Applications of Large Scale Solar Modeling in the Built Environment

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Abstract

This paper describes the development and applications of a simulation engine developed by the author to rapidly and accurately predict solar insolation within the urban realm. This tools works within the finite-volume framework of the open source computational fluid dynamics (CFD) package OpenFOAM; allowing tight integration of solar results with CFD analyses and the ability to leverage existing pre and post processing tools and processes. The utility combines a fast geometric analysis of sunlight ray paths with advanced modeling techniques to provide direct and diffuse solar loads throughout the study domain. The output of this utility has been compared to that of the industry standard RADIANCE engine (used via the DIVA-for-Rhino software package) and has been found to match RADIANCE predictions of annual solar insolation within 10%. The utility also leverages the same domain decomposition schemes used by OpenFOAM, allowing for simple parallelization, significantly reducing run times compared to RADIANCE.

1 Introduction

As urban densities increase and architects increasingly leverage the sun to light, heat and power their designs, understanding the interaction between the sun and the built environment is critical. A poor understanding of this interaction has led to several high profile instances where reflected sunlight caused adverse consequences such as dangerous or distracting glare [Hayward 2012], localized heating of roads and nearby buildings [Schiller & Valmont 2005] and solar radiation concentration leading to property damage [Wainwright 2013] and personal injury [Flatley 2010]. Increased building density can also cause the reverse problem, buildings that once had good solar exposure suddenly face a significant increase in shadowing by a new development, [Sarnoff 2013] potentially rendering day-lighting or solar energy harvesting systems useless. Indeed certain jurisdictions have regulations in place to ensure buildings receive adequate daylight and/or that new buildings do not reduce the amount of daylight falling on a home [Rights of Light Act 1959 (UK)]. Therefore it is imperative to have the ability to identify potential solar issues at relatively large scales early on in the design, and to be able to do so in a timely fashion to keep up with the rapid pace of the initial design stages.

Existing Tools

There are numerous tools available to study solar insolation levels in and around buildings and they can be broadly grouped into two categories: *rendering* based tools and *geometric* tools.

Rendering based utilities include the 'mental ray' engine [Mental Ray 2013] found in Autodesk products, and the Radiance engine [RADIANCE 2013] which can be used on its own or as the simulation engine for a variety of products (OpenStudio, Daysim, DIVA-for-Rhino). Such tools create photorealistic images of a specific scene and are able to include the effects of a wide variety of material types, sky and lighting conditions, and physical phenomena re-

lated to light propagation. Not only do these tools generate photorealistic renderings but the user is also able to extract highly accurate estimations of illuminance/irradiance, glare and other metrics from the scene. Radiance in particular is often considered the industry standard for daylight simulation programs due to its flexibility and accuracy. Daysim, for example, has been found to match measured internal illuminance values with a Root Mean Squared Error (RMSE) between 6-26% [Reinhart 2001]. The drawback to these types of tools is that they can have steep learning curves, tend to have limited parallelization options leading to long calculation times, and require detailed material properties. This can be a critical bottleneck when insolation levels are required over large areas or at high spatial or temporal fidelity, or when material properties are unknown. The results can also be cumbersome to work with at large scales and cannot always be easily incorporated with other data sets like CFD models.

The simpler, geometric tools, such as Ecotect's Split Flux Method [Ecotect 2013], Sandia National Laboratory's Solar Glare Hazard Analysis Tool (SGHAT) [Ho & Khalsa 2010] or the Solar Analysis Tool in ESRI's ArcGIS package [ArcGIS 2013] usually focus on solving for specific metrics, (daylight factors, retinal irradiance and surface insolation respectively) using only the geometric relationship between the sun/sky, obstructing surfaces and test points with simplifying assumptions made to speed up the computation process. This relationship is usually determined through a ray-casting like process, where virtual rays are projected out from each point of interest. These rays are then tested for intersections with obstructing objects to gauge that point's exposure to the sun/sky. (SGHAT is the exception, ignoring obstructions entirely.) These tools typically do not account for more than a single reflection (Ecotect and SGHAT account for a single bounce, ArcGIS neglects reflected light entirely), nor do they account for diffuse inter-reflections between surfaces. This class of tools also tend to not use climate data as an input, instead relying on analytical models or fixed values to set the amount of direct and diffuse radiation available at a given point in time. Material properties also tend to be simplistic, typically only a single transmittance or reflectivity value is able to be set, if at all, neglecting important physical properties such as the variability of the reflectivity of glass with angle of incidence. Similar to the rendering based utilities, geometric solvers typically also have limited options for parallelizing the work flow, making large scale data sets difficult to generate, post process and cumbersome to integrate into other models.

A Different Approach

The tool presented here is designed to be a hybrid of the two classes of daylight simulation software. It combines a fast geometric analysis with additional physics modelling to better simulate insolation within the built environment. By building it within the framework of the popular open source CFD package OpenFOAM [OpenFOAM 2013], we are able to not only easily integrate solar results into an existing CFD domain, but also take advantage of OpenFOAM's parallelization capabilities. The focus of this tool is primarily on external applications, in particular, solar insolation; used for energy potential, sunlight availability for plant growth, external thermal comfort studies, over-shadowing/sky exposure analyses and glare, so it is within this context that design decisions and modelling assumptions were made. Though it will be shown later that it can also yield rough estimations for various internal day-lighting parameters.

2 Methodology

In general terms, this utility has four steps:

1. Pre-processing
    a. Geometry setup
    b. Sensor point definition (i.e. table of points, surface files or 3D CFD mesh)
    c. Climactic data definition

2. Parallelization (distributing the sensor locations amongst multiple CPUs)
3. Simulation
    a. Determine the location of the sun relative to the site for the current time and date
    b. Compute sensor direct solar exposure based on solar position and transmittances of the geometry that a virtual ray passes through as it travels from sun to sensor
    c. Compute sensor diffuse solar exposure using Perez Sky Model [Perez et al 1990]
    d. Compute any other desired metrics (illuminance, thermal comfort levels, etc.)
    e. Repeat a-d for each entry in the input climate record, tracking average and/or maximal values as required
4. Post-processing
    a. Depending on how the sensor points were input, the utility will output the computed data in a tabular, surface or finite volume format.

Each of the above steps will be explained in greater detail below.

Pre-processing

Geometry

As with any other solar modelling tool, representing the domain is as much of an art as a science. Overly detailed models lead to increased run times, and over simplifications can influence results. Where ever applicable, users of this tool follow industry standard best practices, which are succinctly outlined by the Illuminating Engineering Society of North America [IES 2012].

This utility requires that all surfaces (buildings, glazing, terrain, etc.) be input in *STereo-Lithography* (STL) format, (also referred to as *Standard Tessellation Language*). This is a simple, open-source format designed to store the minimum amount of information to define three dimensional surfaces. This format tessellates surfaces into triangles, with the points and face normal of each triangle stored using a three-dimensional Cartesian coordinate system. This format was chosen due to its simple nature and wide-spread use in 3D CAD packages and also for its native compatibility with OpenFOAM. The STL syntax does not enforce any geometric restrictions, (i.e. closed surfaces, consistent orientation of face normals, etc.) so it is important that during the initial modeling phase that care is taken to correctly represent the surfaces. Face normal orientation is particularly important, as the direction of the surface normal defines the "outer" face of the surface and the direction light will reflect from it.

Surface properties are defined by assigning the outer face reflectivity and transmittance values at 10 degree increments (from 0 – 90 degrees) plus a final 'hemispherical average value'. This input is designed to mimic the output structure from Lawrence Berkley National Laboratory's WINDOW software [WINDOW7 2013], allowing the user to model complex glazing systems within WINDOW and include the results in the simulation. This method of defining material properties has the added advantage of being conceptually easier for novice users to understand compared to other simulation tools.

Sensor Locations

The tool has three choices for inputting the points of interest where data is to be collected, requiring varying levels of additional pre-processing. The first method is to simply provide a list of points where solar data is to be determined. The points are referenced using the same Cartesian coordinate system used to define the STL files. By default the program assumes that the user requires horizontal insolation values, so it assumes the point normals point in the Z+

direction. This can be overridden if the user provides a second list of "target points", then a unit vector pointing from the point of interest to its associated target point is taken to be the normal. For studies involving solar reflections it is also useful to only consider reflections within a certain angular distance from the point normal. This is applied in situations where the concern is reflected light impacting an individual who is performing a task that prevents them from simply looking away, (i.e. those driving cars/buses, piloting aircraft, etc.). A third optional input specifies this maximum angular distance from normal that a reflection can emanate from to be included in the analysis, by default this value is 90°, to include reflections from any point in the hemisphere.

The second method to define test points is by using the STL surfaces themselves. In this mode the centre of each STL triangle, offset by 0.01m in the face normal direction, is taken to be the test point with the associated face normal defining the orientation of the point. This mode of operation is useful when the concern is solar impacts on buildings themselves, rather than on the areas around them.

The final input method for this tool is by using a properly generated finite volume mesh in the OpenFOAM format. The centre of each cell is taken to be a test point, for surface boundary cells this point is offset similarly to the STL input case. Point orientation is determined based on the type of cell; surface boundary cells have associated normal defined so these are used directly, cells within the fluid domain are assumed to have a normal in the Z+ direction so output values are horizontal insolation. This method is used most frequently as part of external thermal comfort calculations so that in every cell in the study domain there is both wind speed and insolation information without the need for interpolation.

Climate Data

This tool reads in a local climate time history file which defines the location, time and dates to be analyzed as well as the recorded direct normal and diffuse horizontal radiation levels used to determine insolation levels within the domain, (other meteorological parameters must also be included for thermal comfort studies). The reason for using a custom format, rather than one of the more common weather input files is because of the required flexibility for performing different analyses. For example, when performing external glare analyses it is often desirable to check for glare at intervals less than one hour, which is the typical time step between records for common weather files, and for thermal comfort analyses it is desirable to use multiple years of climate records to increase statistical confidence in the results. By allowing the tool to simply iterate over each entry in the record, glare and other solar information can be computed with any temporal accuracy and over any length of time. Another reason for not choosing to use an existing climate file format is because of the method used to determine a "typical" month based on a long term climate history. Because these file formats are used mainly in building energy simulation programs, the weighting factors used to determine how "typical" a given month is, are skewed heavily towards solar radiation and temperature values. [Su et al. 2009]. For thermal comfort studies, where wind speeds and directions are also critical, this weighting process can alter the distribution of these parameters, potentially changing results. Therefore the flexibility to read in climate data from any source is important.

Parallelization

After defining the simulation configuration (sensor points, climate file and surface geometry); the test points are distributed across an arbitrary number of processors based on OpenFOAM's domain decomposition techniques (i.e. the domain is subdivided into several smaller domains, each one solved for by a different processor, with boundary conditions communicated between processors at each iteration). For the point and STL based input modes, the indi-

vidual points are evenly distributed amongst the different processes regardless of their position in the domain. For mesh based runs, the standard OpenFOAM decomposition utility is employed to divide the test cells as evenly as possible using a custom script to manually define the destination processor for each cell. Once the test points have been divided, each processor then begins the actual simulation process.

Simulation

Solar Positioning

Given the site's latitude, longitude, time zone and the date and time of the current entry in the met record, the sun's position is computed using the Solar Position Algorithm developed by the National Renewable Energy Laboratory [Reda & Andreas 2008]. This methodology has been found to be highly accurate, being able to compute solar zenith and azimuth angles to within 0.0003°. Details of the model can be found in the reference text.

Direct Insolation

Direct insolation is the solar radiation that follows a straight line path from the sun to each point in the domain. Given the current solar position, rays are traced from the location of the sun to each test point in the domain. Each ray is then tested for intersections with each triangle of the surface STL's. Each intersection reduces the direct insolation contribution by a given factor, determined by the angle of incidence of the ray on the surface and the surface's angular-dependant transmittance properties. Refraction is neglected to simplify the computations. Once all intersections have been checked, the direct normal radiation value is scaled a final time based on the angle between the point normal and the ray. This utility also accounts for a single reflection of light, making the assumption that in the outdoor realm the extra insolation from rays that have bounced more than once is negligible. Additional rays are traced from any surface triangle that is exposed to direct insolation in the direction of the specular reflection vector with the insolation value at that point scaled by the angle-dependent reflectance factor for that surface.

Diffuse Insolation

Diffuse insolation is the solar radiation that emanates from the entire sky dome due to the scattering effects of the atmosphere; this radiation is further reflected by surfaces on the ground. Computing the diffuse exchange of radiation is a time consuming process, as the exchange between each surface with every other surface must be considered, including the impacts of multiple reflections. This utility assumes that in the outdoor environment the diffuse surface-to-surface contribution is negligible compared to the sky dome and as such is neglected. This assumption is validated in Case Study 1, and is found to match reasonably well to RADIANCE simulations. This utility uses the Perez Sky Model [Perez et al 1990] to approximate the diffuse sky irradiance distribution for a given time and date. Details of the model can be found in the referenced text, but broadly, this model superimposes three distributions onto the sky dome to better approximate the distribution of diffuse radiation. There is a base isotropic value of diffuse irradiance across the dome; added to this is a horizonal component, accounting for increased light at the horizon due to surface albedo; and the final distribution is the circumsolar component, accounting for the additional diffuse radiation emanating from the area immediately around the sun. Each distribution has an associated shading factor which moderates the impact of each distribution. This utility determines these shading factors by using a similar ray casting process as the direct insolation. For the dome and horizonal shading, a Monte-Carlo style process is used, firing thousands of rays randomly into the hemisphere to determine the fraction of the sky dome and horizon visible at each point. The circumsolar shading is assumed to be the same as the direct insolation shading factor computed above. Because the horizon and sky dome shading factors do not vary with time, they are only com-

puted once at the beginning of the simulation, leaving only the direct/circumsolar shading factor to be computed at each time step.

Derived Metrics

Once the direct and diffuse insolation values are computed for a given point in space and time numerous other metrics can then be computed. In addition to insolation based metrics for solar energy potential [Compagnon 2004], illuminance levels can be estimated by using the Perez method for estimating luminous efficiency (i.e. the conversion factor from watts to lumens) [Perez et al 1990]. Once illuminance values are available it becomes possible to compute various internal day-lighting metrics such as Daylight Autonomy [IES 2012] or Useful Daylight Illuminance [Nabil & Mardaljevic 2006].

Photosynthetically active radiation (i.e. the fraction of irradiance capable of driving photosynthesis in plants) can also be estimated (commonly taken to be approximately 50% of ground level irradiance [Earl 2008]) for assessments related to plant growth. Insolation values can also be combined with CFD wind speeds and climate data to produce thermal comfort information [Rose et al 2010], and reflected direct irradiance values can be used to estimate the potential for distracting or damaging glare [Ho & Khalsa 2010].

Post-processing

For mesh based analyses, the resulting metrics are stored using the same finite volume field format used by OpenFOAM, allowing the user to leverage existing post processing workflows. For cases where the test points were given as STL files, output files are generated in the Visualization Toolkit (VTK) format, storing all data sets as cell-based fields connected to the underlying geometry. The VTK format is open source and thus is able to be imported into a wide variety of 3D modelling and other post processing software. Point based run results are output as simple comma separated value (CSV) files, where each line represents the results for a given time and date in the climate record. CSV files can be read in any text editor or spreadsheet software maximizing the options available for post processing.

3 Results

Case Study 1: Façade Solar Insolation on a Suburban Neighbourhood

To investigate the accuracy of the solar insolation models discussed above, a model of a suburban neighborhood was generated. This model, shown in Figure 1, consists of 226 individual buildings, spread across 25 hectares (62 acres), ranging from small bungalow style homes to 3 story row houses, to low rise commercial/office space. Buildings are aligned in a rough grid

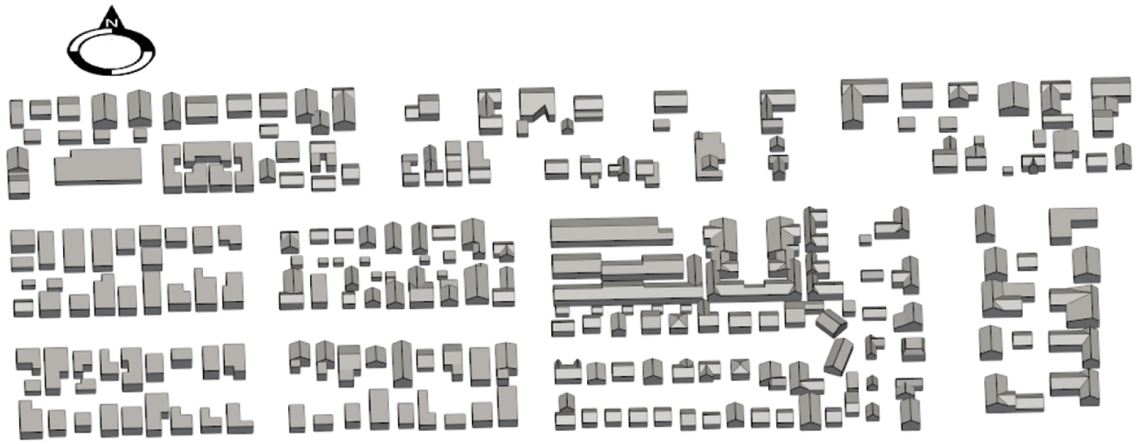

Figure 1: 3D Model of sample neighborhood

layout, rotated slightly west of north with a variety of roof configurations to increase the diversity of the test point normals. This model was run using the STL triangle centres as the test points, resulting in 4,457 points to be tested. The model was imported into Rhino and annual solar insolation statistics at each point were generated using the DIVA-for-Rhino plugin and annual climate data in the EnergyPlus format for 15 cities across the globe at various latitudes. Figure 2 below shows one of the possible output methods from the tool, illustrating surface insolation on each of the test surfaces. The point insolation values were then compared to results generated using the same model and climate file in this tool.

A statistical analysis of the two sets of points was performed, computing the Mean Bias Error (MBE) and Root Mean Squared Error (RMSE) for each location, Table 1 summarizes the results of this comparison. Because this utility neglects diffuse reflections from surfaces, the DIVA analysis was repeated twice, with and without a ground plane (the largest source of diffuse reflections) to judge the relative impact of the surface albedo on the model and to ensure a direct "apples-to-apples" comparison of what this tool simulates. The bracketed error values in Table 1 indicate errors compared to DIVA without a ground plane, and values without brackets indicate error relative to the DIVA case with a ground plane. For both cases the RMSE values are at acceptable levels, falling within the benchmarked precision of Daysim [Reinhart 2001], which is the underlying simulation engine (with Radiance) of DIVA. The proposed utility also tends to under-predict values, making the results conservative for most applications.

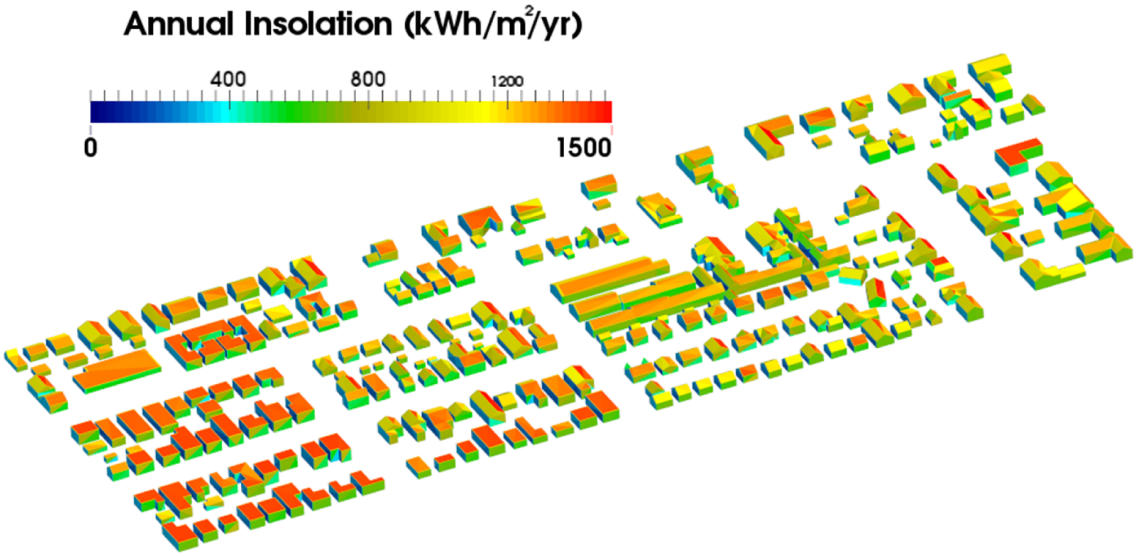

Figure 2: Annual insolation values predicted for Beijing

Table 1: Annual insolation error values for various cities

City	Latitude	RMSE	MBE
Abu Dhabi	24.47	14% (8%)	-12% (-5%)
Adelaide	-34.93	17% (13%)	-12% (-5%)
Ankara	39.88	13% (9%)	-11% (-5%)
Beijing	39.91	13% (9%)	-11% (-5%)
Berlin	52.54	14% (10%)	-11% (-6%)
Bogota	4.71	10% (9%)	-8% (-1%)
Brasilia	-15.80	12% (7%)	-10% (-3%)
Houston	29.76	12% (9%)	-9% (-3%)
Johannesburg	-26.20	13% (9%)	-10% (-3%)
London	51.51	14% (10%)	-12% (-6%)
Mumbai	18.98	14% (11%)	-10% (-3%)
Punta Arenas	-52.98	14% (10%)	-12% (-7%)
Singapore	1.30	11% (9%)	-8% (0%)
St. Petersburg	59.95	14% (9%)	-8% (-1%)
Toronto	43.70	13% (9%)	-11% (-5%)
Average		**13% (10%)**	**-10% (-4%)**

In terms of simulation run-times; each DIVA-for-Rhino simulation ran in around 60 minutes when using the default quality parameters, (i.e. 6 ambient bounces, 1000 ambient divisions and a direct threshold value of 0). Taking advantage of the parallelization capabilities of this tool, no simulation run time exceeded 30 seconds when utilizing 12 cores. Simulation time decreases approximately linearly, to the limit of the cores available for this case study, with an average simulation time of less than 10 seconds at 36 cores.

Case Study 2: Internal Day-lighting

Given the assumptions noted above, the utility is not expected to achieve internal day-lighting values to the same degree of accuracy as the external isolation levels noted above. However, it is worthwhile to investigate how this tool performs in a potential role as a quick first check to compare the relative differences between multiple designs, before committing to a detailed lighting simulation of the best performer. As a simple test case we take our domain to be a square room (Figure 3), aligned with the cardinal directions with an east facing window and skylight each made of 6mm float glass (88% transmittance). A test plane made up of 3200 points was generated at 0.8m above the floor and horizontal illuminance was determined using based on the Berlin climate file. Berlin was chosen as it was a median performer from the external insolation study above.

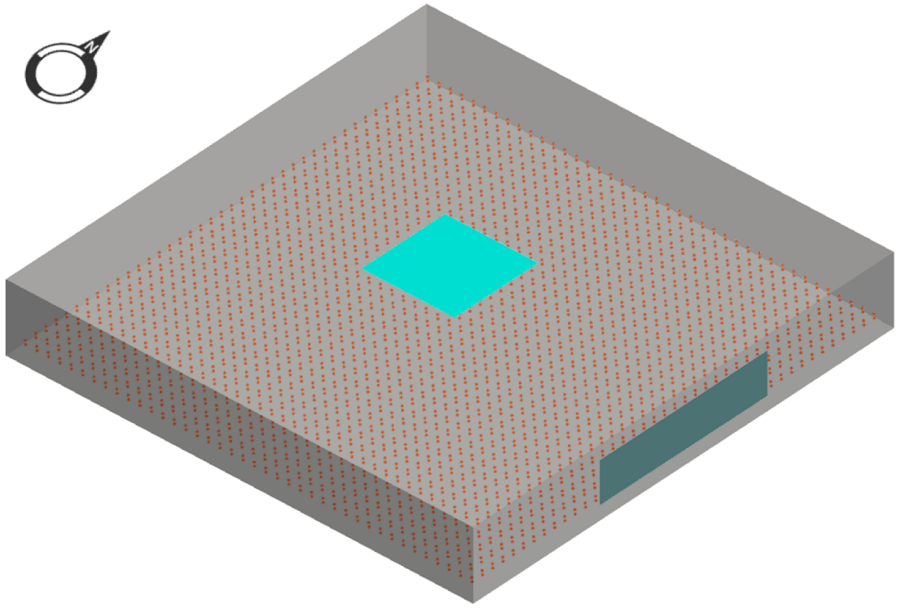

Figure 3: Schematic view of test room. (Sensor points in orange, window teal, skylight in cyan)

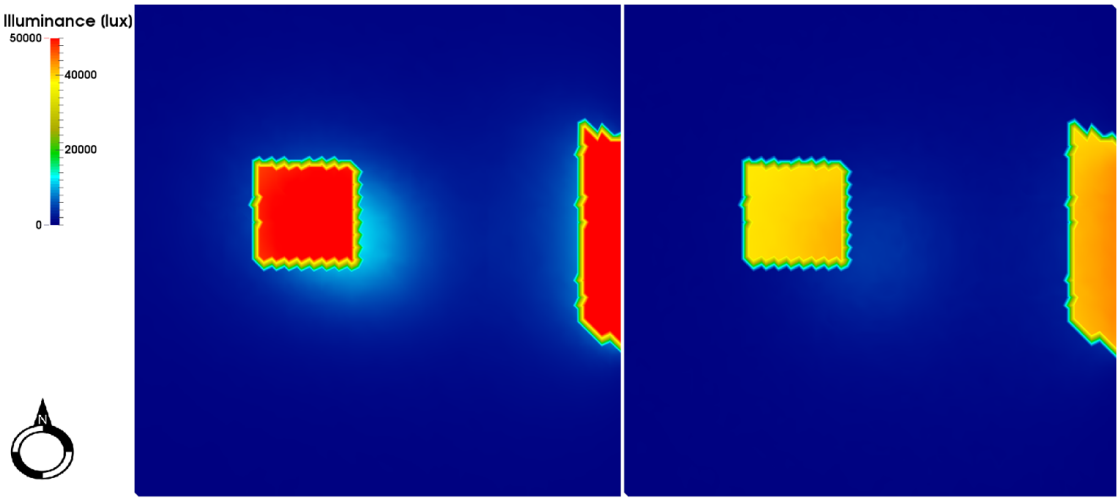

Figure 4: Illuminance distribution at working level for 0900, August 8 in Berlin from DIVA (left) and this utility (right)

A typical result can be seen in Figure 4, for a given hour the spatial distribution of light is very close between this tool and DIVA, but as expected the magnitude of the luminance is lower by approximately 30% (slightly less than 50 klux from DIVA, compared to 37 klux from the proposed tool). This is not unexpected, as once one moves indoors diffuse light plays a much larger role than it does outside.

When we look at the climate based day-lighting metrics, we see a similar trend, where the relative distribution of light is similar, with significant differences in magnitudes. Figure 5 compares contours of Daylight Autonomy (i.e. the percentage of hours where plane illuminance exceeds 300 lux). The general distribution of DA is consistent between the two cases, and when looking at the fraction of the plane considered "daylit" (i.e. a DA of 50% or more) they match well (Figure 6); with DIVA predicting 43% of the plane as daylit, compared to this

tool's prediction of 38%. Table 2 summarizes the errors found for the daylight related parameters tested, both in terms of percentages and also in actual average deviation values, since the frequent values of 0 can skew percentage based metrics. The average deviation values with units are enclosed in brackets.

As expected these results fall outside of acceptable error ranges when compared to DIVA/Radiance. However, given that in general the distribution of daylight is comparable, and that this tool is orders of magnitude faster that DIVA (seconds compared to hours) it is proposed that this tool can be used as a first check of internal day-lighting, provided the user is aware of the limitations, and that final confirmation of daylight levels are simulated using a more thorough tool like DIVA.

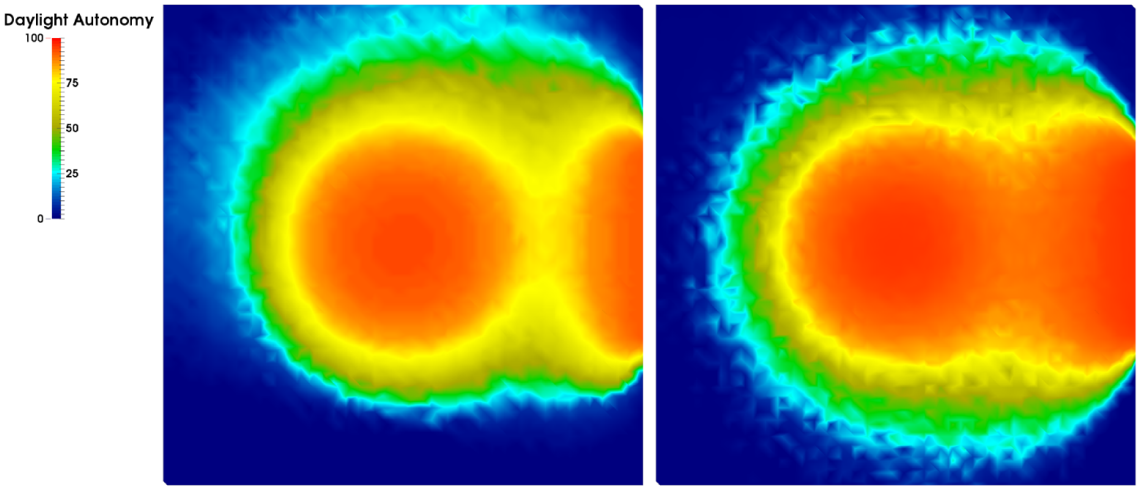

Figure 5: Daylight Autonomy contours based on Berlin climate data from DIVA (left) and this tool (right)

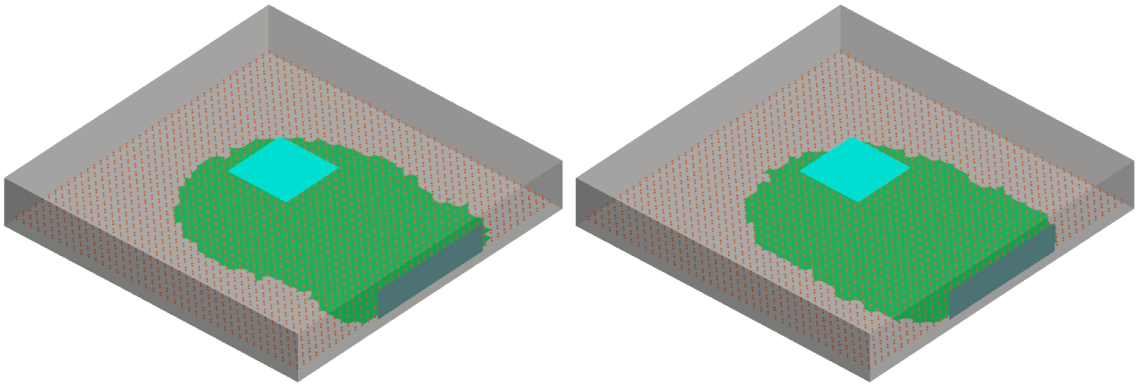

Figure 6: Daylit area (green) as predicted by DIVA (left) and this tool (right)

Table 2: Errors for Climate Based Internal Day-lighting Metrics

Metric	RMSE	MBE
Hourly Illuminance	42% (1.8 klux)	-38% (-1.8 klux)
Daylight Autonomy	68% (7.5% of hours)	37% (2.2% of hours)
Continuous Daylight Autonomy	29% (8.7% of hours)	25% (7.5% of hours)
Useful Daylight Illuminance		
Under Lit	40% (12% of hours)	-38% (-10% of hours)
Well Lit	84% (16% of hours)	80% (14% of hours)
Over Lit	36% (4.5% of hours)	-1.5% (-3.5% of hours)

4 Discussion

Validity

The results have shown that this tool yields sufficiently reliable results for any analysis requiring external solar insolation values, or any values derived from insolation. With an average RMSE of 13% compared to Radiance best practices; this tool is well within the error bounds of DIVA (6-26%). In the external realm all assumptions appear to be justified. When looking at interior spaces, this tool is not appropriate for detailed work. However, if the user understands the limitations of this tool, it is still useful as a first check of indoor day-lighting levels, particularly when speed and having a general idea of the lighting of a space, are more important than absolute accuracy.

Computational Effort

This tool has been used at scales ranging from small neighborhoods (<50 ha) to entire master planned cities (>1000 ha). Size and complexity of geometry, test sensor and temporal spacing are key factors influencing run times so striking the right balance between those three factors is important. This can be mitigated by the parallelization options, meaning the main practical limit is the number of available cores and the amount of memory on each compute node. This allows for a significant speedup compared to other tools, allowing for almost real-time feedback on the interaction of the sun and the built environment, even at large scales.

Future Work

Moving forward, the author is planning to further improve the parallelization performance by optimizing how common data is stored among the processes, ideally leading to a smaller memory footprint while not significantly degrading performance. Improving the modelling of diffuse radiation indoors is also being investigated. Implementing a radiosity based algorithm using the OpenFOAM finite volume radiation solvers is one option, though implementing the analytical correlation between facade and work-plane illuminance found in [Dogan et al 2012] is also being examined as a better alternative. Further comparisons between the interior illuminance values predicted by this tool and Radiance are also being conducted to see if the discrepancy can be reduced. Likely sources of the error are the differences in material property definitions, the use of the Perez method to determine luminous efficiency and the lack of diffuse reflections. The author is also researching better metrics to holistically "score" an entire master plan, ideally based on a combination of factors including energy generation potential, pedestrian level wind speeds, solar exposure, day-lighting potential, thermal comfort, and natural ventilation potential.

5 Conclusions

The utility presented here has been found to be able to accurately predict external solar insolation for a wide variety of locations around the world. It agrees well with results from the industry standard Daysim/DIVA approach but at significantly lower run-times. This allows for the efficient study of very large domains at very fine spatial and temporal fidelity. By allowing for multiple input and output modes, including using existing finite-volume meshes, the results of these studies can be easily integrated into spreadsheets, 3D visualizations, or even with CFD results.

6 References

ArcGIS, 2013, ESRI, USA, viewed 09 December, 2013 <http://help.arcgis.com/en/arcgisdesktop/10.0/help/index.html#/Understanding_solar_radiation_analysis/009z000000t8000000/>

Compagnon R., 2004, 'Solar and daylight availability in the urban fabric', *Energy and Buildings*, vol. 36, issue 4, pp. 321-328

Dogan, T., Reinhart, C.F., Michalatos, P., 2012, 'Urban daylight simulation: Calculating the daylit area of urban designs', *Proceedings of SimBuild 2012*, Madison, Wisconsin, USA.

Earl, H., 2008, *Introduction: Solar radiation and irradiance*, lecture notes for Crop Physiology at The University of Guelph, viewed 09 December 2013, <http://www.uoguelph.ca/plant/courses/pbio-3110/lectures/lec05_08.pdf>

Ecotect, 2013, Autodesk, USA, viewed 09 December, 2013 <http://usa.autodesk.com/ecotect-analysis/>

Flatley, J.L., 2010, 'Vdara hotel 'death ray' claiming victims in the Las Vegas Strip', *Engadget.com*, 29 September, viewed July 29, 2013, <http://www.engadget.com/2010/09/29/vdara-hotel-death-ray-claiming-victims-in-the-las-vegas-strip>

Hayward, M., 2012, 'Airport controllers complain of solar panels' glare', *New Hampshire Union Leader*, 30 August, viewed 29 July 2013, <http://www.unionleader.com/article/20120830/NEWS02/708309966/0/SPORTS>

Ho, C. K. & Khalsa, S.S., 2010, 'Hazard Analysis and Web-Based Tool for Evaluating Glint and Glare from Solar Collector Systems', *Proceedings of SolarPACES 2010*, Perpignan, France, September 21-24.

IES, 2012, *Approved Method: IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE)*, IES LM-83-12, Illuminating Engineering Society of North America, USA

Mental Ray 2013, Autodesk, USA, viewed 09 December, 2013 <http://www.autodesk.com/products/mental-ray-standalone/overview>

Nabil, A. & Mardaljevic, J., 2006, 'Useful daylight illuminances: A replacement for daylight factors', *Energy and Buildings*, vol. 38, issue 7, pp. 905-913

OpenFOAM 2013, The OpenFOAM Foundation, UK, viewed 09 December, 2013 <http://www.openfoam.org/>

Perez, R., Ineichen, P., Seals, R., Michalsky, J., Stewart, R., 1990, 'Modeling Daylight Availability and Irradiance Components From Direct and Global Irradiance', *Solar Energy*, vol. 44, issue 5, pp. 271-289

RADIANCE 2013, Lawrence Berkley National Laboratories, USA, viewed 09 December, 2013 <http://www.radiance-online.org/>

Reda, I. & Andreas, A., 2008, 'Solar Position Algorithm for Solar Radiation Applications', National Renewable Energy Laboratory, Colorado, USA

Reinhart, C.F., Walkenhorst, O., 2001, 'Validation of dynamic RADIANCE-based daylight simulations for a test office with external blinds', *Energy and Buildings*, vol. 33, issue 7, pp. 683-697

Rights of Light Act 1959 (United Kingdom), viewed date 10 December, 2013, <http://www.legislation.gov.uk/ukpga/Eliz2/7-8/56>

Rose, D., Wu, H., Beyers, M., 2010, 'Spatial and temporal computation of thermal comfort inputs in outdoor spaces', *Proceedings of the Fifth International Symposium on Computational Wind Engineering*, Chapel Hill, North Carolina, USA, May 23-27

Sarnoff, N., 2013, 'Lawsuit over high-rise says shadow would hurt neighborhood', *Houston Chronicle*, 2 May, viewed 12 November 2013, <http://www.chron.com/default/article/Lawsuit-over-high-rise-says-shadow-would-hurt-4484642.php>

Schiller, M. & Valmont, E., 2005, 'Microclimatic Impact: Glare Around The Walt Disney Concert Hall', *Proceedings of the Solar World Congress 2005 Joint American Solar Energy Society / International Solar Energy Society Conference*, Orlando, FL, August 6-12

Su, F., Huang, J., Xu, T., Zhang C., 2009, 'An evaluation of the effects of various parameter weights on typical meteorological years used for building energy simulation', *Building Simulation*, vol. 2, issue 1, pp. 19-28

Wainwright, O., 2013, 'Walkie Talkie architect "didn't realise it was going to be so hot"', *The Guardian*, 6 September, viewed 5 October 2013, <http://www.theguardian.com/artanddesign/2013/sep/06/walkie-talkie-architect-predicted-reflection-sun-rays>

WINDOW7 2013, Lawrence Berkley National Laboratories, USA, viewed 09 December, 2013 <http://windows.lbl.gov/software/window/7/>