataset	Geotiles.nl	.laz	(Dataset: Actueel Hoogtebestand Nederland 4 (AHN) and PDOK, 2023)
2	Building footprint	BAG dataset	PDOK/Kadaster	.gpkg	https://app.pdok.nl/lv/bag/download-viewer/
3	EPW Weather data – Typical Meteorological Year	PVGIS, Ladybug tools	EU-JRC	.epw, .csv	(EU-JRC, n.d.)
4	3D building models in Netherlands	3D BAG building models	3D geoinformation research group (TU Delft) and 3DGI	.obj, CityJSON	(Peters et al., 2022)

Table 3 - Datasets used in developing the PSS workflow

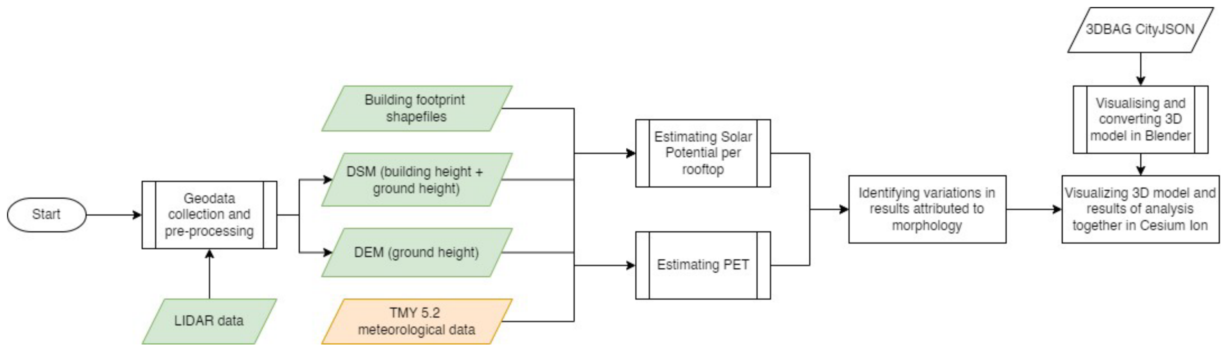

Figure 2 – Methodological process, where datasets in Green can be substituted for other geographical locations outside of the Netherlands. Weather data (in Orange) needs to be changed as per geographical location

Using these open-source datasets, slope and aspect of roof is calculated in GIS tools, and clipped to building footprints, which are then filtered by suitability – minimum contiguous area, optimum orientation, calculated solar irradiation on pixel surface etc. Shadows are estimated using the UMEP plug-in in QGIS, which uses the DSM to create shadows (Li-Lian, 2022). Solar panel output can be estimated by the Solar Energy on Building Envelopes (SEBE) function in UMEP, which uses solar irradiance data from the EPW file.

Total irradiance is calculated as the sum of direct, diffuse and reflected radiation as given in Equation 1, and stored as an attribute of the pixel.

$$R = \sum_{i=0}^{p} [(I\omega S + DS + G(1 - S)\alpha)]$$

Equation 1 - Calculating total irradiance on a pixel.

Where: p is the number of patches on the hemisphere.
I is the incidence direct radiation,
D is diffuse radiation
G is the global radiation originating from the ith patch.
α is the surface albedo
S is the shadow calculated to each pixel.
ω is the Sun incidence angle as explained in (Lindberg et al., 2015)

This method estimates an approximation of total solar irradiation per pixel, accounting for shadow as well as the angles and orientation of the roof surfaces derived from the DSM. A suitability analysis is done to extract only the usable pixels (explained further in the results), and the usable areas and estimated production values are joined back to the building roof vector file via Zonal Statistics.

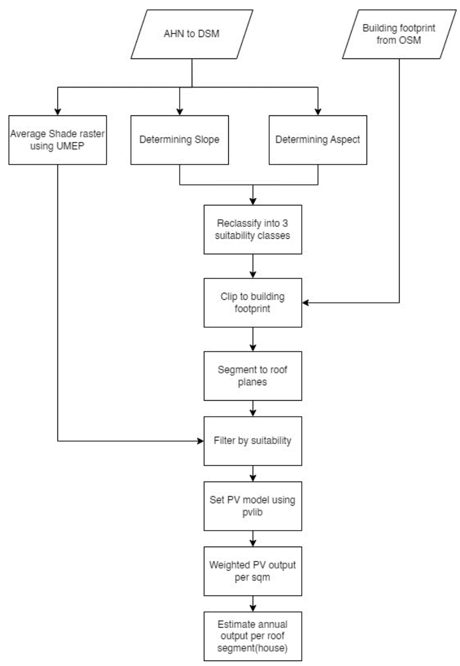

Figure 3 - Simplified open-source methodology for determining approximate solar potential.

2.2 Analysing thermal comfort – SOLWEIG, UROCK and PET

In addition to the analysis of solar potential, the research estimates outdoor human thermal comfort using the Physiological Equivalent Temperature (PET) indicator, but only retaining the built morphology as the input. This is done as in this research, the contribution of vegetation, water bodies and major surface material variations are not accounted for, which strongly affects the thermal comfort. Thus, the analysis estimates an approximation of PET using only building form information derived from DEM and DSM, and weather information of the location.

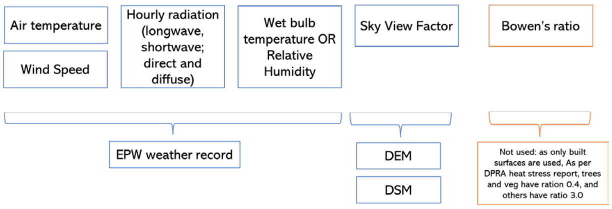

Figure 4 - Variables used to estimate PET.

Outdoor human thermal comfort is dependent on radiation (Gál and Kántor, 2020). To analyse thermal comfort, two major sub-indicators are calculated using UMEP Processors (Lindberg et al., 2018)– Thermal Mean Radiant temperature (TMRT) using SOLWEIG (The solar and longwave environmental irradiance geometry model) (Kong et al., 2022; Lindberg et al., 2008), and wind modelling using URock2023a (Johansson et al., 2016).

TRMT using the SOLWEIG model considers both shortwave and longwave radiation fluxes from six directions using Höppe's (1992) method. While the full model of SOLWEIG has the capability to incorporate vegetation as well as ground cover data along with built form, it is used in this research to only estimate spatial variations of 3D fluxes using the urban built form.

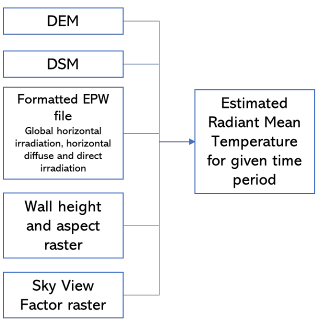

Figure 5 - Variables used to estimate Tmrt

URock estimates wind fields using a 'semi-empirical wind model' adapted from Röckle (1990) (Bernard et al., 2023). The outputs of these sub-indicators are fed into a Spatial Thermal Calculator Model which estimates the Physiological Equivalent Temperature.

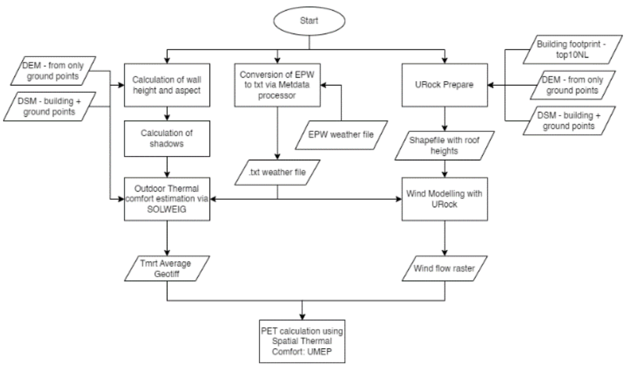

Figure 6 - Simplified open-source methodology for approximating thermal comfort.

3. Results

3.1 Solar Potential Estimation per rooftop

Following the given methodology, solar energy potential per rooftop was estimated. Shadow pattern was calculated in UMEP using the Summer Solstice of June 21st, which casts the least shadow, as seen in Figure 7.

Figure 7 – Shadow Estimation done for June 21

Using the input of the shadow raster files calculated per hour for June 21st, as well as the annual solar irradiance data estimated from the TMY5.2 weather file, average annual solar irradiation in kWh/m^2 was estimated per pixel, as seen in Figure *8* using SEBE in UMEP.

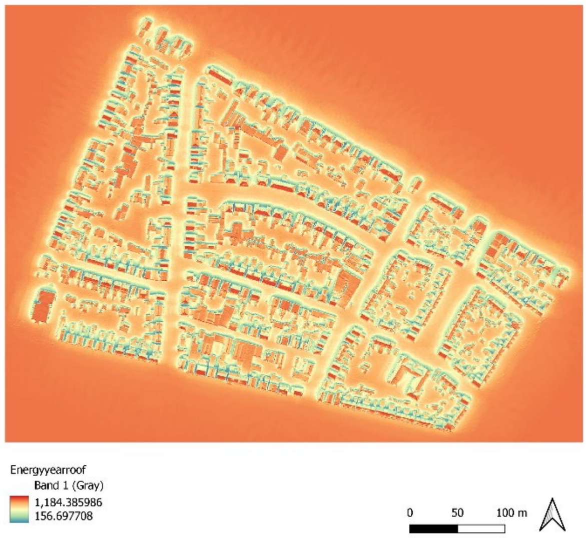

Figure 8 - The average annual solar irradiation calculated per pixel

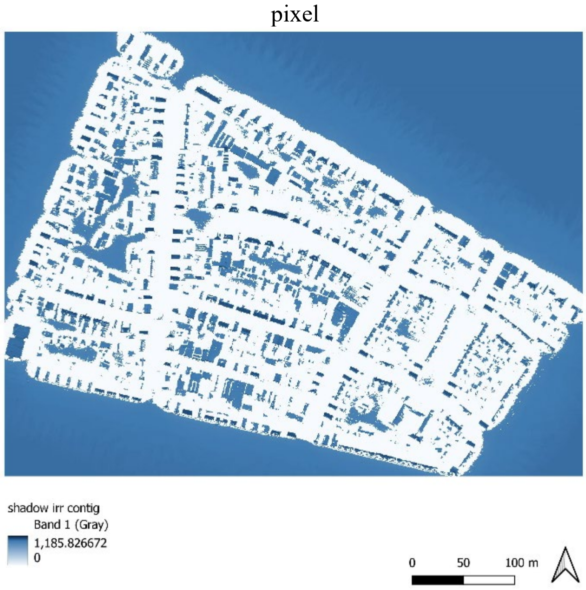

Figure 9 - Usable contiguous cells with annual irradiance and area as required.

Figure 10 - Estimated solar potential per rooftops.

Using a combination of raster processes using r.clump on GRASS GIS, GDAL and raster processor, suitable pixels are identified. They are selected on the basis of being free of shadows for at least 60% of the day, receiving over 950kWh/m^2 and in contiguous clusters over 2sqm (as one single solar panel is 1.6 sqm) are identified per rooftop. The results of this suitability analysis seen in Figure *9*.

Using the output of the suitability analysis in raster format, the values are transferred to the rooftop vector shapefiles using Zonal Statistics, as seen in Figure *10*. This suitability analysis can be repeated in different seasons to get amore holistic idea of the annual production potential by averaging the outputs. This suitability analysis is modifiable by users so as to determine their own cutoff irradiance levels, acceptable shadowing, and contiguous usable areas.

The entire workflow is made concise and replicable using Graphic Modeller and allows for variation in input data and assumptions. The graphical representation of the process is explained in Figure *11*, which reduces the long, tedious 15-step process to one-step. The suitability analysis is modifiable by users so as to determine their own cutoff irradiance levels, acceptable shadowing, and contiguous usable areas.

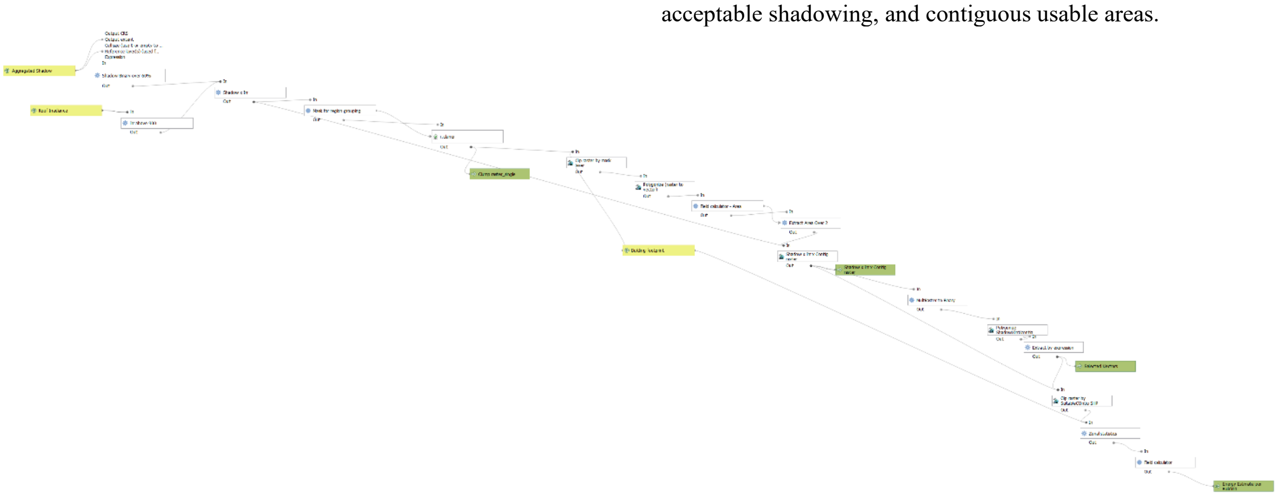

Figure 11 – The GIS processing is made simple using Graphic Modeller

3.2 Thermal Comfort estimation using PET

For calculating PET, the date of June 22, 2017, at 1pm was selected as it was the hottest record in the summer months in the TMY5.2 dataset. Keeping in mind that it is a Typical Meteorological Year, the temperature of 33°C is not the most extreme, but is a temperature regularly seen in the study area in the summer months.

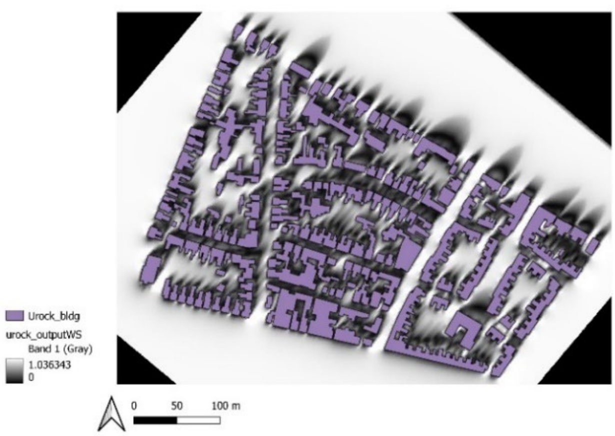

Figure 12 - Wind Flow intensity Raster.

Using the methodology described above, PET was calculated in two steps. In the first stage, wind flow estimation is done using URock2023a. A wind direction of SW at 225 degrees was selected as it is the predominant wind direction for the study area.

As seen in Figure 12, the wind flow intensity is derived from the WD10 value in the TMY5.2 dataset, which records wind speed and direction at 10m height. URock2023a shows a derived output at 1.5m height, which can be considered for human thermal comfort.

Following the methodology described in section 2.2, sky view factor per pixel is calculated in UMEP, as well as wall height and aspect rasters. All these inputs are then utilised to produce the Mean Radiant Temperature estimation for 1pm on June 22nd, 2017, which shows extremely high flux estimations.

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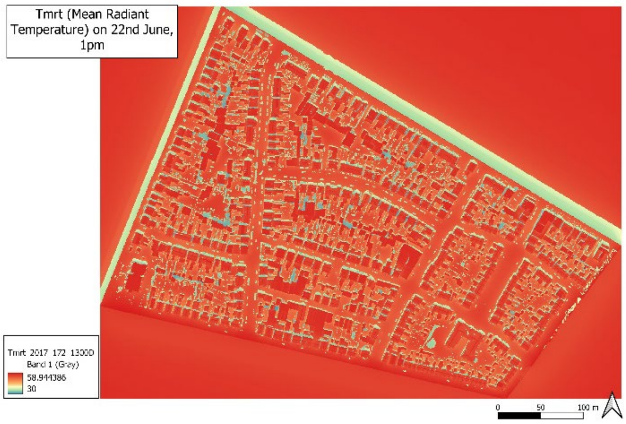

Figure 13 - Tmrt calculation for June 22,2017 at 1 pm.

Using Tmrt in Figure 13 and Wind Flow intensity estimation in Figure 12, and also using standard assumptions as per the SOLWEIG model of thermal comfort, PET is estimated as seen in Figure 14.

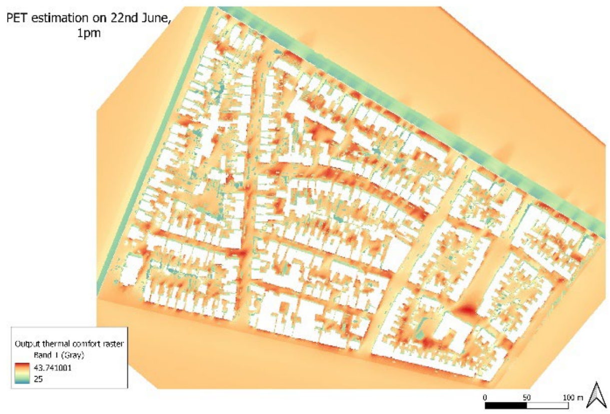

Figure 14 - PET estimation using constrained variables.

3.3 Viewing results on a 3D interface

To view the 3D environment, the DSM can be used. However, for the Netherlands, the AHN-4 data is used to make the 3DBAG dataset, which models the buildings at LOD 2.5 with detailed roof forms. Using Up3Date plugin (Mastorakis, 2020) in Blender, this detailed model is processed on Blender and converted to a .obj format.

The data of the usable roof area and the suitable pixels thus found via GIS analysis are joined to the 3D model using python Blender scripting, and then model is saved in the glTF 2.0 format, which can be read by Cesium.

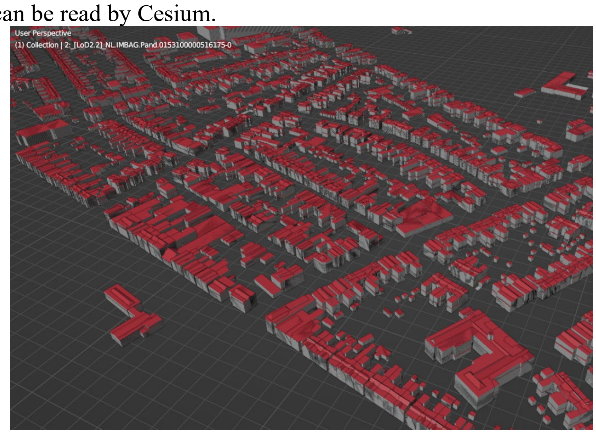

Figure 15 - Viewing and cropping the CityJSON extract to the required study area in Blender.

The results are then uploaded on Cesium Ion as 3D assets and 2D tiles. Viewing the results in 3D clearly shows the variation of PET in open areas beyond the immediate shadow of the buildings. Seen in Figure 16 is the visualisation of the converted 3D BAG model along with the derived PET results. Similarly other 2D or 3D analyses can also be viewed using this workflow.

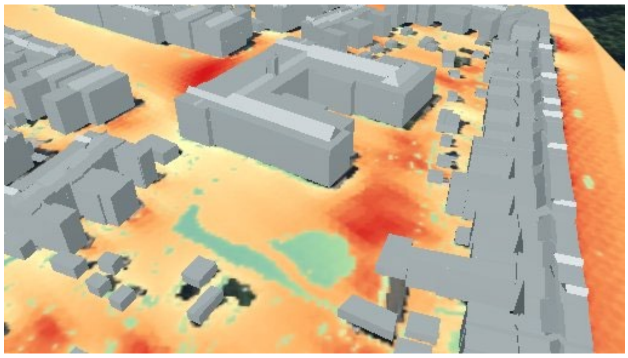

Figure 16 - The results can then be viewed on a 3D web-based platform such as Cesium Ion.

4. Discussion

Implementation of global plans to reduce climate change effect require localisation and implementation at the municipal scale. However, conscientious, and effective adaptation often requires data-driven analysis to aid planning decisions. Resource, capacity, and time constraints are common constraints in this process, and often small municipalities are lagging behind (Fila et al., 2024). This highlights the importance of high quality open-source data and solutions that is reliable, consistent, and verified as there are many smaller municipalities that may not be able to afford creating or buying expensive data or costly software.

The development of these open-source workflows also highlighted the laborious and repetitive steps in raster processing, which can require more familiarity with GIS software and handling the output of spatial data analysis. These can be simplified using a Graphic Modeller or done entirely in a Python environment. While QGIS allows for a familiarity of environment, in many steps such as DEM conversion or repetitive processing, it is indeed to use a python environment, or a toolbox made by Graphic Modeller to save on processing time.

The effect of roof angles and aspect is clear in the solar potential estimation, underlining the importance of location and roof orientation as found in the literature review. Similarly, it is interesting to see the direct effect of building morphology in hindering wind flow, which then directly affects the estimated thermal comfort on the streets, as also stated by Rijal (Rijal, 2012). Thus, as the global meteorological values are kept constant, different morphological parameters of building height, angle, orientation, and grouping affect the environmental indicators.

As the chosen pixel size is kept relatively small at 0.5m, visualising the effect of singular buildings becomes clearer. This extends to modelling future built scenarios, where the modification of environmental indicators can be visualised due to the modification of the built form, for example, decreased solar potential due to a tall neighbouring building, or decreased thermal comfort due to new developments blocking wind flow.

The importance of scenario and variable selection can be deduced from the results. The projected results as well as the existing condition varies greatly as the underlying climatic variables are modified. This drives home the importance of selecting scenarios

– extremes, medians or means – as this greatly influences the projected outcomes of different built scenarios. It is also noteworthy that the thermal comfort estimation is done for a standard of a 35-year-old male in comfortable clothing and is thus only an approximation of human comfort. The results will also vary as the target population of children, or the elderly is considered.
One of the main contributions of this research is to not simply derive a workflow, but also make it easily replicable using Graphic Modeller. The toolbox thus created requires the pre-installation of UMEP, and then produces the final output of Solar Energy Potential estimation per rooftop, and PET from single input windows. By reducing manual steps, the processes now rely solely on the processing system's capabilities to produce results, while still allowing customization in key aspects.

The research and development of the PSS is limited by the accuracy of the UMEP plug-in (Lindberg et al., 2018) which has been used extensively in the analysis. However, according to studies, UMEP is found as a good compromise between accuracy and processing time (Mutani and Beltramino, 2022). As processing time, or strength of processor is also a part of resource constraint, using this simplified workflow using UMEP can be a cost and time-effective solution for initial analysis for urban planners in small municipalities.

5. Conclusion

This research addresses the critical need to analyse and visualise the relationship between urban form and environmental performance in the context of sustainable urban development. By investigating the influence of urban morphology on Thermal Comfort and Solar Energy Potential, the study has provided valuable insights into the complex interactions between built form and environmental indicators.

The findings of this research highlight the importance of considering morphological parameters such as building density, height, orientation, and spacing in urban planning and design processes. By understanding how these parameters impact thermal comfort and solar energy generation, policymakers and practitioners can make more informed decisions to enhance the environmental performance of neighbourhoods.

Furthermore, this research addresses a practical need of smaller municipalities with limited resources. By providing an open-source workflow that is made accessible and adaptable, the research contributes to democratizing urban planning processes and empowering communities to participate in shaping their built environment with 3D.
However, it is important to acknowledge the limitations of this study, including the simplifications made in the modelling process and the reliance on available data sources. Future research should aim to address these limitations and further investigate the complex dynamics between urban form and environmental performance.

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