Large-scale, High-resolution Urban solar potential analysis through semantic 3D city models

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1 Introduction

The WorldBank states that in 2023, 56% of the global population lives in urban areas, and the number is expected to increase to 70% by 2050 [1]. The growing urban population density has brought challenges to the urban energy and climate systems. For example, urban heat island [2] brought by dense built environment in urban areas can increase up to 40% of cooling demand [3]. To tackle the issues brought by dense population and buildings in the built environment, whether through urban planning or market adjustment (such as energy market), quantification of the demand and supply of energy is crucial. Incorrect quantification of the current and expected energy demand or supply of buildings, can lead to erroneous decisions and misguided planning for energy systems. Conversely, accurate estimations can significantly enhance energy efficiency. Research indicates that lowering the thermostat by 1°C could reduce Europe's gas consumption by 240 TWh per year, equivalent to one-sixth of historical imports from Russia, highlighting the substantial potential for improving energy efficiency through precise energy demand predictions [4].

Consequently, determining incoming solar irradiance is critical as it can not only be the source of the distributed solar power grid but also affect the environment and the occupants' behaviour within the building. Research suggest that any surface in urban environment will be able to host solar panels with technology advancement [5]. Therefore, accurate solar radiation estimation in urban environments is highly beneficial.

However, computing the solar radiation hitting surfaces of urban objects (e.g. a building, a shed, or the solar panels placed on top of them) is rather challenging. The complexity arises from the unique geometrical characteristics of these objects (such as surface tilt and inclination), the position of the sun, and varying weather conditions. Consequently, solar irradiance on surfaces in urban areas can exhibit significant variability in both time and space, even at tiny scales.

To account for the variations brought by the complexity of the built environment for solar potential analysis, it is essential to consider the geographical location and surroundings. The required information for such consideration can be obtained from semantic 3D city models [3DCM] [6], datasets that allow for a coherent geometrical and semantic representation of urban features in a well-defined data structure. With 3DCM, we can derive the required parameters to accurately determine the local solar irradiance value on any surface, such as surface orientation and tilt, and shadowing effect.

This thesis will investigate a new framework for calculating solar irradiance at surface level, city scale, and with high temporal resolution. The pipeline will consume the 3DBAG [7], an open dataset containing 3D models of all buildings in the Netherlands. The output will be solar irradiance values with sub-meter spatial and hourly temporal resolutions.

2 Related Work

Over the past decades, researchers have investigated methods for calculating solar irradiance while considering the surrounding environment. These methods can be categorized as view-shed based methods, pixel counting methods, and ray-tracing methods.

2.1 Viewshed-based methods

The viewshed method simulates the view from the perspective of a shadow-receiving position. The general workflow involves sampling rays from a hemisphere originating at the test position. Each ray undergoes an intersection test, producing a viewshed map representing the test point's surroundings which support the solar irradiance calculations. Direct solar irradiance is determined by projecting the sun's location onto the viewshed map; if the solar position overlaps with surrounding objects, the direct beam solar irradiation is masked out. Diffuse solar irradiance is calculated based on the visible sky patch in the viewshed.

Fu and Rich [8] developed one of the first viewshed-based methods. Their approach involves generating a viewshed map and a sun map that plots the sun's locations in the same hemispheric coordinate system. The overlay of the sunmap and the viewshed map supports solar irradiance calculations. However, this method only supports 2.5D Digital Elevation Models (DEM) with limited resolution. Subsequent research has focused on optimizing computation through GPU acceleration [9], [10], voxel octree data structures [11], and data pyramids [12].

Novel methods for deriving viewsheds with 3D data, such as fisheye image rendering [13], have also been proposed. While most models can consider diffuse and reflective components due to the embedded surroundings and sky patches in the viewshed map, they do so in a simplified manner. Furthermore, most methods cannot handle 3D data with high levels of detail (LoD2 or above), and computational requirements and the availability of 3D environmental data often limit the resolution of viewsheds.

2.2 Pixel counting methods

Pixel counting methods leverage modern rendering engines that utilize GPU acceleration. These methods involve rendering images of areas of interest and recording the pixel values of the planes of interest. By validating with ground measurements, a mapping function between pixel values and solar irradiation can be derived, enabling accurate predictions of solar irradiation. Modern rendering engines, designed with physically based rendering principles, can simulate the physical behavior of light, including diffusion and reflection, providing accurate results [14], [15]. However, these methods can be computationally intensive due to the exponential growth of ray path tracing from diffusion, and the need to render new images each time lighting conditions change [16].

Recent rendering engines like Unreal Engine [17] and Unity [18] are designed for photo-realistic real-time rendering, showing great potential for simulating solar irradiance at a city scale. However, since they are optimized for visualization, sample values on surfaces must be manually extracted after rendering [19]. Additionally, these sample values are deeply coupled with the defined surface material and light source properties. For urban-scale simulations with high temporal resolution, the manual effort required to account for extraterrestrial irradiance changes, camera position settings, and the lack of surface material information make rendering engines unsuitable for the majority of users.

2.3 Ray-Tracing based methods

Ray-tracing methods determine solar irradiation by casting ray vectors, and they can be categorized into two types: forward ray-tracing and backward ray-tracing. Forward ray-tracing involves casting rays directly from the solar position, but this approach is often considered inefficient because many rays do not intersect with the plane of interest, leading to redundant computations. Backward ray-tracing is more commonly used as it casts rays originating from the plane of interest toward the sun followed by tests for intersections with objects. The intersection results directly affect the calculation of direct beam solar irradiance.

The SORAM model is a ray-tracing-based solar irradiance calculation method that utilizes 3D city models. For a given point of interest, hemispheric sampling is applied, and energy is accumulated for each sampled ray. However, the 3D models are limited to box representations, and the diffuse and reflected solar irradiation from the surroundings are excluded from the calculations [20]. Wieland et al. developed one of the first models to use semantic 3D city models, employing ray-tracing methods to account for more complex urban environments [21]. In this model, a single ray is cast from the point of interest toward the sun, ignoring the reflected component and simplifying the calculation of the diffuse component without considering the surrounding environment. SURF-SUN3D is another model that applies ray-tracing to account for shadowing effects in solar irradiance computation. To reduce computation, it employs view-frustum culling and radius culling methods to decrease the number of ray-object intersection tests. However, the model also disregards the reflected and diffuse components from surrounding objects, directly computing these components using the r.sun model [22], [23]. To minimize redundant ray-object intersections, various techniques such as solar azimuth filtering, nightside filtering [24], semantic bounding volume hierarchy [25], and bounding volume hierarchy [26] have been employed. These methods enable fast and accurate determination of direct beam irradiance but make little consideration for reflected and diffuse irradiation.

Essentially, viewshed-based methods and pixel-counting methods are also ray-tracing-based methods. The difference lies in that viewshed methods precompute a viewshed map, while ray-tracing methods determine shadowing effects on the fly. Pixel-counting methods are indirect, sampling values from rendered images, whereas ray-tracing methods provide direct results.

3 Research Objectives

3.1 Research questions

The main research question of the thesis is:
How can a solar irradiance simulation tool be developed to balance accuracy and computational efficiency for city-scale simulations while utilizing semantic information from 3D city models?

This question is extended further by the following sub-questions:

- In what ways can semantic data derived from 3D city models refine the precision of solar irradiance simulations by considering the direct, diffuse and reflected solar components?
- What are the potential trade-offs between accuracy and computation simplification when utilizing 3D city models for estimating solar irradiance at an urban scale?

3.2 Scope of research

The thesis will focus on developing and testing a easy to use methdology that is able to compute large-scale, high resolution solar irradiance with 3D city models to suppport energy transition, architecture design, and urban planing. An easy-to-use model with case study values will be the final product.

4 Methdology

4.1 Viewshed Calculation Development and Optimization

View-shed map will be calculated for Sky-view Factor (SVF) calculation, essential for diffuse and reflected components of solar irradiance. The derivation of SVF [11] can be formulated as:

$$SVF = \frac{1}{2\pi} \int_{-\pi}^{\pi} \frac{2}{\pi} \int_{0}^{\frac{\pi}{2}} (1 - M_{shadow}(V(\theta, \omega))) d\theta d\omega \tag{1}$$

In addition to the single SVF value, the view-shed map can include semantic information to allow for more accurate analysis.

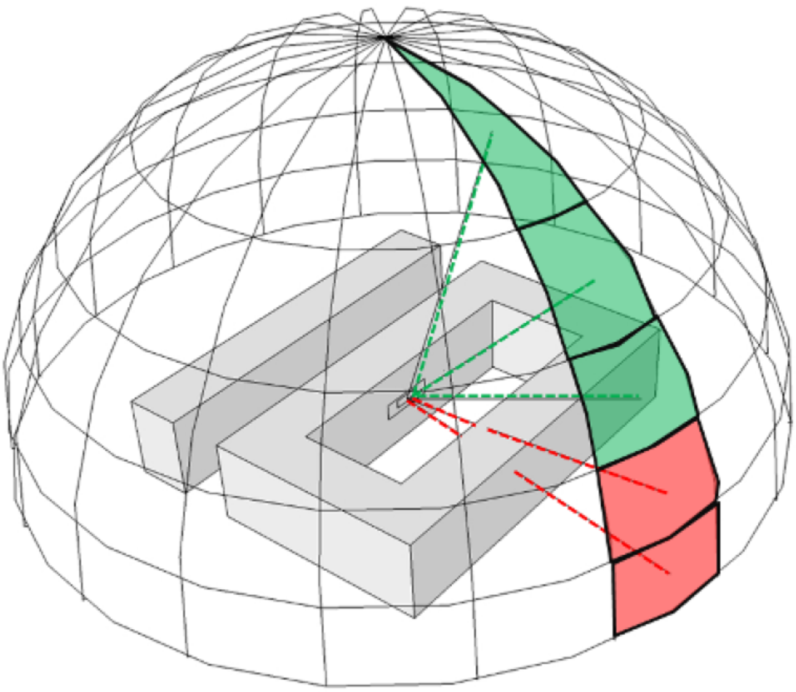

Figure 1: Illustration of the viewshed calculation with 3D city model [27].

4.2 Solar Irradiance Calculation

4.2.1 Simplified Calculation

It is essential to utilise a transition model based on meteorological data to analyse the solar irradiance impacting tilted surfaces. This data provides measurements of solar irradiance that reach the ground, which are expressed by 2 [28].

$$GHI = DHI + DNI \cdot \cos(\theta_Z) \tag{2}$$

GHI, DHI, and DNI represent Global Horizontal Irradiance, Direct Normal Irradiance, and Diffuse Horizontal Irradiance, respectively. θ_Z represents the solar zenith angle. The diffuse components are divided into sky and horizon 2. The general form of the transition model is formulated as 3.

$$I_{S,\beta} = I_{S,dir,\beta} + I_{S,diff,\beta} + I_{S,refl,\beta} \tag{3}$$

Where $I_{S,dir,\beta}$, $I_{S,diff,\beta}$, $I_{S,refl,\beta}$ represent the direct beam irradiance, sky diffuse irradiance, and ground reflected irradiance. $I_{S,\beta}$ represent the total solar irradiance and β stands for surface inclination. The determination of the direct beam solar irradiance is articulated as 4.

$$I_{S,dir,\beta} = M_{shadow} \cdot DNI \cdot \cos\delta \tag{4}$$

Here, M_{shadow} represents the binary shadow mask and δ represent the angle between surface normal and the solar vector.

The methods to estimate the sky diffuse component of total solar irradiance have been extensively studied over the past decades. In general, different models require varying amounts of input data. In the thesis, an initial choice will be Isotropic [29] and the Perez [30]–[32] models. *Isotropic model* considers the sky as a uniform source of diffuse radiation. The motivation for choosing this simple model is that our study focuses more on accurately estimating direct beam solar irradiance, which is significantly affected by shadows. The diffuse components of solar irradiance in the isotropic model can be formulated by 5.

$$I_{S,diff,\beta} = DHI \cdot SVF \tag{5}$$

In most cases, SVF is simplified [33] as:

$$SVF = \frac{1 + \cos\beta}{2} \tag{6}$$

The ground reflected solar irradiance in a similar simplified setting can be determined as:

$$I_{S,refl,\beta} = I_{S,tot} \cdot \gamma_{refl} \cdot (1 - SVF)) \tag{7}$$

Where γ_{refl} represent the albedo.

Perez model is an empirical model adopted widely and tested to show promising alignment with ground truth data [28]. Compared with the Isotropic, the Perez model decomposes the sky into three parts: the circumsolar disc, the horizon band and the isotropic background. The model also requires more parameters, such as airmass. Eq. 8 details the basic form of this model [28]:

$$I_{S,diff,\beta} = DHI \times \left[(1 - F_1) \left(\frac{1 + \cos\beta}{2} \right) + F_1 \left(\frac{a}{b} \right) + F_2 \sin\beta \right] \tag{8}$$

Where F_1 9 and F_2 10 are complex empirically fitted functions that describe circumsolar and horizon brightness, respectively. Additionally:

- $a = \max\left(0, \cos\left(AOI\right)\right)$
- $b = \max\left(\cos\left(85^\circ\right), \cos\left(\theta_Z\right)\right)$
- AOI is the angle of incidence between the sun and the plane of the array

$$F_1 = \max\left[0, \left(f_{11} + f_{12}\Delta + \frac{\pi\theta_Z}{180^\circ} f_{13}\right)\right] \tag{9}$$

$$F_1 = \max\left[0, \left(f_{11} + f_{12}\Delta + \frac{\pi\theta_Z}{180^\circ} f_{13}\right)\right] \tag{10}$$

The f coefficients are defined for specific bins of clearness (ε), which is defined as 11:

$$\varepsilon = \frac{(DHI + DNI)/DHI + \kappa\theta_Z^3}{1 + \kappa\theta_Z^3} \tag{11}$$

where: κ is a constant equal to 1.041 for angles in radians, or 5.535×10^{-6} for angles in degrees.

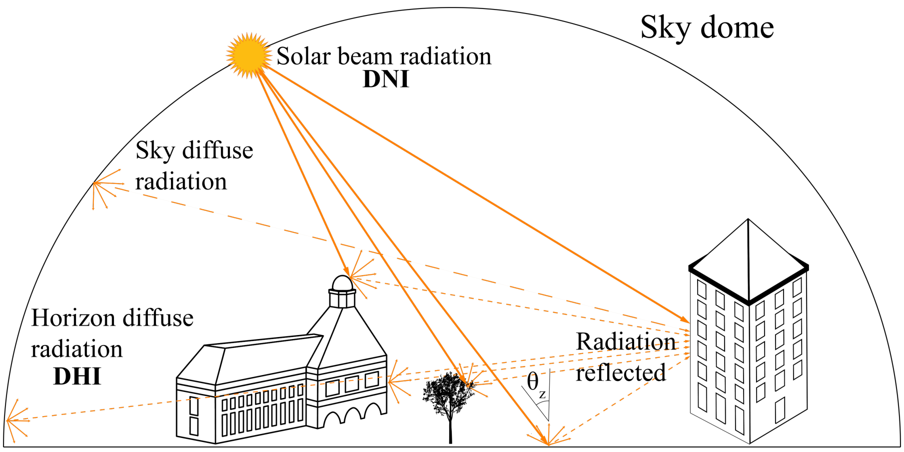

Figure 2: Solar irradiance component

4.2.2 Physically based Calculation

Considering the actual distribution of energy, the solar irradiance components holds true for equation 3 and 4. But for calculation of diffuse and reflected components, simplification is not applied. Here the definition from [16] is adopted. The diffuse components are defined as:

$$I_{S,diff,\beta} = \int_{\Omega_V} I_{\text{sky}}(\mathbf{r})\,(\text{r} \cdot \mathbf{n})\,\mathrm{d}\Omega \tag{12}$$

The equation describes the process that integrating diffuse solar irradiance from direction $\mathbf{r}$ from all visible sky patches Ω_V and $\mathbf{n}$ represent the surface normal.

Similarly, the reflected components can be derived by integrating reflected solar irradiance from all blocked sky patches Ω_B.

$$I_{S,refl,\beta} = \int_{\Omega_B} I_{\text{refl}}(\mathbf{r})\,(\mathbf{r} \cdot \mathbf{n})\,\mathrm{d}\Omega \tag{13}$$

The accurate determination of I_{sky} and I_{refl} for each direction, however is very difficult as the bouncing of rays need to be simulated. The essence of the equations is the concept that has been integrated into rendering engines, which is utilized by pixel counting techniques.

The thesis aims to find a balance between the simplified and the physically based method for solar irradiance calculation that can balance accuracy and computation requirements.

4.3 Ground Truth Data Validation

Ground measurements are required to validate the final estimation of solar irradiance. In this thesis, these values will be the data collected by the PVMD group that has been used in their research [5], [16].

5 Time Planning

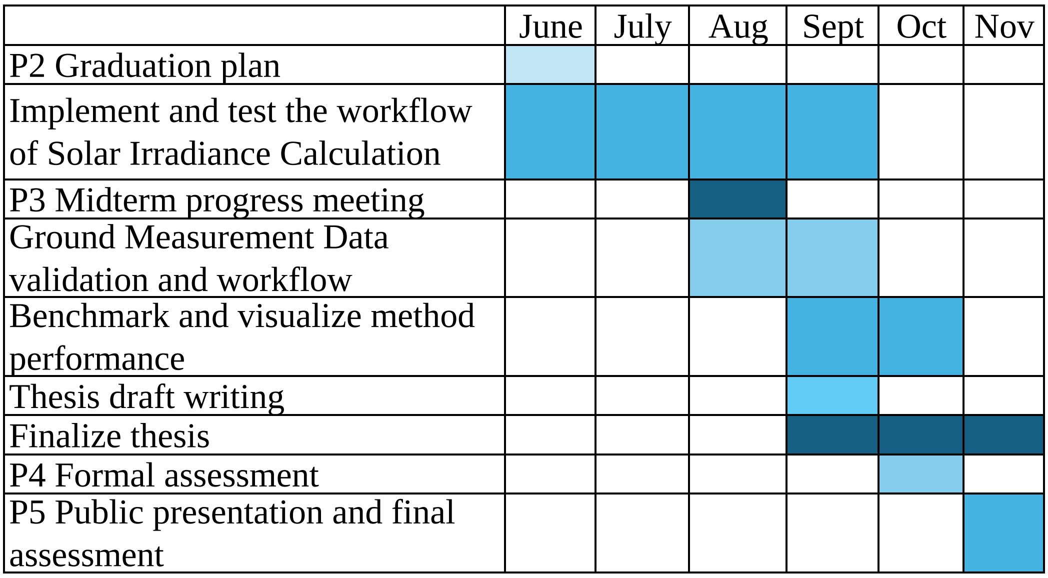

Figure 3: Gantt diagram of the graduation timeline

6 Tools and Datasets

Tools: C++, Python, and other open source libraries

Datasets: 3DBAG [7], ground measurements from PVMD group [5], [16].

References

[1] The World Bank, *World development indicators — DataBank*, 2024. [Online]. Available: `https://databank.worldbank.org/Urban-2023/id/1623846f` (visited on 05/10/2024).

[2] T. R. Oke, "The energetic basis of the urban heat island," *Quarterly journal of the royal meteorological society*, vol. 108, no. 455, pp. 1–24, 1982.

[3] D. Mauree, E. Naboni, S. Coccolo, A. T. D. Perera, V. M. Nik, and J.-L. Scartezzini, "A review of assessment methods for the urban environment and its energy sustainability to guarantee climate adaptation of future cities," *Renewable and Sustainable Energy Reviews*, vol. 112, pp. 733–746, 2019.

[4] I. Staffell, S. Pfenninger, and N. Johnson, "A global model of hourly space heating and cooling demand at multiple spatial scales," *Nature Energy*, vol. 8, no. 12, pp. 1328–1344, 2023.

[5] A. Calcabrini, "Solar resource modelling and shading tolerant modules for the urban environment," 2023.

[6] G. Agugiaro, F. G. G. González, and R. Cavallo, "The city of tomorrow from . . . the data of today," *ISPRS International Journal of Geo-Information*, vol. 9, no. 9, 2020, ISSN: 22209964. DOI: `10.3390/ijgi9090554`.

[7] R. Peters, B. Dukai, S. Vitalis, J. van Liempt, and J. Stoter, "Automated 3D Reconstruction of LoD2 and LoD1 Models for All 10 Million Buildings of the Netherlands," *Photogrammetric Engineering and Remote Sensing*, vol. 88, no. 3, pp. 165–170, 2022, _eprint: 2201.01191, ISSN: 00991112. DOI: `10.14358/PERS.21-00032R2`.

[8] "Design and implementation of the solar analyst: An arcview extension for modeling solar radiation at landscape scales," in *Proceedings of the nineteenth annual ESRI user conference*, San Diego USA, vol. 1, 1999, pp. 1–31.

[9] S. Tabik, A. Villegas, E. L. Zapata, and L. F. Romero, "Optimal tilt and orientation maps: A multi-algorithm approach for heterogeneous multicore-gpu systems," *The Journal of Supercomputing*, vol. 66, pp. 135–147, 2013.

[10] N. Stendardo, G. Desthieux, N. Abdennadher, and P. Gallinelli, "Gpu-enabled shadow casting for solar potential estimation in large urban areas. application to the solar cadaster of greater geneva," *Applied Sciences*, vol. 10, no. 15, p. 5361, 2020.

[11] J. Liang and J. Gong, "A sparse voxel octree-based framework for computing solar radiation using 3d city models," *ISPRS international journal of geo-information*, vol. 6, no. 4, p. 106, 2017.

[12] M. Oh and H.-D. Park, "A new algorithm using a pyramid dataset for calculating shadowing in solar potential mapping," *Renewable energy*, vol. 126, pp. 465–474, 2018.

[13] J. Liang, J. Gong, X. Xie, and J. Sun, "Solar3d: An open-source tool for estimating solar radiation in urban environments," *ISPRS international journal of geo-information*, vol. 9, no. 9, p. 524, 2020.

[14] M. Hegazy, K. Yasufuku, and H. Abe, "Validating game engines as a quantitative daylighting simulation tool," Apr. 2021. DOI: `10.52842/conf.caadria.2021.2.285`.

[15] G. J. Ward, "The radiance lighting simulation and rendering system," in *Proceedings of the 21st annual conference on Computer graphics and interactive techniques*, 1994, pp. 459–472.

[16] C. Andres, C. Ruben, G. David, *et al.*, "Time-varying, ray tracing irradiance simulation approach for photovoltaic systems in complex scenarios with decoupled geometry, optical properties and illumination conditions," *Progress in Photovoltaics: research and applications*, vol. 31, no. 2, pp. 134–148, 2023.

[17] E. Games. "Global illumination in unreal engine." Accessed: 2024-05-31. (2023), [Online]. Available: `https://dev.epicgames.com/documentation/en-us/unreal-engine/global-illumination-in-unreal-engine`.

[18] U. Technologies. "Global illumination introduction." Accessed: 2024-05-31. (2023), [Online]. Available: `https://docs.unity3d.com/560/Documentation/Manual/GIIntro.html`.

[19] S. Meines, "Luminacity: A real-time daylight analysis tool for architectural and urban development using unreal engine," 2023.

[20] R. Erdélyi, Y. Wang, W. Guo, E. Hanna, and G. Colantuono, "Three-dimensional solar radiation model (soram) and its application to 3-d urban planning," *Solar Energy*, vol. 101, pp. 63–73, 2014.

[21] M. Wieland, A. Nichersu, S. M. Murshed, and J. Wendel, "Computing solar radiation on citygml building data," in *18th AGILE international conference on geographic informaton science*, 2015.

[22] J. Liang, J. Gong, W. Li, and A. N. Ibrahim, "A visualization-oriented 3d method for efficient computation of urban solar radiation based on 3d–2d surface mapping," *International Journal of Geographical Information Science*, vol. 28, no. 4, pp. 780–798, 2014.

[23] J. Liang, J. Gong, J. Zhou, A. N. Ibrahim, and M. Li, "An open-source 3d solar radiation model integrated with a 3d geographic information system," *Environmental Modelling & Software*, vol. 64, pp. 94–101, 2015.

[24] X. Wang, X. Zhang, S. Zhu, *et al.*, "A novel and efficient method for calculating beam shadows on exterior surfaces of buildings in dense urban contexts," *Building and Environment*, vol. 229, p. 109 937, 2023.

[25] V. Jaillot, F. Pedrinis, S. Servigne, and G. Gesquière, "A generic approach for sunlight and shadow impact computation on large city models," in *25th International Conference on Computer Graphics, Visualization and Computer Vision 2017*, 2017, 10–pages.

[26] L. Xu, C. León-Sánchez, G. Agugiaro, and J. Stoter, "Shadowing calculation on urban areas from semantic 3d city models," in *International 3D GeoInfo Conference*, Springer, 2023, pp. 31–47.

[27] D. Trigaux, B. Oosterbosch, K. Allacker, and F. De Troyer, "A design tool to optimize solar gains and energy use in neighbourhoods," *PLEA 2015-Architecture in (R) Evolution*, vol. 1, 2015.

[28] P. G. Loutzenhiser, H. Manz, C. Felsmann, P. Strachan, T. Frank, and G. Maxwell, "Empirical validation of models to compute solar irradiance on

inclined surfaces for building energy simulation," *Solar Energy*, vol. 81, no. 2, pp. 254–267, 2007.

[29] N. Kamphuis, C. Gueymard, M. Holtzapple, A. Duggleby, and K. Annamalai, "Perspectives on the origin, derivation, meaning, and significance of the isotropic sky model," *Solar Energy*, vol. 201, pp. 8–12, 2020.

[30] R. Perez, R. Seals, P. Ineichen, R. Stewart, and D. Menicucci, "A new simplified version of the perez diffuse irradiance model for tilted surfaces," *Solar energy*, vol. 39, no. 3, pp. 221–231, 1987.

[31] R. Perez, R. Stewart, R. Seals, and T. Guertin, "The development and verification of the perez diffuse radiation model," Sandia National Lab.(SNL-NM), Albuquerque, NM (United States); State Univ ..., Tech. Rep., 1988.

[32] R. Perez, P. Ineichen, R. Seals, J. Michalsky, and R. Stewart, "Modeling daylight availability and irradiance components from direct and global irradiance," *Solar energy*, vol. 44, no. 5, pp. 271–289, 1990.

[33] D. Heim and D. Knera, "A novel photometric method for the determination of reflected solar irradiance in the built environment," *Renewable and Sustainable Energy Reviews*, vol. 137, p. 110 451, 2021.