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ANNUAL SOLAR IRRADIATION MAPPING AND VISUALIZATION FOR COMPLEX GEOMETRIES

Simon Rees[1], John Mardaljevic[2]

[1]School of Civil Engineering, University of Leeds, UK
[2]School of Civil and Building Engineering, Loughborough University, UK

Email: S.J.Rees@leeds.ac.uk

ABSTRACT

We introduce an innovative approach to producing annual solar irradiation data for complex geometries in urban settings. The method uses advanced ray-tracing and ambient sampling approaches with cumulative sky models derived from hourly climate data. In contrast to earlier approaches that have produced annual irradiation maps in the form of images from pre-selected viewing points, this method produces results for all the surfaces of the scene simultaneously. In this approach polygon surface meshes are derived from imported building and terrain digital models. Irradiance are calculated at mesh vertices by making use of Radiance software tools. This hybrid ray-tracing and statistical sampling analysis allows inter-reflection between and obscuration by other surfaces to be accounted for with high fidelity. The resulting polygon and irradiance data sets are combined to form 3D models for interactive visualization. The method has a number of advantages over existing image-based approaches and is capable of being applied to detailed study of building designs and larger scale urban scenes.

INTRODUCTION

Quantitative evaluation of annual solar irradiance and its spatial variation over building façades and extended urban scenes is of interest to building designers, planners and developers. There has been significant interest in generating and interrogating large solar irradiation data sets for the evaluation of renewable energy proposals in the last decade in particular. This has been partly driven by growing interest in exploiting solar energy technologies and has, at the same time, been enabled by wider availability of digital geometric data and increasingly powerful analysis tools.

The feasibility of being able to make solar irradiation calculations over large-scale urban scenes (e.g. city block scale or larger) is firstly dependent on access to digital surface models (DSM) that represent both terrain and building (and possibly vegetation) geometries. Two-dimensional building footprint/roof area data obtained by extracting roof features from areal images (Wiginton et al., 2010), or in combination with Graphical Information System (GIS) data (Rylatt et al., 2001), has been used to give useful estimates of potential solar energy yield in residential areas. Where building heights vary significantly and there is a high likelihood of partial shading by adjacent buildings, two-dimensional data must be regarded as inadequate however. The availability of remote sensing data such as LiDAR (Lukač et al., 2013) has enabled many data sets to be extended to include building height information (so-called 2.5D data), for example (Lindberg et al., 2015). However, where the geometry of vertical surfaces has to be inferred, calculated irradiances may have higher levels of uncertainty than horizontal surfaces (Lindberg et al., 2015).

There is a growing body of building and terrain geometric data available, defined in polygon primitives, that can be used to construct DSM with higher levels of façade and roof detail: approaching what could be expected in CAD models in some cases. The growth in availability of such data has been driven by development of browser-based visualization tools (where building models may be crowd-sourced) (Counsell et al., 2006), open-source data exchange initiatives such as CityGML (de Laat and van Berlo, 2011), and academic/governmental initiatives (Horne, 2009). Progress towards geometric data sets that could be described as Virtual City Models is indeed evident (Morton et al., 2012). These DSM with relatively high levels of façade detail have partly been enabled by automated laser scanning technology. There are consequently a range of such data sources that are freely available (open-source) or available as commercial data products. It is becoming increasingly common for larger building development projects to make use of such data sets combined with CAD/BIM models of proposed buildings for various forms of analysis, e.g. solar access, daylighting, pedestrian comfort, CFD for wind loadings and ventilation.

We propose a method for generation of detailed solar irradiation mapping data that makes use of the latter forms fully three-dimensional data. These data sets are readily translatable to polygon primitives that can be processed by solar irradiation models and reformed into 3D data embodying both annual irradiation values and polygon geometric data. A number of forms of solar irradiation model could conceivably be applied to analysis of such data. In our case we apply the tools of the Radiance software (Larson et al., 1998). Solar illumination data is derived from annual hourly climate data sets and represented by cumulative sky models. Our initial motivation has been to study particular buildings in a university campus setting. In this paper we use one particular building with complex geometric features to demonstrate the potential of the method.

METHOD

Many of the developments in urban-scale solar mapping have focussed on evaluation of solar renewable technologies and have relied on the type of GIS/LiDAR 2.5D data noted above and made use of analytical methods to evaluate the effects of shading/blockage on particular surfaces (Karteris et al., 2014; Liang et al., 2014) in order to calculate net irradiance. Other approaches have employed true 3D building and terrain data and used tools like Radiance to calculate irradiance maps (raster data sets) that can be used for visualization in the form of false-coloured 2D images (Mardaljevic and Rylatt, 2003). Radiance has also been used by defining grids of calculation points (virtual pyronometers) and using the data to derive parameters that normalise the exposure to direct and diffuse insolation that are later used to calculate cumulative irradiance from hourly climate data (Compagnon, 2004; Kovach and Schmid, 1996). In the latter approaches the emphasis is on deriving synoptic data for particular surfaces (solar panel locations) and visualization of the results is a separate task.

The approach presented here uses Radiance to calculate irradiances at virtual pyronometer locations on the building surfaces. A cumulative sky model derived from climate data sets is used to make a one-time calculation of total annual solar irradiance: no intermediate surface parameters need be derived (Compagnon, 2004). Rather than establish uniform distributions of virtual pyronometer locations (Kovach and Schmid, 1996), we use model surface meshes (or subsamples of them) to define the locations and normal directions. Rather than use Radiance to further calculate view-dependent images, we construct new data sets that combine the calculation results and the surface meshes. These unstructured data sets can then be readily viewed with a range of interactive visualization tools and exported in a range of formats e.g. VRML. This approach could be termed surface mesh based. The modelling workflow is shown in Fig.1.

The building and terrain surface meshes form a basis for defining calculation points and for defining the scene geometry used in the ray-tracing calculations. In the examples presented later the building data originated in triangular polygonal form (Steriolithography format, STL) and a series of scripted tools were used to translate this data to that required by Radiance (.rad) and to generate a list of calculation points at the triangle vertices (the method is not restricted to triangles). The results of the Radiance calculations are lists of irradiance values. Further scripted applications are used to combine the results with the original polygon data to produce a visualization data set. The format we have used for these data sets is that used by the open-source

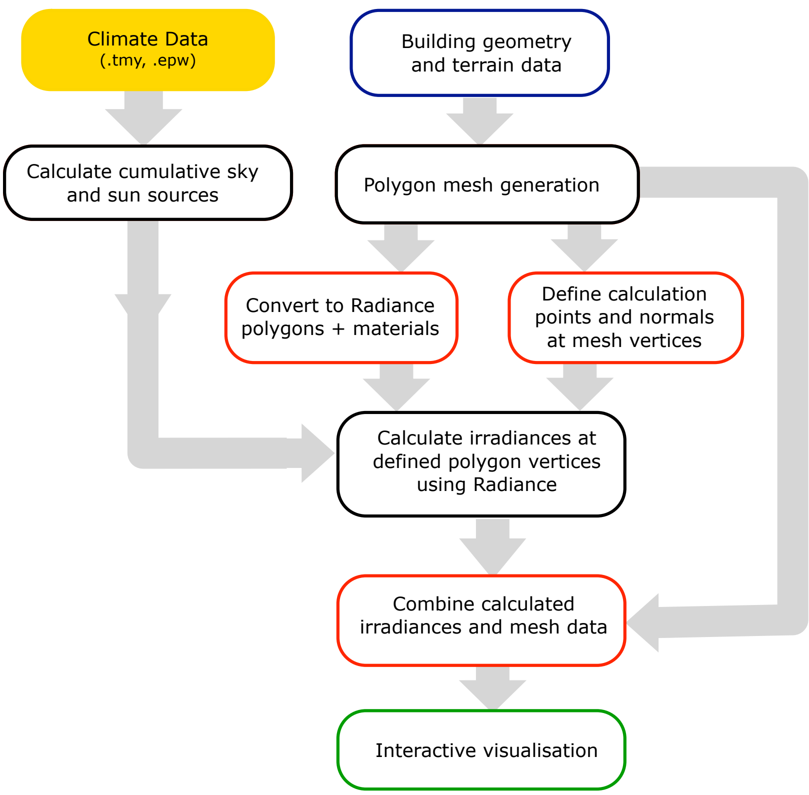

Figure 1: The data processing, calculation and visualization process .

Visualization Tool Kit (Schroeder et al., 2001) which can be readily viewed and interrogated using the related multi-platform paraview application (Henderson et al., 2004). The tools used in this modelling and visualization process are all open source. The data is kept in ASCII form and so is easily manipulated with python scripts. Besides these scripts, no new software platform has been required.

Surface mesh generation

Model geometry in the form of polygon data sets is required. This may come from a number of sources such as Google Earth, CityGML models or CAD tools. In the particular example used below, the data has been exported in STL format from a building simulation tool. It has been used with models from a mixture of data sources in a larger model of the De Montfort University campus. The polygon data derived from data sources of this type intentionally has a minimal polygon count. This usually means that the minimum number of polygons have been used to completely define the building surfaces and the ratio of polygon sizes can be quite large. This data might be used with Radiance directly in an image based approach (Mardaljevic and Rylatt, 2003) but further treatment is necessary to generate a surface mesh for use in the proposed method. The base input geometry used to generate the results presented later is shown in Fig.2.

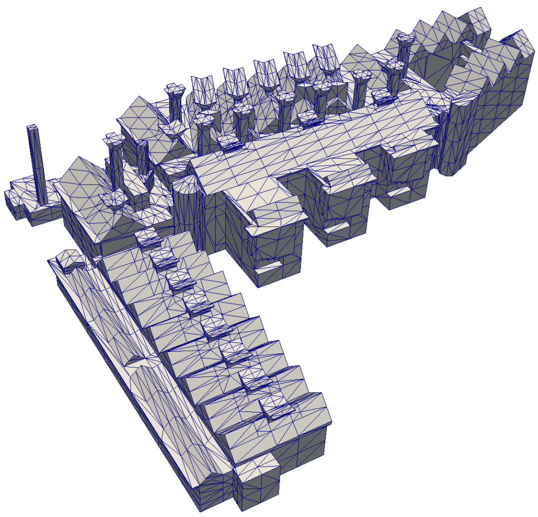

Figure 2: The base polygon mesh for the Queens Building at De Montfort University.

To avoid the additional data input and user interaction required to define further grids of calculation points we desire to use surface mesh vertex locations. This generally means that finer surface meshes have to be derived from the original polygon mesh given by the base building models. Our experience has been that such models can have polygons with a wide range of aspect ratios and are not guaranteed to be manifold such that some polygons may overlap. (The consequences of these features are discussed later.) A simple approach to increasing the mesh density (and subsequently the resolution of the calculation points) is to subdivide the base mesh and this can be done in an automated manner. However, this does not address any problems with polygons of differing size or with high aspect ratios. Simple subdivision also does not address issues of non-manifold surfaces. The other approach we have tried amounts to wrapping the base mesh in a finer surface mesh. This results in more uniform mesh distributions that are completely manifold.

To implement the surface mesh wrapping idea we have made use of the CFD meshing tools that are part of the OpenFOAM toolkit (Weller et al., 1998). In particular, we have used the tool SnappyHexMesh which is intended to generate hex-dominant volume and surface meshes by subdividing a background rectilinear mesh (Kortelainen, 2009). At object surfaces cells are firstly subdivided according to the local surface feature complexity and then 'snapped' to the underlying surface. Our motivation for using this tool is partly that the campus study is also concerned with modelling the wind environment using CFD.

For the purposes of generating the surface meshes for solar irradiation calculations, the volume mesh generated by the SnappyHexMesh tool is ignored and only the surface mesh extracted - again as a polygon data set in STL format. The resulting mesh is necessarily finer but also more uniform in the distribution of vertices. An example of applying this approach to the base geometry (Fig.2) is shown in Fig.3. The relatively high density of this particular mesh is simply a consequence of the geometric complexity of the building—particularly the roof light and ventilation stack details—and could be controlled to have lower density in the case of more regular building geometries.

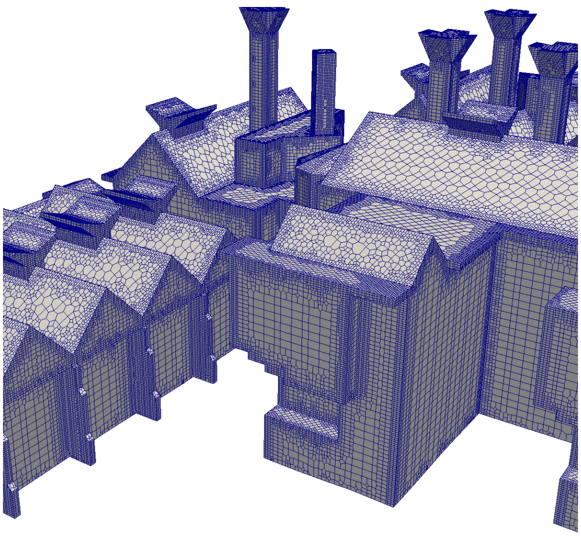

Figure 3: A surface mesh generated by wrapping and subdivision.

Polygon surface properties can be specified according to user defined material types and can be varied throughout the scene if required. For the purposes of testing and demonstrating the method, all polygons have been assigned properties representative of dark coloured building and ground surfaces in the results presented here. Reflectances were assigned to be 0.2 and surfaces assumed to be both smooth and non-specular.

Cumulative sky data

Standard climate datasets contain hourly values for various irradiation and illumination quantities. From these it is possible to derive hourly-varying sky and sun conditions for use in lighting simulations. Equally, it is possible to synthesise cumulative radiance or luminance "maps" for arbitrary periods (e.g. annual, monthly, etc.) that contain the aggregated contribution of all the unique hourly sky and the sun configurations. Separate radiance maps for the annual cumulative sun and the annual cumulative sky were synthesised from the standard climate dataset for Nottingham – the nearest such location to Leicester.
The sky radiance pattern at each timestep was based on a blend of CIE clear and CIE overcast sky models depending on the Perez clearness index (Mardaljevic, 2008). The sky radiance at each of the 145 patches of the Tregenza pattern Tregenza (1987) was converted to the *Radiance* `brightdata` format using the method described for the validation of *Radiance* using measured sky scans Mardaljevic (2000). The `brightdata` radiance map for the annual sky was the numerical sum of all the individual timestep `brightdata` values from the blend model. Thus, in the simulation, the cumulative radiance sky was treated in exactly the same way as any standard sky brightness pattern (e.g. CIE clear sky), only the pattern was described using the `brightdata` type and the radiance at each point on the sky vault interpolated from the associated data file.
The radiation from the sun was modelled by considering all the possible sun radiance values / sun positions and aggregating their contribution into a set of 'binned' sun positions based on a regular grid in altitude and azimuth (Mardaljevic and Rylatt, 2003). Thus the *Radiance* description of the cumulative sun contribution was a scene file containing several hundred 'suns'. Whilst this is less computationally efficient than, say, incorporating the sun contribution into the `brightdata` description of the sky, keeping the sun computation in the domain of deterministic sampling does ensure that the shadow gradients due to direct sun illumination are sharp and not 'smeared' as they would be if simulated using hemispherical sampling with interpolation of ambient values.

RESULTS

The building model used to evaluate the methods ability to generate high quality models for visualization of the spatial variations in annual solar irradiation, is based on the Queens Building at De Montfort University. This is one of a number of campus buildings being studied and has been selected for testing purposes because of its complex geometry. Much of the complexity lies in the geometry of the roof lights (the butterfly shaped constructions in Fig. 2) and the ventilation stacks. These are of particular interest in that they cast significant shadows over what would otherwise be good candidate roof surfaces for locating solar panels.

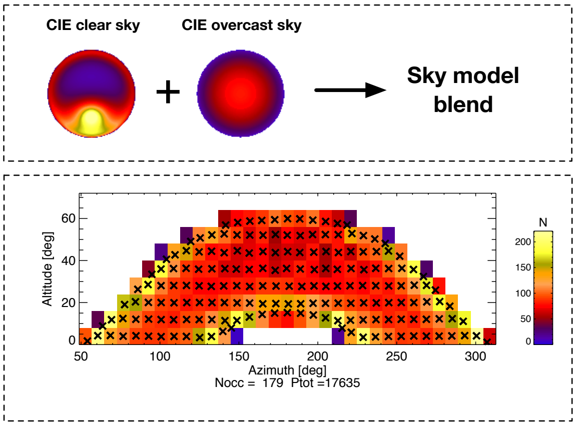

Figure 4: Blended sky radiance models and binned sun data.

Surface discretization

The distribution of the solar irradiation calculation points over the surface is entirely dependent on the mesh vertex locations. It is worth noting that at surface edges and over curved surfaces, where the surface normal changes relative to a neighbouring polygon (the feature edges of the mesh), the calculation points at the vertices are duplicated. These duplicates are associated with the respective neighbouring polygons with different normals specified accordingly. In these cases irradiance values naturally differ according to the normal directions.
Capturing significant spatial variations in solar irradiation—principally where shadows fall part way across planar surfaces—is dependent on local surface mesh resolution. Where the mesh is derived directly from the imported model polygon data, or a subdivision of it, it is possible that particular planar surfaces are represented by relatively large polygons. It is also possible that adjacent polygons have very different aspect ratios. For example, long thin triangles can be present. Such features can disrupt the distribution of calculation points resulting in poor local resolution of shadow related features. Furthermore, as the final visualization and colour mapping relies on linear interpolation of values across the polygons, visual artefacts can result.
Results using the base mesh are visualised in Fig. 5 and with the mesh subdivided in Fig. 6. These are enlarged views of the central part of the building viewed from the East. A ground plane was used in the calculations but is not shown in the visualization. The highest levels of annual irradiation are shown as expected, over the unobstructed southerly facing upper roof surfaces (centre and centre-right of the figure).

The roof surfaces belonging to the wing of the building at the left of these figures are southeast facing and might be expected to receive high levels of solar irradiation. However, the results for these surfaces highlight the cumulative effect of the shadowing effect of the large roof lights on the ridge of these roofs. These can be seen to limit full exposure to the parts of the roof surfaces nearer the gable ends and towards the roof ridges.

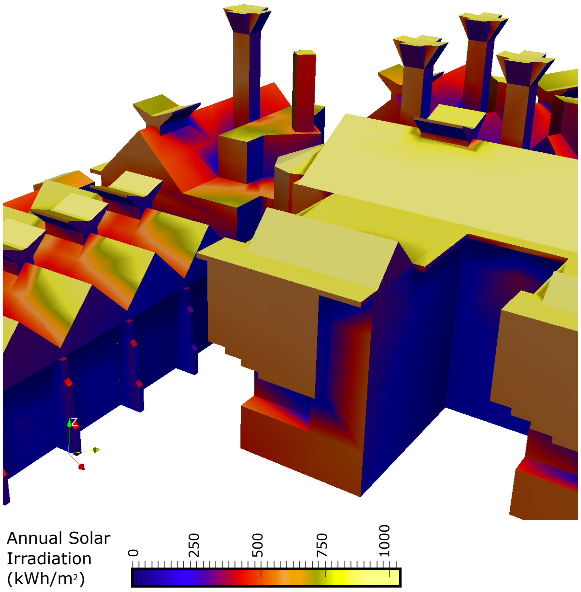

Figure 5: Solar irradiation visualised after false colouring viewing from the East. This calculation is based on the base mesh in Fig. 2.

The central area of the images in Figs. 5 and 6 show a three storey section of the building that has an area of roof that creates a large overhang at its corner. This façade faces southeast and a significant shaded area is created on the wall below. This area also shows triangular features that arise from the interpolation across the polygons in this area. These suggest an overemphasised shadow with triangulated corners. The shadowing indicated around the base of the roof lights also shows some signs of limited resolution and angular shapes arising from the underlying polygon representation. It could be said that these initial results are of sufficient resolution for general visualization purposes and for extracting the most useful irradiance quantities i.e. in the areas of higher irradiation. Nevertheless, we have examined the benefits of higher resolution meshes.

Doubling the resolution of the original mesh (Fig. 6) shows better resolution of the shadowing features around the roof lights. However, some triangularisation of the shadow details remains. This could be improved by manual editing of the polygon mesh to selectively reduce the size of the larger polygons. However, we desire a more automated approach.

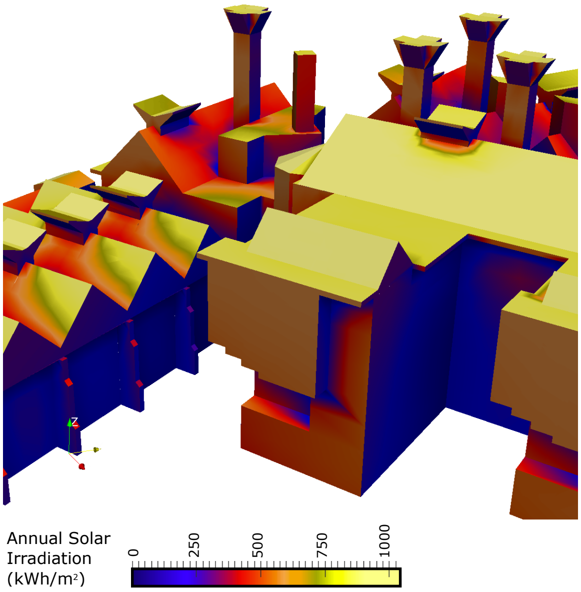

Figure 6: Results using a 2 $\times$ subdivided base mesh.

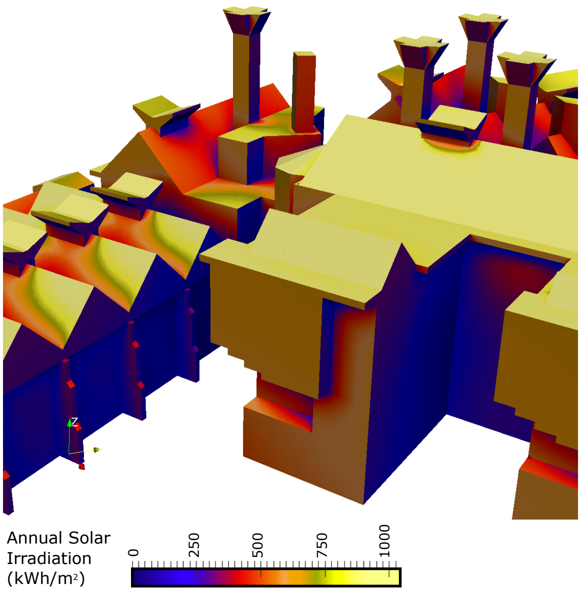

Figure 7: Results using the final mesh generated using the surface wrapping approach (mesh shown in Fig. 3).

One conceivable automated approach to optimising the mesh resolution would be to adaptively adjust or subdivide the mesh locally in response to the irradiance gradient across the surfaces. However, this would lead to an iterative approach. Our approach to overcoming the limitations of the underlying polygon meshes has been to use the wrapping technique using the mesh generation tools described earlier. Results generated this type of mesh (Fig. 3) are shown in Fig. 7 using the same viewpoint. In these results the shadowed area noted earlier is no longer overemphasised and all the solar irradiance gradients across the surfaces and around the roof features can be seen to be smoothly resolved.

Visualization and output

The final data sets produced using the approach outlined above (the workflow indicated in Fig. 1) consist of unstructured surface meshes and irradiance values at each vertex. This type of data is readily converted into a number of formats that can be interpreted by general purpose 3D model visualization tools—paraview being the tool used to process the results shown here (Henderson et al., 2004). This is a significant advantage over image-based approaches to solar irradiation mapping.

Such tools employ visualization pipelines that essentially reconstruct the mesh and map colours to the vertices according to the input vertex data and user specified lookup tables that define the colouring scheme. The result is a collection of polygon primitives displayed through standard graphics libraries and making use of graphics hardware acceleration where possible. Colouring of the polygon surfaces in this environment is done at a low level in the graphics libraries and hardware by linearly interpolating across the polygon using the vertex data values. Interactive visualization is then possible and modern graphics hardware makes handling large numbers of polygons straightforward. Accordingly, it becomes possible to rotate and zoom the model to view model details from any angle. Two views of the final model are shown in Fig. 8.

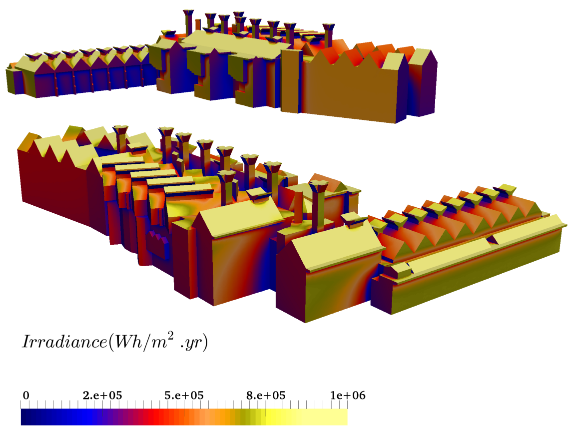

Figure 8: A view of the final model from the East (above) and Northwest (below).

A further advantage of using general purpose visualization tools with data in the form proposed here, is that it becomes possible to further process the data, for example to make animations of the visualization process and sequences such as fly-throughs. It is also straightforward to combine the results with other models and imagery. Export in the formats such as VRML and x3d for exchange with other tools and dissemination of the results is also straightforward.

We have furthermore investigated novel ways of making hard copies of the results. Given a polygon based model with embedded data (or colours) opens the possibility of using modern 3D printing technology. We have produced one physical model in this way using a printing technology that allows colorisation of the model. In this case the data was exchanged with the printer in VRML format. The model has proved useful in explaining the solar mapping concept to students, visitors and architects. The model—approximately 250mm in width—is illustrated in Fig. 9.

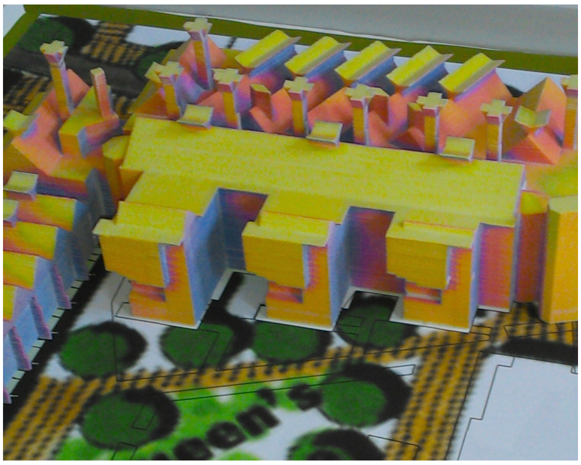

Figure 9: A 3D printed model derived from the final results.

The final method used to export the results in physical form has been to use colour digital holographic printing. One further step that is required to export the data to the holograph production process is to convert the vertex colour data into model texture maps. This is possible using a number of tools to carry out vertex baking. This results in an image that is mapped as a series of parts onto particular polygons. The resulting hologram of the Queens Building model can be viewed online (Rees et al., 2014).

CONCLUSIONS

In this paper we have introduced an innovative surface mesh based approach to producing annual solar irradiation data for complex geometries in urban settings. In contrast to earlier approaches that have produced annual irradiation maps in the form of images from preselected viewing points, this method produces results for all the surfaces of the scene. Surfaces meshes are used to define the location of the irradiance calculation points (virtual sensor locations). We have applied Radiance's tools to calculate annual solar irradiation using cumulative sky models derived from climate data sets. This has enabled inter-reflection between and obscuration by other surfaces to be accurately accounted for. The cumulative sky models include multiple discrete sun sources and this allows accurate evaluation of the effects of temporal variations in direct solar irradiance.

Two approaches to deriving surface meshes have been examined. Employing the underlying polygon representation of the imported model and subdividing the mesh to achieve an appropriate overall resolution of the solar irradiation map may be sufficient for general visualization and evaluation purposes. However, features in the imported mesh can lead to unwelcome visual artefacts and poor interpolation of the irradiance data in the final results. We have tested an automated mesh wrapping procedure that ensures good control of the mesh resolution and adaption to any complex geometric features in a robust manner. We have demonstrated that it is possible to produce models that capture the subtleties of the cumulative effects of shading and inter-reflection in highly complex geometries with high fidelity. We have also shown how the resulting polygon and irradiance data sets are combined to form 3D models for interactive visualization and output to other forms for dissemination of the results or export to further analysis tools. We intend to develop the approach demonstrated here through further validation, testing of the mesh generation procedures and enhancement of the data handling and parallel processing algorithms.

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