Modelling the Built Environment in 3D to Visualize Data from Different Disciplines: The Princeton University Campus

Kian Wee Chen[1], Forrest Meggers[1,2]

[1]Andlinger Center for Energy and the Environment, Princeton University, Princeton, NJ/USA · chenkianwee@gmail.com

[2]School of Architecture, Princeton University, Princeton, NJ/USA

Abstract: In this research we have developed a 3D city model of Princeton University campus for the Campus as Lab (CAL) program using openly available 3D data. The sources include the official open data portal from the United States Geological Survey, OpenStreetMap and Google Maps. The 3D city model is used as a tool for visualizing and analyzing multidisciplinary data to enhance the communication of research between different disciplines. We demonstrate the 3D model's capabilities through a use case where we investigate the viability of powering a golf cart for short commutes across the campus with a Photovoltaic panel. We visualized environmental and transportation data. The two sets of data are solar irradiation and the travel behavior of the golf cart. Through the use case, we show that the 3D model is useful for conducting research that requires data from different disciplines. Our long-term goal is to establish the use of the 3D city model as a tool for the documentation, visualization and communication of research results in the context of the CAL program.

Keywords: Geodesign, integrative design, GIS, geo-informatics

1 Introduction

Campus as Lab (CAL) is a program that encourages academics in the university to conduct research using the campus as a testing ground. The campus is an ideal ground for testing new solutions as it is like a mini-city. The campus is run by a single entity, the facilities department, which makes implementing a pilot study on campus easier than in an actual city.

The CAL program funds research from all disciplines that use the campus as a testing ground. At the end of the research, the results are published as written reports and scientific articles within respective disciplines. To break through disciplinary walls and enhance the communication of research results between fields, we propose the development of a 3D city model that allows the simultaneous visualization of the spatial-temporal data generated from the different research projects of CAL. The 3D model will allow researchers to have an overview of the research projects conducted under the program, and allow them to explore their research of interest. With the right visualizations and analysis techniques, researchers can readily explore data from different disciplines to better understand the built environment and potentially discover knowledge gaps for their next research project. Other than providing a visualization tool, the 3D city model also provides data for running simulations in the built environment (BILJECKI et al. 2015). The 3D city model becomes the base map for the campus and will periodically be updated with new findings from funded CAL research projects.

Currently, we are not aware of any CAL program that maintains a 3D city model for communicating research results. Our contribution is in developing a 3D model for such a purpose. This will include specifying the use cases, spatial operations and the Level-of-Detail (LoD)

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of the 3D model for such an application (BILJECKI et al. 2015). We will also propose a workflow for using the model. In this research, we develop the 3D model for the Princeton University Campus. To put this research in context, we will first discuss our research in relation to existing studies that have used their 3D models for visualization. This is followed by a description of the use case, the spatial operations and the 3D city model. We then demonstrate the capabilities of the 3D city model through the use case, and conclude with a discussion about the use of the 3D city model for research communication.

1.1 3D City Models

We have reviewed studies that have used 3D models for the visualization of research results and separated the studies into two main groups. They are studies that have used the 3D model for 1) execution and visualization of simulation/analysis, and 2) visualization only. Studies in the first group used the 3D model as inputs for their thermal, noise and morphological simulations and analyzes, and the results are geometrically visualized on the 3D model (TARA et al. 2019) or as heat maps on 2D maps (XU et al. 2017, YANG & CHEN 2016) or 3D models (HSIEH et al. 2011, STOTER et al. 2008). In these studies, the 3D models are of LoD 1 or 2 as defined by the cityGML standard, where LoD 1 has building massings are simplified to have flat roofs while in LoD 2 the building massings include the roof shape. The spatial operations required are morphologically related, such as computing the area of a building envelope and the volume of building massings. From these studies, we can see that a 3D model is very useful in facilitating the understanding of the built environment. As a result, there are researchers that have proposed the development and maintenance of 3D models up to LoD 3; textured 3D models with facade features, as data sources for executing and visualizing built environment-related simulations/analyzes in city planning (LESZEK 2015, SABRI et al. 2015).

Among the visualization-only studies, we have found that 3D models were predominantly used as platforms for visualizing future design scenarios in architectural and urban design applications (BECKER et al. 2013, LEWIS et al. 2012, VIRTANEN et al. 2015). The 3D models are of LoD 2 to 3 due to the demand for realistic representation and communication for design scenarios. Spatial operations include the ability to model or import design scenarios in 3D, and perform spatial inquiries, such as the distance between two positions or the filtering of an object based on spatial conditions.

In comparison to these visualization-only studies, our research focuses on the simultaneous visualization of spatial-temporal data, usually quantitative attributes, in a 3D environment to support researchers in viewing their results in relation to other related research. Our research requirements are similar to those of the first group of studies; we do not require the 3D model to provide a photo-realistic representation of the built environment like in the visualization-only studies. However, studies from the first group only visualize results from each simulation/analysis independently and not simultaneously. For both groups, the spatial operations implemented are useful for our research. Morphological-related operations support the understanding of research results in relation to urban forms, and spatial inquiries will allow researchers to explore and process the research results that have been represented geometrically in the 3D model. Based on the specifications derived from our purpose and the review, we developed a 3D city model for the Princeton University campus, and have demonstrated the capability of the model through a use case.

2 Method

The Princeton University is 243 hectares in surface area, consisting of four main campuses; the Central, East, Lake and Forrestal campuses. The university has a student population of about 8,200 and staff population of 7,000 of which 1,300 are faculty. Most of the departments are located at the Central and East Campuses. The Forrestal Campus is located about five kilometers away from the Central campus. The Lake Campus is currently in the planning and design stage.

The Princeton University CAL program encourages faculties and students to conduct teaching and research on campus ground, facilitated by various big and small funding mechanisms. From 2008-2017, the program has funded 93 smaller projects and 21 bigger research projects. Other than providing funding, the program also provides openly accessible campus data such as electricity usage and hydrometeorology data, and upon request campus data such as food, spatial, natural habitat, and waste data.

For our research, we have requested campus-wide spatial data from the CAL program. We received the spatial data in the GeoDatabase (GDB) format, which can be accessed by major Geographical Information System (GIS) software such as ArcGIS and QGIS. From the data, we have sufficient information for developing a LoD 2 city model without trees. It is common for most campus facilities to have at least a LoD 0 (2D) model of the campus for operation purposes. It is also important to note that the facilities department's 3D model cannot be openly published or distributed, which could be a potential issue for the purpose of research communication. Keeping this restriction in mind, we look for other data sources to develop our 3D model.

2.1 Developing and Distributing the 3D City Model for Research Communications

We were able to find a 3D point cloud data set openly distributed in the LAS format by the United States Geological Survey (USGS) data portal (USGS 2020). The 3D scan was performed in 2015 for the state of New Jersey, Mercer County where Princeton University is located. We were also able to find the Digital Elevation Model (DEM) and 2D GIS data of the impervious surfaces of New Jersey, Mercer County. The impervious surface data consists of three classes of impervious surfaces; building footprints, roads and other impervious surfaces. These data were generated by USGS with data sources such as satellite images and point cloud data from 2007-2015.

Other than the USGS data portal, we looked at semantically labelled crowd-sourced data from OpenStreetMap (OSM). As OSM data are crowd-sourced, the quality of the data varies from place to place. The OSM data of Princeton University includes building footprints, building types, building names and transportation network. With these data sets, we developed a LoD 1 3D city model of Princeton University Central campus as shown in **Fig. 1**a. As we have the 3D point clouds, we were able to model the trees with their height data, which were not available from the 3D city model provided by the campus facilities.

Considering that target users, researchers from different disciplines, do not necessarily have GIS expertise to access the 3D model, we also developed a simple application software (app) for visualizing the 3D model, where different information layers can be overlaid onto each other (**Fig. 1**b). The app is developed with Python and deployed as an anaconda app (CHEN 2020b). The app aims to provide a convenient way for researchers to explore and visualize the data without GIS expertise, and export data into different open formats for further processing. For GIS experts, they can readily access the data without the app for performing advanced spatial operations. Using the app as a template, we can develop variations of the app for different use cases and maintain the data and 3D model accordingly.

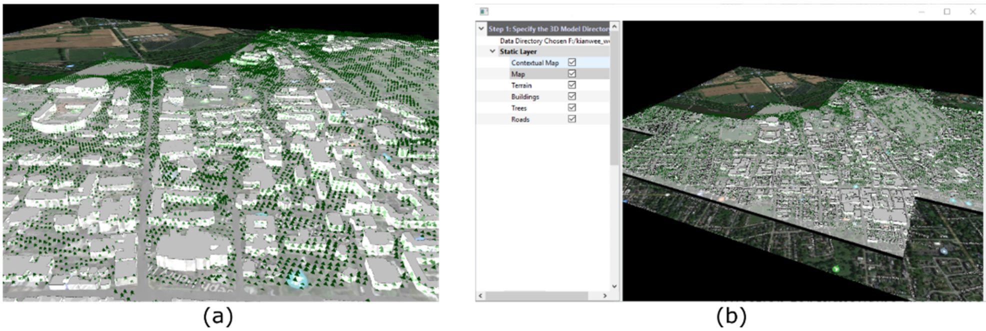

Fig. 1: (a) LoD 1 3D model with tree heights (green triangles) of the Princeton University Central campus, (b) simple visualization app distributed with the 3D model

2.2 Use Case: Assessing the Solar Potential in Powering Golf carts for Campus Commutes

In this use case, we proposed installing Photovoltaic (PV) panels on a golf cart that is used for short commutes within the Princeton University campus. The cart travels only short distances and is parked most of the time. The high parking time to travelling distance ratio makes it viable to power the electric golf cart solely through a PV panel installed on the roof when parked. This proposal can potentially be scaled up to retrofit all golf carts in the campus to run on solar power. This use case is an on-going project undertaken by a physics undergraduate with guidance from architectural and mechanical engineering researchers.

Two sets of spatial-temporal data from the environmental and transportation fields are useful for informing this project. They are solar irradiation data of the whole campus and the travelling behavior of the golf carts. The solar irradiation data informs us of the solar capacity of the campus while the travel behavior informs us of the electricity demand of the cart. Using these two data sets as the boundary condition, we can optimize the electrical system of the golf cart to be solely powered by solar energy. Thus, obtaining and visualizing these two sets of spatial-temporal data will greatly facilitate the research. We ran a solar simulation on the 3D model with Daysim (REINHART & WALKENHORST 2001) to obtain the annual hourly solar irradiation data. We are in the process of using a Global Positioning System (GPS) device to track the travel behavior of the golf cart.

It will be difficult to visualize and explore these two sets of spatial-temporal data in the form of table and graphs. A 3D model is a valuable tool for communication as researchers can simultaneously visualize and explore the two data sets in the 3D model. The 3D model is distributed with a simple app (CHEN 2020a). The app enables all researchers to readily visualize and explore the data with no need for GIS expertise. Using the app as a platform only requires one researcher in a research team to learn to customize the template app for the purpose of the use case at hand. This researcher would translate the solar results from Daysim and GPS data into the correct format for visualization.

3 Result

Fig. 2 shows a snapshot of the simultaneous visualization of the two data sets with a simple app called solar + travel. With the data structured and represented on the 3D model, researchers can have a quick overview of the relationship between the two sets of data. They can explore the hourly data by either manually or automatically stepping through them.

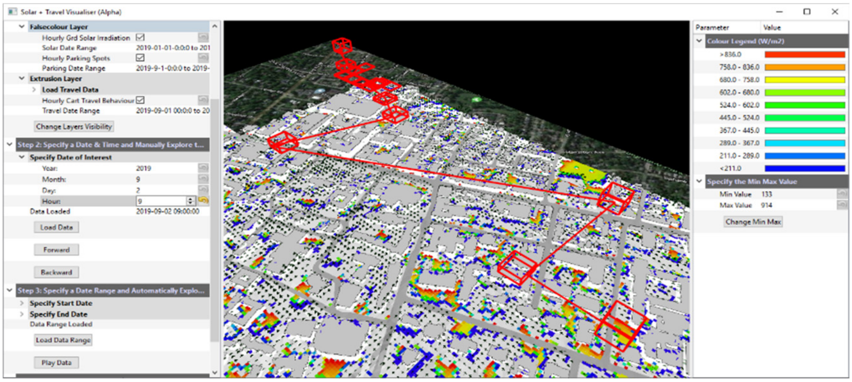

Fig. 2: Visualizing travel behavior (red paths) and the solar irradiation falling on the ground (color legend). The red extrusions (50 m × 50 m grid) represents the time spent at a location. Taller extrusions mean a longer duration.

We implemented basic spatial operations to quickly assess the feasibility of the proposal. Firstly, we used morphological operations to calculate the parking duration to the distance travelled by the golf cart. The extrusion heights are based on the stationary time, and we obtained the distance travelled from measuring the length of the red paths (**Fig. 2**). **Fig. 3** shows the calculated results in both graph and 3D model visualizations from the solar + travel app. The graph provides a temporal overview of the day while each snapshot of the 3D model provides spatial details not available on the graph.

Next, we wanted to find potential parking spots based on locations and the solar irradiation data. We defined the golf cart as parked when it stopped at a location for more than 30 minutes. For each parking location, we used spatial inquiries to filter out irradiation grids outside of a given radius, in our case we used a 50 m radius, and obtained the maximum, median and minimum irradiation values within the radius. **Fig. 4** shows a plot of the parking duration and the median solar irradiation value for each hour and the corresponding 3D visualizations of the potential parking spots within the radius. The ability to visualize and analyze the data on the 3D model has been essential in providing an understanding of the two sets of data and how they relate to each other.

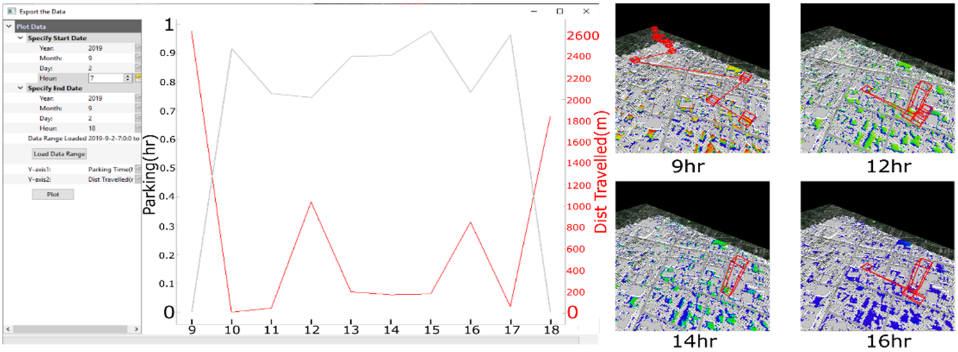

Fig. 3: Calculated parking duration (black line) and distance travelled (red line) for a day (2019-09-02 9hr – 18hr) based on travelling data. The corresponding 3D model visualizations for the times of the day (right).

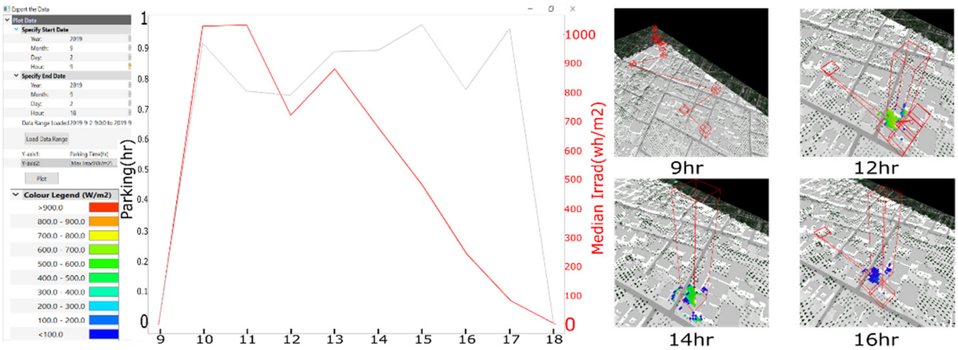

Fig. 4: Calculated parking duration (black line) and the median solar irradiation within 50 m radius of the parking spot (red line) for a day (2019-09-02 9hr – 18hr) based on travelling data. The corresponding 3D model visualizations for the times of the day (right).

3.1 Discussion

The use case has demonstrated a prototype workflow for distributing and using the 3D model for research communication in a multidisciplinary team. The visualizations and analyzes described in the use case have informed the researchers about the boundary conditions of the campus and have assisted them in deciding the next step in their research project. The cart analysis will be further refined with new data measured directly on multiple carts. This data can be input into the visualization tool and inform further analysis. Eventually, the mapping tool could also be used by cart operators in a mobile app to both locate and orient parking locations to maximize charging, so that the carts can run entirely on solar power.

In this use case, we only considered an instance where the researchers retrieve the 3D model for visualizing collected data. There are many other examples of CAL data that have been collected and for which, more advanced utilization could be achieved through visualization. Still, we have not considered how researchers can create or destroy data and update the 3D model with their research results. For the 3D model to be fully functional as a tool of communication on campus, we will require a well-designed database, and a version control system to better handle the potentially large amount of spatial-temporal data updates from different projects. Prospective technologies to explore include the 3DcityDB (YAO et al. 2018) and git versioning for city models (VITALIS et al. 2019). The two technologies are not necessarily compatible. It will require further investigations and adaptation to integrate these technologies in implementation.

4 Conclusion

The research has developed a LoD 1 3D city model with tree heights for the Princeton University main campus. The model has been distributed together with a simple app for researchers of all disciplines to access the data. We have demonstrated a prototype workflow, using the 3D model with an app, through a use case. The 3D model was used to run a solar simulation and visualizing solar and travel behavior data simultaneously. Spatial operations have been used to further explore and interrogate the data on the 3D model. Through this use case, we have demonstrated the capability of the 3D model in visualizing data from different disciplines and the model's potential as a tool for informing research of a multidisciplinary nature. We hope to establish a workflow where the 3D city model is used as a tool for documenting, visualizing and communicating research results from different disciplines in the context of a CAL program. Through the workflow, the 3D city model becomes the base map for the campus where it will be maintained and be appended with data from other research projects.

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