Cool by Design – An Urban Design Decision-Support Tool for Outdoor Thermal Comfort

Jessica Monahan

1st supervisor: Clara García-Sánchez
2nd supervisor: Hugo Ledoux

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1 Introduction

As cities continue to grow rapidly due to urbanization, climate change has become an increasingly critical challenge. Urban designers play an important role in addressing these challenges by developing climate-driven urban designs that reduce environmental impacts. The need for sustainable and resilient urban design rises, as cities must adapt to the changing climate while mitigating its effects (Cheshmehzangi et al. 2022).

Effective climate-driven urban design requires the exchange of urban microclimate (UMC) knowledge from researchers to urban designers and planners. However, as noted by Bherwani et al. (2020) and Aleksandrowicz (2022), the practical application of UMC research is limited. This is partly due to the complexity of existing tools, which are often unsuitable for practitioners. There is a need for user-friendly tools integrating UMC into city planning.

As Besserud and Hussey (2011) explain, simulation tools for urban design must provide fast results to allow for comparison between many design options, feature intuitive user interfaces accessible to non-experts, and support inputs and outputs appropriate for early-stage design.

One existing UMC tool is UMEP (Urban Multi-scale Environmental Predictor), an open-source QGIS plug-in for urban climatology and planning, designed for both researchers and service providers like architects and urban planners (Lindberg et al. 2018). However, it is not yet a user-friendly tool for urban design. It requires QGIS proficiency, data preparation, and does not readily accommodate the insertion of own designs or comparison between design options.

UMEP includes multiple climate models. For urban design, human outdoor thermal comfort (OTC) is particularly interesting, as it directly affects the quality of urban open spaces and plays a role in sustainable city design (Abdollahzadeh and Biloria 2021). The major meteorological parameters affecting OTC are wind speed, air temperature, relative humidity and solar radiation (Stathopoulos et al. 2004). Of these, wind speed and solar radiation are particularly responsive to urban design interventions, as they can be significantly modified by the arrangement of building clusters and vegetation (Xie et al. 2018). UMEP includes two relevant models for urban design: SOLWEIG, which focuses on solar and longwave irradiation (Lindberg et al. 2008), and UROCK, which models wind speed (Bernard et al. 2023).

Between the two models, SOLWEIG offers greater value for urban design applications. Recent studies highlight the increasing frequency, duration and intensity of heatwaves, which worsen urban heat stress through high solar radiation and reduced wind speeds (Kong et al. 2021). To enhance urban resilience, addressing solar radiation through effective design interventions is needed, and SOLWEIG is suited for this. Furthermore, preliminary testing of both models has shown that SOLWEIG is more stable, with results that appear more accurate for assessing thermal comfort in urban environments.

This research aims to develop the framework for a fast and user-friendly design decision-support tool that helps urban designers evaluate and incorporate UMC impacts during early design phases. The tool will not be developed from scratch but will build upon the SOLWEIG model. By bridging the gap between research and practice, the proposed tool will support climate-driven urban design.

2 Related work

2.1 Urban Design Process

This thesis focuses on developing a tool to integrate climate-driven decision-making into the urban design process by evaluating the impact of design options on UMCs. Achieving this requires understanding the urban design process, the role of UMC in this process, and identifying when such a tool would be beneficial.

Urban design is a multifaceted process aimed at creating better places for people, with an emphasis on equity, sustainability, and the importance of place-making. It integrates creativity, exploration, and problem-solving to balance diverse objectives and constraints. This process addresses technical, functional, and aesthetic criteria holistically, ensuring designs achieve structural integrity, utility, and visual appeal while also considering economic and environmental impacts (Carmona et al. 2010).

The urban design process is iterative and cyclical, adapting to new information and changing circumstances, making it exploratory and inherently uncertain. The process typically includes goal setting, analysis, visioning, synthesis, decision-making, and evaluation. These stages are not strictly linear but overlap and repeat (Carmona et al. 2010).

Interviews by Van Esch (2015) with Dutch urban designers in 2010 show they recognize the importance of microclimates but rarely seek information on the subject, indicating a gap. Additionally, they collect data primarily during the orientation and sketch phases of the design process. Consequently, the dissemination of expert knowledge on microclimates should be targeted at these early stages.

Can expert knowledge on microclimates be effectively shared with urban designers through the proposed tool? Van Esch (2015) observes that computer tools in urban design, particularly simplified expert programs, often fail to support the creative and iterative nature of the process. These tools are primarily analytical and may lead to errors or misinterpretations when designers lack the necessary theoretical knowledge. Moreover, the vast number of tools required to cover all knowledge fields can overwhelm designers and complicate decision-making. Van Esch suggests that providing basic principles, guidelines, and example projects may better support designers.

Others emphasize the value of simulation tools. For instance, Wong et al. (2011) and Ebrahimabadi (2015) argue that while simplified climate design principles aid early stages, advanced analytical tools are crucial for later stages to evaluate and refine concepts. Additionally, Besserud and Hussey (2011) highlight how simulation tools can complement design principles, introducing greater rigor and rationality into urban design. By integrating principles with the ability to simulate and compare design options, such tools help designers access complex data intuitively, improve decision-making, and accelerate design iterations.

2.2 Urban Climate Tools

For this thesis, UMEP was selected as the urban climate tool due to its open source code. However, it is not the only option available. Vurro and Carlucci (2024), have analyzed 25 different urban climate tools. These tools are predominantly commercial, with only 8 of the studied tools being open source. They can be categorized based on their primary functions as follows:

- **Computational Fluid Dynamics (CFD) Tools**: These tools simulate fluid flow and heat transfer. With 10 out of 25 tools studied, they are the most common typology. CFD tools are further divided into:
  - *General-Purpose CFD Tools* (e.g., OpenFoam, Fluent, Autodesk CFD): These tools provide extensive customization options. However, they require expertise in CFD modeling. They do not include pre-set urban item libraries (e.g., pre-made vegetation or surface models) requiring users to build simulations from scratch.
  - *Specialized Microclimate CFD Tools* (e.g., ENVI-met, Ladybug DragonFly, UrbaWind): Designed specifically for UMC modeling, these tools have limited customization options and offer pre-set urban item libraries.
- **Surface Energy Balance Models**: Tools such as RayMan, SOLWEIG, and SUEWS focus on modeling the exchange of energy between surfaces and the atmosphere, essential for understanding urban thermal dynamics.
- **Building Energy Models (BEM)**: Tools like TAS and the BEM features of Ladybug tools simulate energy use and thermal behavior within buildings.
- **Air Quality Models**: Tools like the ADMS Temperature and Humidity model are designed to analyze air quality conditions in urban areas.
- **Environmental Design-Oriented Tools**: Ladybug Tools is an open-source suite designed for environmental building design, enabling climate analysis, energy modeling, airflow simulation, and urban-scale studies through integrating simulation engines in CAD environments.

Ladybug Tools stands out as the only tool explicitly designed to integrate microclimate and environmental modeling within the design process.

2.3 Urban Climate Tools used in the Design Process

Klemm et al. (2014) describe how climate-responsive design was integrated into a re-design proposal, incorporating UMC considerations at every stage. Initial microclimatic analysis guided the applation of heat mitigation strategies like cool materials and greenery, with *RayMan* software used to simulate radiation fluxes and thermal comfort. *ENVI-met* simulations then evaluated the thermal comfort, leading to the addition of some vegetation. High-resolution *ENVI-met* models confirmed the heat reduction goals were met.

Huang et al. (2019) focus on integrating simulation tools into the design process to develop informed, evidence-based strategies for mitigating heat stress in a urban renewal project. Tools such as *+CityComfort* and *HTB2-Virvil* were employed to assess UMC conditions and pedestrian thermal stress. Simulation results were iteratively fed back to designers at early stages of the project, as seen in Figure 1, enabling the development of adaptive design strategies.

Most studies found using UMC tools for urban design, focus on comparing design options for specific cases to find the best option in regards to outdoor comfort, and to generate general guidelines for outdoor comfort. However, there is a lack of literature on the direct application of UMC tools by urban designers themselves. Examples include:

Eldarwish et al. (2020) used *ENVI-met* to compare two urban design proposals and the current situation, selecting the best option based on outdoor comfort metrics like T_{mrt} and surface temperatures. Ambrosini et al. (2014) assessed the impact of converting traditional roofs to green roofs in a historic city center using *ENVI-met*. Hsieh and Kangli (2024) applied CFD simulations to evaluate the effects of various design proposals on pedestrian wind comfort, highlighting the influence of factors such as building mass, layout, height, and open spaces on the wind environment.

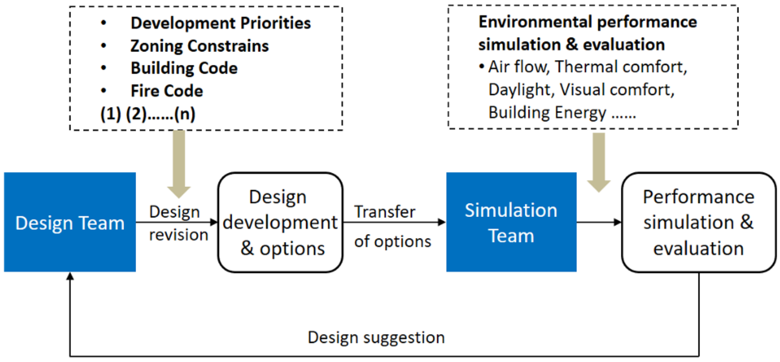

Figure 1: Simulation interaction between the design and simulation team (Huang et al. 2019)

2.4 Background on Mean Radiant Temperature

The main part of this thesis will be the adaptation of SOLWEIG (solar and longwave environmental irradiance geometry-model), which simulates the spatial variation of 3D-radiation fluxes and the mean radiant temperature (T_{mrt}) in urban settings (Lindberg et al. 2008). The T_{mrt} is an important parameter for evaluating outdoor thermal comfort (OTC).

According to investigations on OTC conducted in inland cities during clear-sky weather, radiant exchange is the dominant meteorological factor influencing thermal comfort during the daytime (Lee et al. 2013). The T_{mrt} quantifies this radiant exchange and is directly influenced by built geometry, surface materials, and vegetation. This makes T_{mrt} an effective measure for evaluating the efficiency of different strategies aimed at reducing radiant heat (Thorsson et al. 2014). Consequently, it is a valuable metric for comparing various design options in urban planning.

The T_{mrt} is the total of all shortwave and longwave radiation fluxes, both direct and reflected, that the human body is exposed to. Lindberg et al. (2008) mention the definition of T_{mrt} given by the ASHRAE, which is "the uniform temperature of an imaginary enclosure in which radiant heat transfer from the human body equals the radiant heat transfer in the actual nonuniform enclosure".

In SOLWEIG, T_{mrt} is computed six radiation flux components (longwave and shortwave radiation from upward, downward, and the four cardinal directions), together with the angular and absorption factors of a person (Lindberg et al. 2008).

To make evaluation of design options possible, it helps to understand what levels of T_{mrt} are acceptable. OTC is commonly assessed using indices such as the Physiological Equivalent Temperature (PET), which represents how the thermal environment feels as if the person were indoors, without wind or direct sunlight. A key factor influencing PET is T_{mrt}, particularly on windless days (Höppe 1999). However, it is not possible to define a specific minimum or maximum as ideal or problematic. This is because its effect is context-dependent, varying with other environmental factors such as air temperature, wind speed, and humidity. For instance, high values are desirable during cold weather conditions to enhance thermal comfort. This relationship is illustrated in Figure 2.

Scenario	**T_a (°C)**	**T_{mrt} (°C)**	**v (m/s)**	**VP (hPa)**	**PET (°C)**
Typical room	21	21	0.1	12	**21**
Winter, sunny	–5	40	0.5	2	**10**
Winter, shade	–5	–5	5.0	2	**–13**
Summer, sunny	30	60	1.0	21	**43**
Summer, shade	30	30	1.0	21	**29**

Figure 2: Examples of PET values for different climate scenarios. T_a air temperature, v air velocity, VP water vapour pressure (Höppe 1999)

2.5 Background on UMEP Tool and SOLWEIG

UMEP is an open-source tool designed for researchers and service providers, for analyzing urban OTC, energy use, and climate change mitigation. It integrates 1D and 2D models, allowing data input from various sources and scales to generate outputs as maps, graphs, and datasets. Built as a QGIS plug-in, it contains three main elements: a pre-processor for data preparation, a processor for running models, and a post-processor for analyzing results (Lindberg et al. 2018). This thesis shall adapt the SOLWEIG (solar and longwave environmental irradiance geometry-model) model integrated in the UMEP tool.

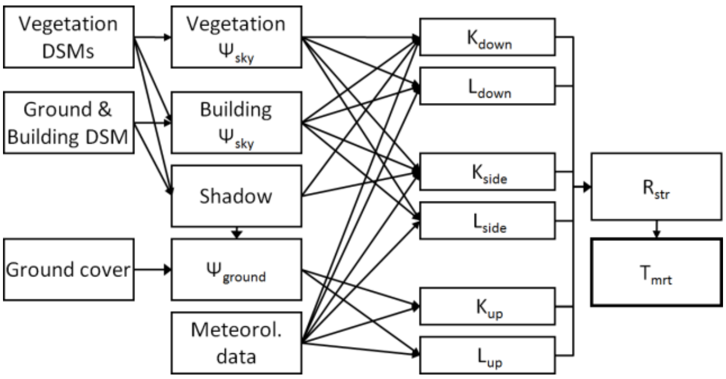

Figure 3: Overview of SOLWEIG (Lindberg and C. S. B. Grimmond 2019)

SOLWEIG calculates T_{mrt} in urban environments. This involves determining six longwave and shortwave radiation fluxes (upward, downward, and from the four cardinal points) using inputs of global shortwave radiation, air temperature, and relative humidity (Lindberg and S. Grimmond 2011). To compute T_{mrt} (K), the mean radiant flux density (S_{str}) is calculated as follows:

$$S_{str} = \xi_k \sum_{i=1}^{6} K_i F_i + \epsilon_p \sum_{i=1}^{6} L_i F_i \tag{1}$$

Which is the sum of all fields of long (L_i) and shortwave (K_i) radiation in three dimensions ($i = 1, \ldots, 6$), together with the angular (F), absorption (ξ_k) and emissivity (ϵ_p) factors of a person (Lindberg et al. 2008). The Stefan-Boltzmann law is used to calculate T_{mrt} when S_{str} is known:

$$T_{\mathrm{mrt}} = \sqrt[4]{\frac{S_{\mathrm{str}}}{\epsilon_p \sigma}} + 273.15 \tag{2}$$

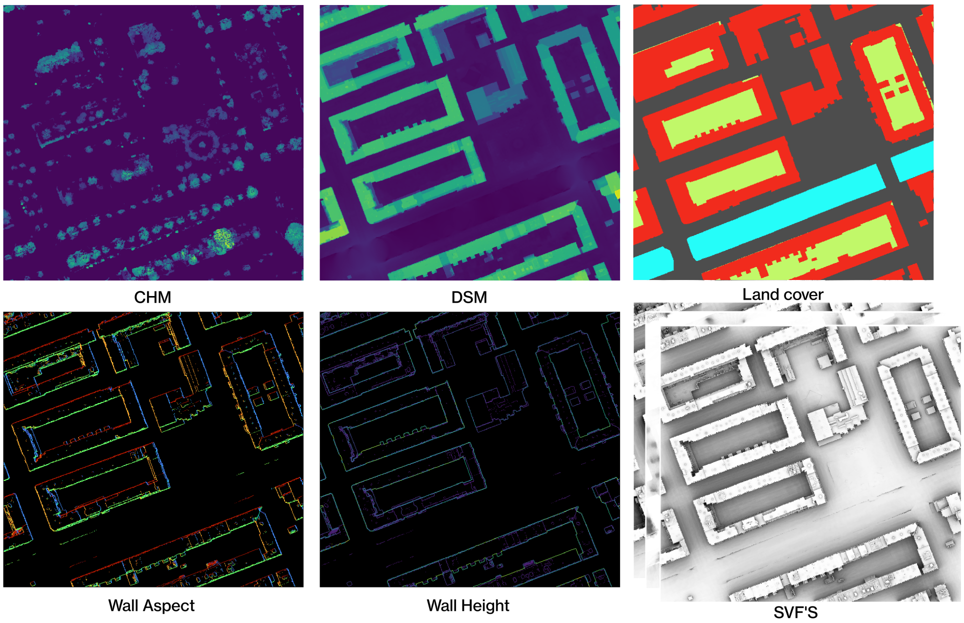

Figure 4: Overview of the required inputs for SOLWEIG.

SOLWEIG relies on the following inputs to calculate radiation fluxes and T_{mrt} (Figure 4):

- **Meteorological Data**: Includes direct, diffuse, and global shortwave radiation, air temperature, and relative humidity. If direct and diffuse radiation are unavailable, the model estimates them from global radiation data (Lindberg and S. Grimmond 2011).
- **Digital Surface Model (DSM)**: Contains building and ground height values, used to calculate spatial variations in sky view factor (Ψ_{sky}, SVF) and shadow patterns. Shadow casting is performed by translating the DSM based on the sun's altitude and azimuth angles (Lindberg et al. 2008).
- **Canopy Height Model (CHM)**: Contains vegetation height values, also used to calculate spatial variations in SVF and shadow patterns (Lindberg et al. 2016).
- **Environmental Parameters**: Surface albedo and emissivity values for walls and ground are required (Lindberg et al. 2008). Alternatively, a **land cover raster** can be used to assign pixel-specific values, which also adjusts radiation fluxes and surface temperatures based on shading, sunlight exposure, and thermal properties (Lindberg et al. 2016).
- **Pre-Processor Data**: Datasets generated using UMEP preprocessor tool. These are:
  1. **SVF Maps**: SVF quantifies the extent to which the sky is visible from a specific point. The maps are calculated for building and vegetation components, and the four cardinal directions. Total SVF is calculated using aforementioned shadow casting technique with 653 (or 153) uniformly distributed sun positions. The ratio that each pixel is shaded determines the SVF value (Lindberg and S. Grimmond 2010).
  2. **Wall height and Aspect Maps**: One raster map of the height of walls, one of their orientation (Lindberg et al. 2018).

Over the years, improvements have been added to the SOLWEIG model. First, the possibility to consider the human body as a cylinder, instead of a box, which caused some anomalies (Holmer et al. 2015). Second, the possibility to make use of an anisotropic diffuse shortwave scheme (Wallenberg et al. 2020), and an anisotropic longwave scheme, where emissivity increases with zenith angle (Wallenberg et al. 2023).

The output of SOLWEIG contains of six different 2D rasters; T_{mrt} incoming shortwave and longwave radiation, outgoing shortwave and longwave radiation.

3 Research questions

3.1 Objectives

The main objective of this thesis is to develop a framework for an online tool, based on the SOLWEIG model, that enables designers to visualize current urban climate conditions at the neighborhood scale in the Netherlands and to evaluate, visualize and compare the potential impacts of proposed designs on these conditions for the human comfort.

To achieve this, the research involves three steps. First, the validation of the original SOLWEIG model. Second, the creation of the tool, with a pipeline that automatically generates the necessary input for the SOLWEIG model and allows urban designers to modify the current situation. Third, the application of the designed tool on real-world examples from Dutch cities.

For the first step, the main question will be:

> *What level of accuracy does the SOLWEIG model achieve in reflecting real-world urban climate conditions according to literature, and can it be validated for the Netherlands using sensor data and / or CFD?*

For the second step, the main question will be:

> *How can a tool be developed to visualize the current urban climate conditions at the neighborhood scale in the Netherlands using the SOLWEIG model, and how can design alternatives be integrated and compared?*

This step includes the following subquestions:

- How can the data pipeline be automated to extract and create the Dutch location data required for the SOLWEIG tool?
- To what extent can the 2.5D SOLWEIG model be transformed into a 3D tool?
- To what extent can the SOLWEIG model be optimized for computation time?
- How can user input be integrated as input for SOLWEIG?
- What additional outputs or post-processing steps are required after the SOLWEIG model to compare and rank different urban design options based on their microclimatic impact?

For the third step, the main question will be:

> *How can the tool be used to analyze the effects of urban design proposals on microclimatic conditions in various Dutch urban typologies?*

3.2 Scope

The scope of the research and the priorities are defined with the MoSCoW method:

3.2.1 Must

- **Automatic Pipeline**: The tool must allow users to input their designs, location bounds, and desired calculation days, without requiring additional manual steps.
- **User Interactivity**: Users must have the ability to add or remove buildings, trees, and land cover.
- **Tool Usability**: The tool must enable designers to effectively compare and select the optimal design option.
- **Tool Optimization**: The tool must be fast enough to allow multiple design options to be compared within a reasonable timeframe.

3.2.2 Should

- **Informed Decision-Making**: The tool should identify problematic areas within a design and provide suggestions for improvement.
- **Support for 3D-designs**: The tool should accommodate input designs that include 3D elements such as overhangs and passages.

3.2.3 Could

- **Analysis**: The research could leverage the tool to analyze the effects of various design options within different configurations of Dutch cities.
- **3D Visualization**: The tool's output could be presented in 3D.

3.2.4 Will Not

- **Climate Physics**: No changes will be made to the SOLWEIG model at the level of climate physics or underlying formulas.
- **Data Collection**: The research will not involve collecting sensor data for model evaluation and new surface material parametrization.
- **Other Microclimate Effects**: Effects such as wind speed will not be integrated, as they are outside the scope. Addressing these effects would however enhance decision-making.
- **Functional Online Tool**: The tool will not be developed into a fully operational online platform; the focus will remain on creating a framework.

4 Methodology

The general overview of the methodology is given in Figure 5. Each step will be further highlighted in the following sections.

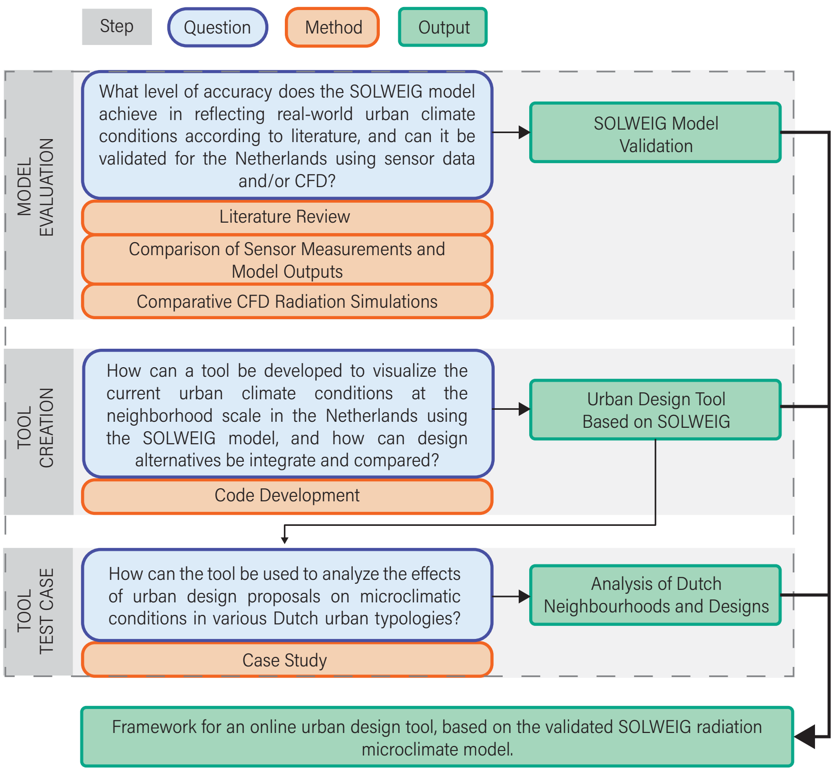

Figure 5: Overview of the research and the research methodology.

4.1 Model Evaluation

The SOLWEIG model will be evaluated through two methods: a literature review and own testing.

4.1.1 Literature Review

Multiple studies have assessed the performance of the SOLWEIG model, comparing it against measurement data or other climate models. An overview of papers evaluating SOLWEIG will be provided, highlighting its strengths and weaknesses. Through this review, the model's limitations and usability will be identified.

4.1.2 Own evaluation

The climate bike, a cargo bicycle equipped with instruments to measure micrometeorological conditions (Heusinkveld et al. 2013), might be used for evaluation. Sensor data capturing the six shortwave and radiation fluxes recorded by the climate bike may be obtained, for locations in Wageningen and potentially Amsterdam. Using this data, SOLWEIG simulations will be run for a location passed bi-hourly by the bike, using meteorological data from the nearest weather station. The simulated results will then be compared with the radiation flux measurements.

Should the climate bike data be unavailable or insufficient for model validation, an alternative approach is to use Computational Fluid Dynamics (CFD) simulations for solar radiation and compare those results with SOLWEIG outputs.

4.2 Tool Development

The main part of the research will be the development of the tool. An overview of the tool development process and its components is provided below in Figure 6.

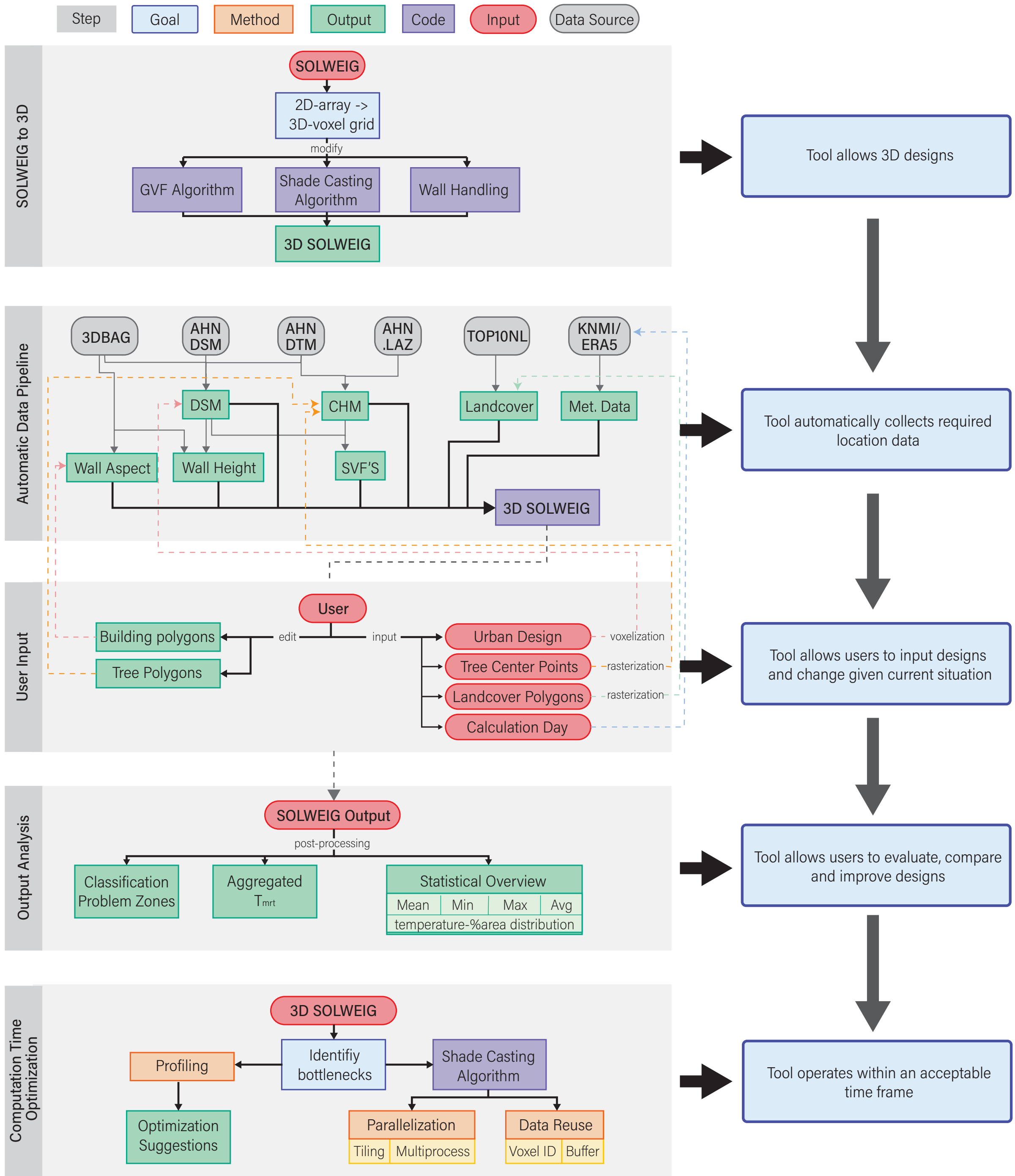

Figure 6: Overview of the tool components and development.

4.2.1 Automatic Data Pipeline

As outlined in Section 2.5, SOLWEIG requires several datasets, whose acquisition and processing will be automated:

- **Digital Surface Model (DSM)**: Created using elevation data and building polygons from the 3DBAG (`https://docs.3dbag.nl/en/`) to extract building heights. Two methods will be evaluated:
  - Using AHN WMS to retrieve DTM and DSM data, fill gaps and merge building heights from DSM in DTM.
  - Generate DSM directly from .LAZ point cloud data from GeoTiles (`https://geotiles.citg.tudelft.nl/`) by using the existing building and ground classification.
- **Canopy Height Model (CHM)**: Vegetation points can be extracted from .LAZ point cloud data using the Normalized Difference Vegetation Index (NDVI). These will then be post-processed and rasterized.
- **Wall Height and Aspect**: The building polygons can provide wall height and aspect by rasterizing the boundaries, segmenting them into lines, and calculating aspect values.
- **Land cover**: Land cover will be approximated from TOP10nl (`https://api.pdok.nl/brt/top10nl/ogc/v1`), rasterized, and classified for SOLWEIG..
- **Meteorological Data:** Example datasets for hot, tropical and summer day weather scenarios (35°C, 30°C, 25°C) will be preprocessed from ERA5 or KNMI data. Users can also request a specific day.

4.2.2 User Input

Users will have the ability to select and remove existing buildings and tree clusters from the simulation. The methodology for incorporating user input involves enabling users to modify the current urban landscape by adding or removing elements such as buildings, trees, and ground surface classification.

- *Modifying Existing Elements*: Users can remove buildings and tree clusters by selecting them within the simulation. The polygons of removed objects are used to mask and update the CHM and DSM.
- *Tree Insertion*: Tree placement involves adding points to the map, with users specifying parameters such as crown size, height, and trunk height. Preset options for common Dutch tree species are included. These points are rasterized and added into the CHM.
- *Land Cover Classification*: Land cover can be changed by creating polygons directly on the land cover map. These polygons are rasterized and integrated into the simulation.
- *Urban Design Integration*:
  1. *Georeferencing*: Designs can be georeferenced using one of three methods:
     - Input EPSG:28992 coordinates for precise alignment.
     - Use a drag-and-drop interface for manual rotation and translation.
     - Create a placement frame, align the design in external CAD software, and re-import the model.
  2. *Model Conversion*: Designs must be exported to a common 3D format, and shall be voxelized by the tool (Section 4.2.3). Voxelization involves detecting intersections of target lines with the edges of voxel boundaries, as detailed by Ohori et al. (2024).

4.2.3 SOLWEIG to 3D

The current SOLWEIG model uses a 2D array for height data, allowing only one height per cell, creating a 2.5D representation (Figure 7a). To model designs with passages and overhangs, a 3D representation is needed, where multiple height values can exist at the same horizontal location (Figure 7b). Voxelization is the logical next step, requiring modifications to the SOLWEIG model.

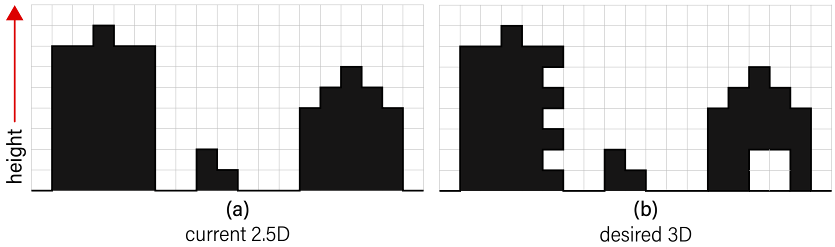

Figure 7: Vertical sections of height data illustrating **(a)** the current 2.5D situation, where a 2D array is extruded to represent height, and **(b)** the desired 3D situation, where multiple height values can exist at the same horizontal location.

The main part of SOLWEIG influenced by introducing 3D, is the calculation of shadow volumes. As described in Section 2.5, shadow casting is done by translating the DSM based on the sun's altitude and azimuth angles. Figure 8 illustrates how this translation creates shadow volumes. For tree shadow casting (Lindberg and S. Grimmond 2011), a trunk zone is needed to represent the area under the tree trunk, which does not cast shade. This trunk zone is translated similarly to the CHM, and shade is created where the translated CHM is above the trunk zone in the same translation step.

For 3D shade casting, a method is proposed where voxels are flagged as empty if there are filled DSM voxels above them. Each translation step these voxels create holes in the shadow volume, as illustrated below Figure 8.

Another area requiring modification are the 2D-arrays of wall heights and aspects (Figure 4) used in Ground View Factor (GVF) calculations. Currently, these arrays hold a single height or aspect per grid cell, which is used to determine sunlit and shaded sections of walls, their areas, temperature changes and their contribution to the GVF.

Finally, the model does not consider surfaces above-head (ceilings) for (reflected) radiation. Incorporating these surfaces would require changes to the radiation physics, which is outside the scope.

4.2.4 Computation Time Optimization

Shadow calculation, which is used for SVF computation, is a time-consuming step in the SOLWEIG model. Optimization will focus on parallel computing and minimizing unnecessary recalculations. Additionally, profiling may be used for identifying additional performance bottlenecks.

Parallel Computing

Two parallel computing strategies will be explored:

1. Calculate the entire area simultaneously across multiple processes.
2. Divide the area into tiles and process in parallel. Manage dependencies or use buffer zones for shadows crossing tiles. The buffer zone method was demonstrated by Li and Wang (2021), speeding up SVF calculations significantly with GPU-based computing.

Data Reuse

Two methods will be considered to optimize recalculating shade:

1. Create a buffer around the altered object, with its size based on the building's dimensions and the sun's position. Recalculation will be confined to this buffer zone.
2. Map each shadow voxel to unique object IDs. Shade removal and addition will be based on the affected objects, offering more precision but requiring more memory.

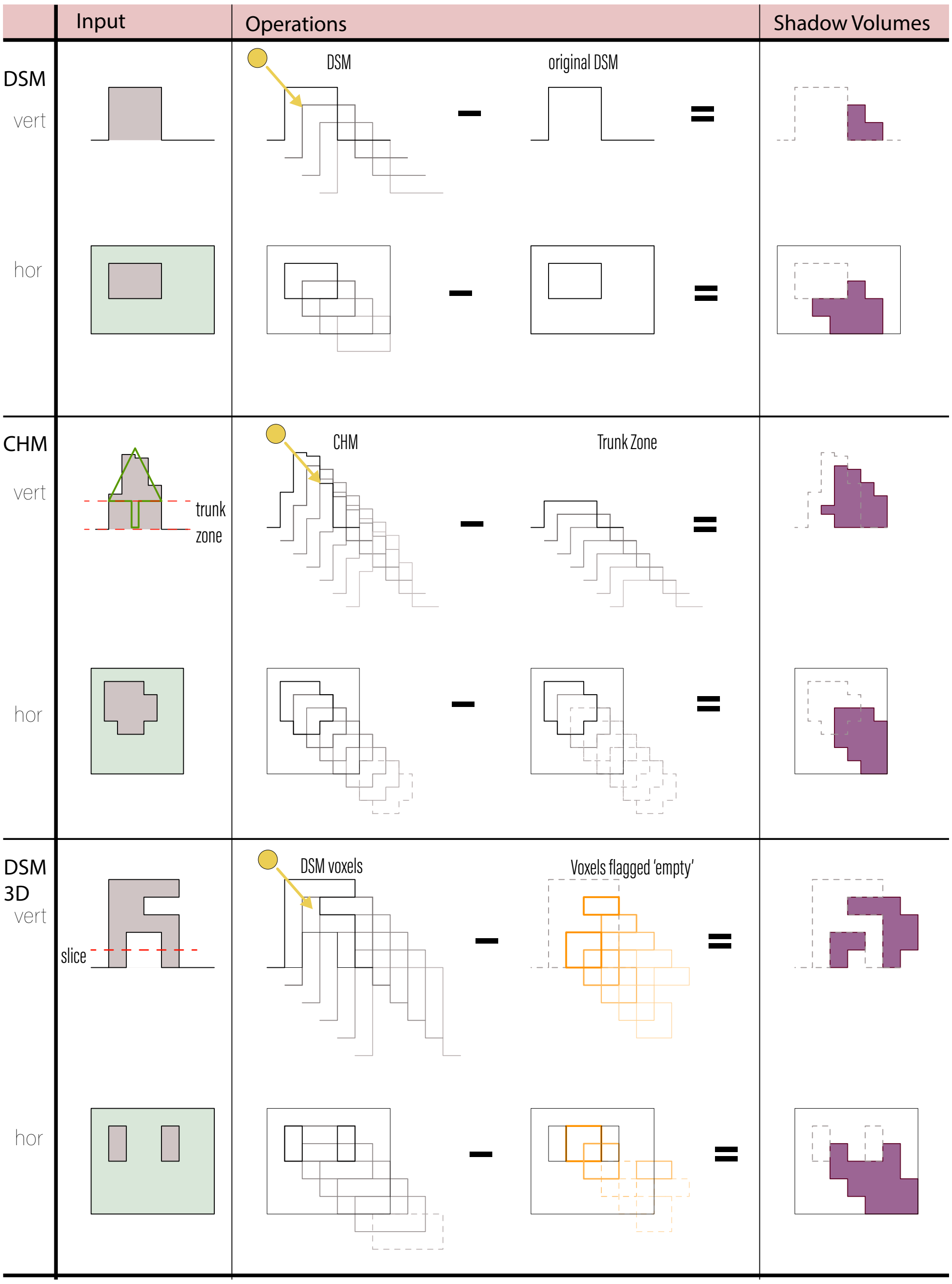

Figure 8: Explanation of the current methods of shadow casting for DSM and CHM, and the proposed method for 3D DSM shadow casting.

4.2.5 Output Analysis

The output of the SOLWEIG model currently includes maps of T_{mrt}, longwave, and shortwave radiation fluxes for each time step provided in the meteorological input file, as well as an overall average map. To enable comparison between design options and identification of problematic areas, these areas should be further processed.

The default output includes a map of T_{mrt} aggregated over the warmest midday hours (13:00–18:00, or meteorology data dependent) for the selected day. The map can be changed to the individual calculated time steps. Additionally, a statistical overview will accompany the map, providing minimum, maximum, median, and mean values of T_{mrt}, and a distribution of area percentages across temperature bins, which helps quantify how much of the area falls within specific temperature ranges.

Expanding evaluation metrics to include basic statistical values, as recommended by Schneider et al. 2023, ensures spatial heterogeneity is not overlooked, which is important for urban planning.

For problematic area identification, a toggle will allow switching to a zone classification map that highlights areas categorized as extremely high-temperature zones, high-temperature zones, and comfortable zones.

When multiple designs are evaluated, users will be able to switch between their respective T_{mrt} maps, changes between scenarios can be highlighted, and the statistical outputs will be shown side by side.

4.3 Tool Test Case

The to-be-developed tool can be used to test urban areas designed from scratch. However, a significant aspect of climate adaptation for Dutch urban areas involves reorganizing existing spaces. Therefore, this test case focuses on assessing the effectiveness of heat mitigation measures proposed in the literature for existing urban areas.

Shade provision is a primary strategy for reducing urban heat stress. Among mitigation options, landscaping elements, particularly trees, are often the most effective. Trees can be integrated into various public spaces, including streets, plazas, gardens, and parks, offering scalable solutions from local interventions to broader urban applications (Aleksandrowicz 2022).

The evaluation of four different scenarios on the T_{mrt} is proposed:

1. *Current Situation Without Trees:* Use only the DSM to simulate the current urban environment without vegetation.
2. *Current Situation With Existing Trees:* Incorporate both the DSM and the CHM to simulate the current environment, including existing vegetation.
3. *New Situation With Optimized Trees:* Use guidelines and formulas from Azcarate et al. (2021) to determine an optimal street tree layout. Simulate with the updated CHM.
4. *New Situation With Building Geometries:* To be decided.

For the areas to be analyzed, a dataset shall be made containing multiple examples of (a part of) the neighbourhood typologies described in the Klimaateffectatlas (Figure 9). The effects of the four scenarios will be evaluated within each typology and compared across typologies.

Figure 9: The different types of Dutch Neighborhood typologies (Klimaateffectatlas 2023)

5 Time planning

The schedules outlined below detail the activities required to achieve the research objectives.

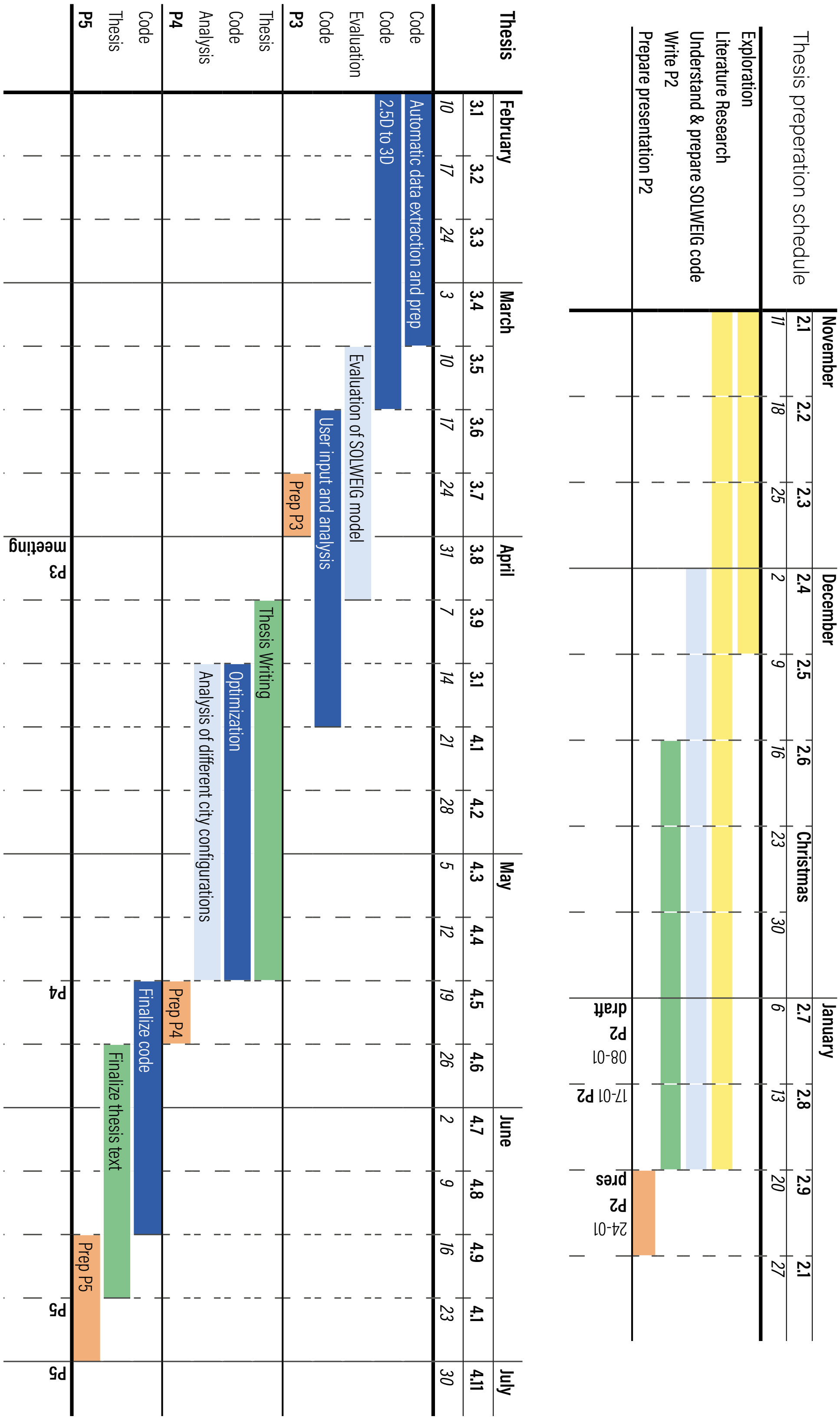

Figure 10: Thesis schedule

6 Tools and datasets

6.1 Tools

The main tool for development will be Python, which will be used for writing the core code. Depending on performance needs, particularly for shadow casting, C++ or Rust bindings might be used. The primary Python packages that will be used include:

- *NumPy*: For handling array-based operations.
- *GDAL*: For geoprocessing tasks, including reading, writing, and transforming raster and vector data, currently used in the SOLWEIG code. Might be substituted with Rasterio.
- *GeoPandas*: For managing and manipulating geospatial data and geometries.
- *momepy*: For calculating urban morphological parameters.
- *Dash or mpi4py*: For parallel computing with dependencies.
- *PyQt5*: For creating a GUI for the user inputs.

Thereby, the SOLWEIG source code of the UMEP tool will be isolated and adapted. The UMEP repository is found at `https://github.com/UMEP-dev`. Finally, QGIS will be used for testing and visualization purposes.

6.2 Datasets

To run the SOLWEIG model, several types of location-specific data is required.

- *Building Footprints*: To identify, extract, and remove existing buildings, a polygon layer of building footprints is required. For this, the 3DBag dataset will be used (`https://docs.3dbag.nl/en/`), at LoD 1.3.
- *Land Cover Data*: To create a land cover grid, land cover information is required. The BRT TOP10NL dataset will be used as a simplified source for this purpose. The relevant area will be queried using the Top10NL API (`https://api.pdok.nl/brt/top10nl/download/v1_0/ui/`).
- *DSM*: To create a DSM that includes both ground and building heights, there are two options. Either:
  - Use the raster-based AHN DTM and DSM by querying the location boundaries through a WMS.
  - Alternatively, use the AHN point cloud from GeoTiles, and its classification data directly, converting the points and rasterizing them.
- *CHM*: To generate the CHM, the height data of trees is required. This will be obtained by filtering tree data from the AHN point cloud and rasterizing it.
- *Meteorological Data*: Meteorological data, including air temperature, relative humidity, and incoming shortwave radiation are required. The most accurate results are achieved when meteorological stations are located close to the target area. Options for meteorological data include:
  - *ERA5*: Hourly estimates from the ERA5 dataset (`https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5`).
  - *Shiny Weather Data*: pre-converted ERA5 data. Recommended by the UMEP developers, however this data can only be manually downloaded (`https://www.shinyweatherdata.com/`).
  - *KNMI Dataset*: The KNMI dataset can be considered, however not all stations collect the required data.

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