IRRADIANCE MAPPINIG FOR LARGE SCALE CITY MODELS

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Abstract. This paper reports on the development of a geocomputational simulation workflow for the irradiance mapping of large scale city models. A fully automated workflow is presented, for importing CityGML city models, generating the simulation input models, executing the simulations, and aggregating the results. In order to speed up the overall processing time, the workflow uses parallel processing across multiple computers and multiple cores. Two case studies are presented, for Singapore and for Rotterdam.

Keywords. Integrated irradiance simulation; Solar potential assessment; Large scale urban 3D model; Houdini; Radiance.

1. Introduction

Irradiance measures the flux of radiant energy per unit area (Quaschning 2003). Calculations of irradiance on building roof and facade helps planners and designers to understand the solar heat gain of the target buildings, and assess the potential of deploying photovoltaic (PV) systems to harness solar energy. In the Building Energy Efficiency R&D Roadmap published by Singapore National Climate Change Secretary (NCCS), out of 8,642 GWh of building electricity consumption, 60% were contributed by cooling (NCCS 2013). Relying more on cleaner sources of energy is crucial in the efforts to battle climate change (Merchant 2018). Singapore, for example, receives an average annual solar irradiance of 1,580kWh/m2/year (Singapore Business Review 2019) with low seasonal fluctuation, resulting in a high efficiency in the nation-wide deployment of Photovoltaic solar panels.

The goal of the workflow proposed in this paper aims to provide a solution for the simulation of a large scale city model. The workflow proposed in this paper has been tested with more than 150,000 buildings and millions of building surfaces, yet achieving detailed results. It has multithreading, pause and continue capability. When the software crashes, it can retain results produced and continue from where it stops. Ideally, the workflow should be able to show progress and output result

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files building by building as they go through simulation handled by the lighting simulation software, Radiance (www.radiance-online.org).

CityGML, or City Geography Markup Language, is a type of file format for 3D models of cities (Opengeospatial 2019). For the proposed workflow, models written in the CityGML file format are used. Though city models in other file formats could be used too, the CityGML file format is preferred, as it is an open, standardised, XML-based format; has a small file size, easy to read, and is defined by various levels of details (LOD), serving different purposes.

In the practice of architecture and planning, the concept of LOD is often employed to minimise the need to show highly detailed model when the model is accessed for various purposes. In many cities, the local planning authorities often creates CityGML files of different LOD for urban planning and mapping. The higher the LOD, the more complex and detailed the building models become. Choosing the correct LOD model for simulation is crucial in order to achieve accurate results without compromising computational speed.

2. Simulation Tools

The current commonly used tools for irradiance simulation are mostly built upon the open-source software Radiance (Ward and Shakespeare 1998). While it works perfectly well for small clusters of buildings, the workflow would quickly be too computationally heavy if the model expands to urban scale.

2.1. RADIANCE

Radiance is a suite of validated programs widely used for lighting simulation. Within this suite of tools, the *rtrace* and *GenCumulativeSky* programs (Robinson 2011) were used as the engine for irradiance simulation. The *rtrace* program applies backward tracking techniques to compute radiance values at specific points within a model. The model includes geometric entities with material properties, describing the buildings and other objects in the scene to be simulated.

Using local irradiance data as input, the *GenCumulativeSky* program generates a file which describes the cumulative irradiance distribution for a specified time period across the sky hemisphere in discretized pattern according to Tregenza (1993) and the Perez luminance/radiance distribution model (1993). Combined with the *rtrace* program, this calculation file enables the simulation of annual cumulative irradiance for a given surface in just one go, rather than conducting the calculation on an hourly basis and aggregating the results afterward, leading to significant speedup of simulation without losing accuracy.

In this paper, a distinction is made between two types of geometric entities. On one hand, there are the geometric entities that make up the building being simulated, which we refer to as the *target building*. On the other hand, there are the geometric entities that make up the surrounding context, including other buildings, which we refer to as the *context geometry*. This context geometry acts as obstructions to the target building, possibly shading the building during certain times of the day or year. Note also that the target building is always included as part of the context geometry since it may be self-shading.

2.2. RADIANCE BASED TOOLS

There are many existing simulation tools that use Radiance as a simulation engine. However, most of these tools are designed for relatively small-scale building simulations. With an input model consisting of millions of polygons, Radiance would simply crash due to lack of memory. Even if enough memory could be obtained, the simulation would be highly inefficient as the whole city would be used as context geometry for each point being simulated.

The advantages and limitations of the existing methods and tools used for irradiance mapping have been compared and reviewed in previous studies (Jakubiec and Reihart 2012; Melius, Margolis and Ong 2013).

Various plugins have been developed for existing 3D modelling platforms, linking to the Radiance simulation engine. Three such plugins were investigated. These were the Honeybee/Ladybug plugins for the Rhino3D Grasshopper platform developed by McNeel; the Diva tool, developed by Solemma LLC as a plugin for Rhino3D; and the OpenStudio plugin for SketchUp, developed as an Open Source project. In all cases, these existing plugins and 3D modelling platforms were found to be incapable of processing such a large dataset.

The input CityGML data set on its own already consisted (in the case of Singapore) of more than 150 thousand files organized into a particular folder structure. Once all the simulations had been run, more than a million files would be generated. What was required was a platform capable of processing such a data set in a highly scalable way. This included automating various processes:

- importing CityGML files from the folder structure,
- creating different representations of each building,
- saving these files back to the folder system,
- running the simulations and saving the simulation output files, and
- reading the simulations output files and creating various aggregated csv files containing the results.

Houdini is a procedural 3D modelling application developed by SideFX, primarily used in the movie industry (SideFX 2019). Due to the demanding requirements imposed by this industry, Houdini has been developed from the ground up with performance and scalability in mind. In March 2019, SideFX released Houdini 17.5, which included a new feature, *Procedural Dependency Graph* (PDG). PDG was developed to better scale and automate processes by distributing tasks across multiple CPUs (SideFX 2019). Although Houdini has no built-in support for running Radiance, the authors have developed a plugin that allows Houdini to run Radiance simulations.

In the irradiance mapping workflow, Houdini is used to process geometries and to run the simulation with the Radiance plug-in, while relying on PDG for its multithreading capability. Two Python plug-ins were developed for Houdini in order to support the irradiance mapping workflow; the first imported CityGML files into Houdini, while the second executed the Radiance simulation.

3. Proposed Workflow

A key strategy of the proposed workflow was the decomposition of the urban scale simulation into smaller building scale simulations. For each building in the model, a separate Radiance simulation was performed, with its own context geometry. The results of these smaller-scale simulations are later then aggregated back together again to generate the final result.

3.1. VALIDATION

Prior to implementing the workflow, validation was conducted to verify the accuracy of irradiance simulation for an unobstructed upward-facing horizontal test surface, the annual total global horizontal irradiance (GHI) as simulated using the cumulative sky irradiance description and Radiance is very close to that calculated from the input file which is based on measured data recorded from the nine weather stations operated by SERIS, and the difference between them can be regarded as marginal.

3.2. SIX STEPS

The proposed workflow consists of six steps as shown in *figure 1*.

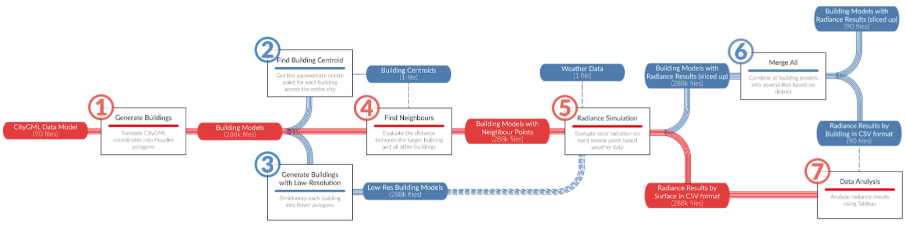

Figure 1. Workflow overview.

In step 1, the CityGML files were imported into Houdini and saved in the native *.bgeo* format. The geometry was imported with any additional attributes that are present. Geometries that were too small (<10m2) and broken geometries were marked and fixed, respectively.

In step 2, the building centroid of each building was calculated. This was used in deciding whether a building should be considered as the context of a target building and be included for the simulation. Buildings that were too far would have an insignificant influence in the simulated irradiance value, as its shading effect would be small, thus excluded. The building centroids were translated up in the z-direction to the full height of the building, as shown in *figure 2*. This allowed the shading angle to be taken into consideration. All building centroids were saved in a single file, and used to find the context geometry for each target building.

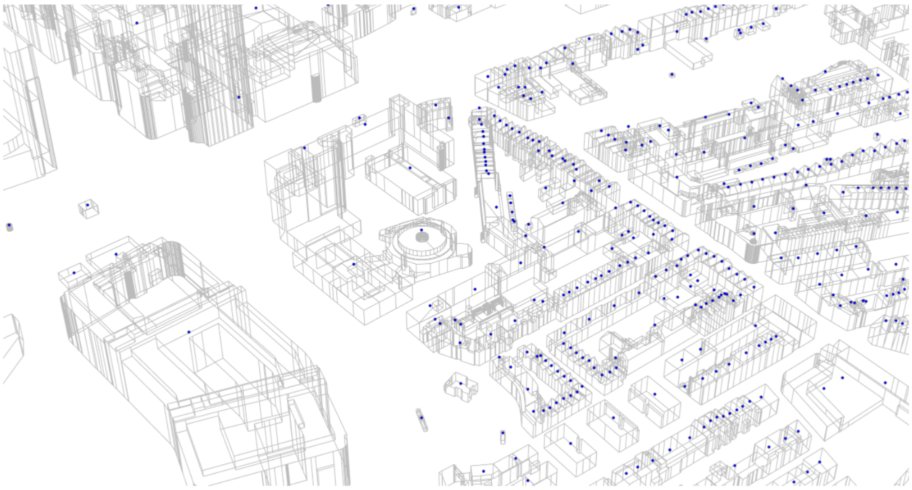

Figure 2. Building centroids with building geometries' outline.

In step 3, each building was converted into a low-resolution version to be used as context geometry. *figure 3* shows a building being "shrink-wrapped". When the low-resolution building model is created, the volume of each of both low resolution and existing building model is measured and compared. The low-resolution building model is saved only when the volume of the low-resolution building model is less than 110% of the existing building model.

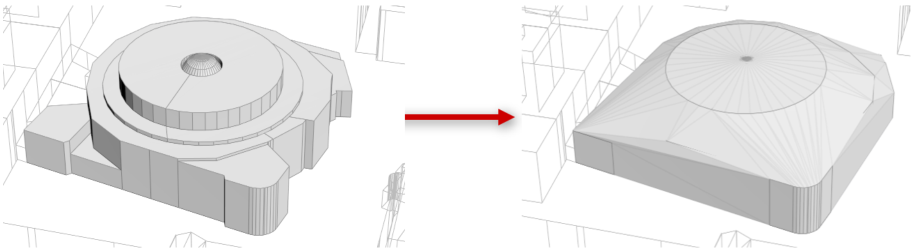

Figure 3. "Shrink-wrapping" a building.

In step 4, the context geometry for each target building was calculated. To accurately capture the impact of shading from the built environment on surface irradiance, neighbouring buildings within a given radius of the target building being simulated were retrieved from the database and imported into the model. When finding neighbours, each building centroid was measured against all other centroids across the entire city. Referring to *figure 4*, for "near" neighbouring buildings within 400 metres of the target building, they were included in the context geometry. Referring to *figure 5*, for "far" neighbouring buildings between 400 to 800 metres, the buildings are included or excluded based on the building height. As shown in *figure 6*, the angle from the edge of the "near" flat catchment to the measured building centroid (at the top) was more than 5 degrees, the building was included. Buildings beyond 800 metres are excluded.

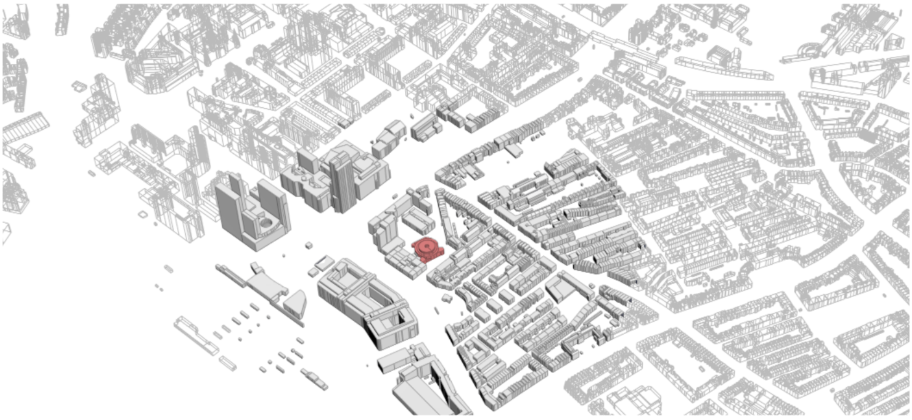

Figure 4. Buildings in context catchment area of less than 400m radius.

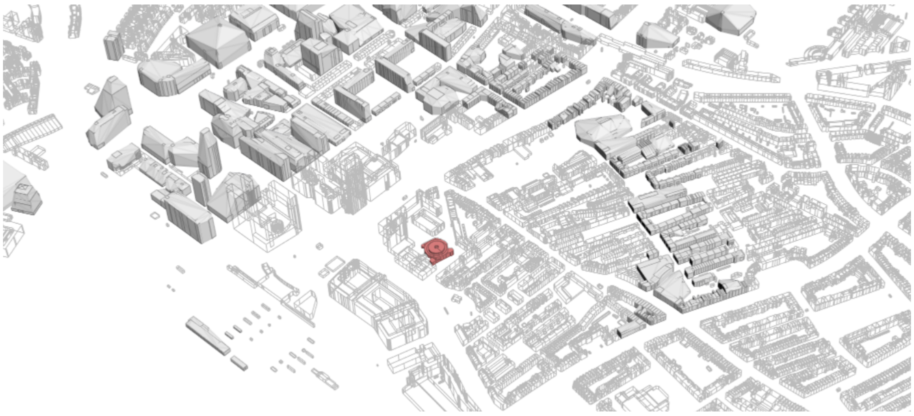

Figure 5. Buildings in context catchment area of 400-800m radius, excluding those with a centroid below 5 degrees.

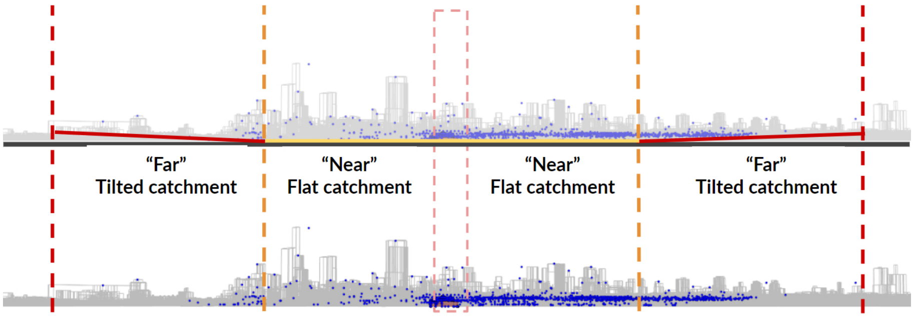

Figure 6. Sectional view diagram of context catchment area.

In step 5, the Radiance simulation is executed. Each target building with its surrounding geometry is loaded into Houdini. For "near" neighbouring buildings, the normal (LOD2) model was used. For "far" neighbouring buildings, the low-resolution model is used. Each surface on the target model was subdivided into patches of 3-by-3 metres. The surface subdivision operation is to ensure that irradiance is evenly sampled across every surface. A simulation input file is then generated for calculating the centroid of each surface patch. The simulation is then executed, using the centroid points, the neighbouring buildings models, and the cumulative sky model.

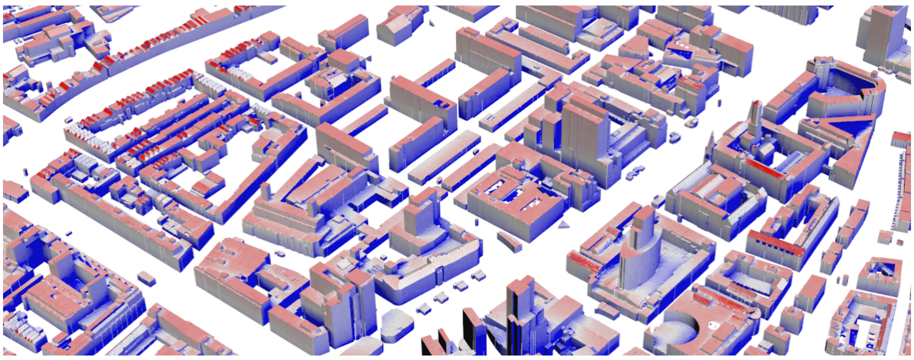

Figure 7. Rendered irradiance map on Rotterdam building facade.

Finally, in step 6, the simulation results are aggregated and processed. Each building is saved as an individual Houdini's *.bgeo* model and a Comma Separated Value (*.csv*) file storing various attributes including irradiance. It then aggregates these models into larger files, allowing data of each district to be visualised.

4. Results

The simulation workflow was applied on CityGML models of two cities: Singapore and Rotterdam. The Singapore model was created and provided by the Singapore Land Authority (SLA); and it is not accessible for the public at the moment. Meanwhile, the Rotterdam model is available for public download.

4.1. SIMULATION SETTINGS

For both models, LOD1 and LOD2 models were tested for simulation. The lack of roof geometry details on LOD1 model was unable to reflect the actual building roof, and thus generating less reliable results compared to the detailed roofs in LOD2 models. LOD2 model was eventually used for analysis targets, and LOD1 model for context geometries.

Surface subdivision size impacts the resolution of rendered radiation map and the simulation time. The smaller the size, the higher the resolution, and the longer the simulation time. Three settings of subdivision sizes of 1-by-1 metre, 3-by-3 metres, and 6-by-6 metres were tested. 3-by-3 metres were first tested as it ensures every floor has at least one measuring point. 1-by-1 metre was then tested as it is the typical resolution used in building-scale solar radiation simulations. 6-by-6 metre was tested as a low-precision option if simulation speed is the priority.

This variable affects the simulation time as the increase in resolution results in increase of number of test points. Since each point has to go through the same process regardless of the size of the surface, the simulation time will be proportional to the number of surface. The accuracy of value obtained for each test point would not be affected by the surface subdivision size. However, reducing number of test points might lead to less accurate simulation result for the entire building due to reduced resolution. 1-by-1 metre subdivision size produces 9 times of the number of surfaces compared to 3-by-3 metre. Yet, the overall building simulation result was similar to that of 3-by-3 metre setting. On the other hand, despite taking less simulation time, 6-by-6 metre surfaces hindered the potential to produce floor-by-floor PV potential data analysis. Hence, 3-by-3 metre was eventually used as it produces simulation points on every floor.

The first context catchment size used was 50 metre radius from building edge as “near”, and 50 to 150 metre radius from building edge as “far”. It produced accurate results in areas with mostly mid-rise buildings and consistent building heights, which is the characteristics of the sample data from SLA. However, it was too small for areas that has tall buildings and low sun angles.

For the same urban model, the simulation time increases as the number of surfaces in the set of context geometries increases. Expanding the overall context catchment size or the “near” context catchment size will both result in an increase in the number of context geometry surfaces. The effect of context setting on accuracy of results varies depending on the urban morphology, building height, and extreme sun angle. In general, the denser the city, the taller the buildings, or the higher the sun, the smaller the context could be. The principle of setting appropriate context catchment size is to ensure all possible shadow-casting objects are included. The best way to determine catchment size is to try a few settings for the same building.

4.2. SINGAPORE

The Singapore model was the first model that this workflow was implemented for. It was an iterative process that the workflow was constantly updated to respond to problems caused by messy 3D models. The dataset was given in the format of "one building per GML file", and the geometry originated from Light Detection and Ranging (LiDAR) scans. Two LOD models were given: LOD1 in which the 3D models were extrusions of building footprint, and LOD2 in which the 3D models have more roof details.

The LOD2 model was used for simulation. However, the LiDAR-based model has significant amount of improperly defined quad surfaces that are non-planar. Initial mechanism to repair the geometries results secondary problems such as distorted geometries that were significantly different from the original geometry. The workflow then employed a more robust and primitive method of triangulation after rounds of iterations to prepare the geometry for simulation.

A context catchment size of 75 metre as "near", and 75 to 250 metre as "far" was used for the Singapore model. This setting produced accurate results in the context of Singapore, where the sun angle is consistently high, and buildings are close to one another. The final simulation run on Singapore model of 156,000 buildings took 160 hours to complete on 36 2.6GHz cores.

4.3. ROTTERDAM

The Rotterdam model were in the format of "one district per GML file", and three LOD models were given in the same GML file. While LOD1 and LOD2 has similar level of details as the Singapore model, Rotterdam model has LOD0 which geometry only contains the building footprint. The LOD2 model was used for simulation, while the LOD1 model was used as "far" context geometry. The workflow was implemented for Rotterdam model after finishing the Singapore model.

However, the context catchment size setting used in Singapore model was insufficient in the context of Rotterdam, primarily due to the low sun angle during winter. Hence, a bigger context catchment size of 400 metre as "near", and 400 to 800 metre as "far" was employed for the Rotterdam model.

Due to the larger context catchment size used and greater number of buildings, despite having generally smaller buildings, Rotterdam model took longer time to complete. The entire workflow took 230 hours to finish for 200,000 buildings.

5. Conclusion

This paper reports an efficient, reliable and integrated simulation pipeline streamlined for city scale simulation as implemented and demonstrated in urban solar potential assessment for all building surfaces for Singapore and Rotterdam. The pipeline provides a solution to one of the primary technical bottlenecks faced by researchers and practitioners in urban studies, esprically in large scale urban modeling, by achieving well balance between efficiency and accuracy. Other than offering the functions in assisting irradiance simulation efficiently, the pipeline also provides the possibility to embed the results back to CityGML database so that the simulation outcomes can be retrieved by alternative software or platform for other analysis. The flexibility and scalability of the pipeline entails that it can be applied in cities around the world regardless of the local urban forms and irradiance conditions so that local solar potential can be assessed accurately and efficiently to support decision-making on policies to encourage deployment of solar PV. This pipeline is not limited to irradiance mapping exercises, but can also be tailored for similar large scale automation-based workflows in other fields.

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