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QUICK PROTOCOL FOR INTEGRATING THE ATTRIBUTE INFORMATION OF UNSTRUCTURED POINT CLOUD DATA INTO A SOLAR ENVELOPE SIMULATION

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ABSTRACT

This study proposes a novel method of solar geometry by considering the potential application of point cloud data combined with the simulation of solar radiation. With the support of geometric and radiometric information stored in the point cloud such as position information (XYZ) color information (RGB), and reflection intensity (I), architects may compensate for missing information on the existing context during the simulation, especially due to the limited capacity of current 3D modelling sites. However, the dataset often comes in the format of unstructured point cloud data retrieved from merged data scans and as a result, the radiometric information is difficult to occupy due to multiple reference points. Through a 3D subtractive procedure, this study not only examines volumetric samples of the three-dimensional matrix that fulfills the criteria of solar envelopes but also finds the optimal values of the merged data scan for input of solar radiation. In this regard, simulation of solar radiation contributes to identifying the most and the least exposed areas to the sun in existing contexts. This provides information related to visible sun hours that can be used to perform ray tracing analysis between the proposed 3D plot and surrounding contexts. Our proposed method ultimately helps architects not only generate solar geometry based on real contextual settings but also to understand comprehensively the microclimate conditions of the design context.

KEYWORDS

solar geometry; point cloud data; solar envelopes; passive design strategy

1. INTRODUCTION

According to the United Nations (UN) Population Division (Ritchie & Roser, 2020), the world's population will grow by 3.2 billion people between 2019 and 2100. This pattern simultaneously

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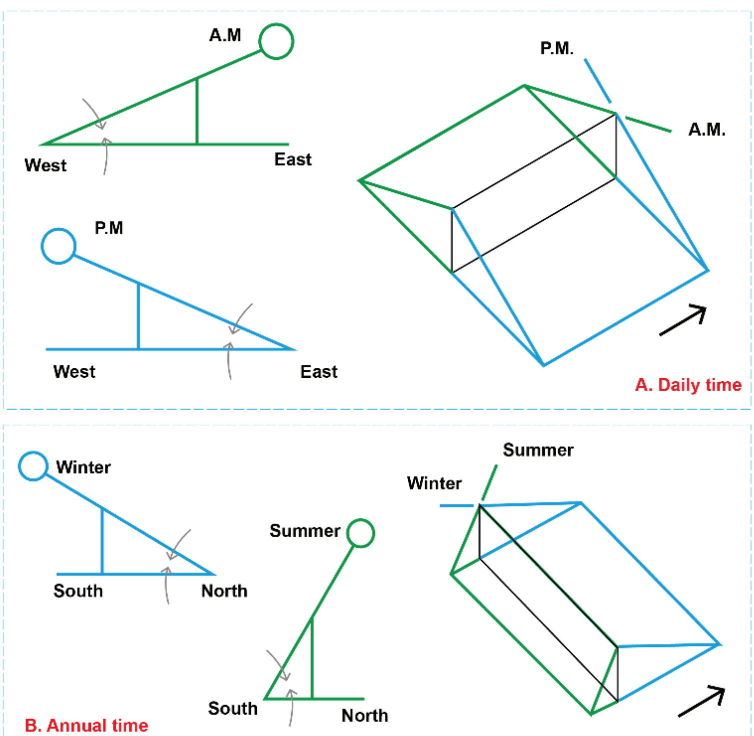
encourages architects to implement the criteria of 11th Sustainable Development Goals (SDG) programs on inclusive, safe, resilient, and sustainable cities (Nations & Department of Economic and Social Affairs, 2019). The integration of a mutual link between a new building and its surroundings plays a crucial role in achieving sustainable future urban planning. Besides, architects are responsible for minimizing the unexpected microclimatic impacts that may occur after the new construction of the building is carried out. In this regard, conceptual design stage becomes a pivotal phase in producing the most significant decision for architects (Sariyildiz, 1991).

As part of passive design strategies, solar geometry is one of the relevant concepts in architectural design practices that addresses environmental performance between buildings and their contexts. It specifically refers to solar envelopes that examine the solar accessibility during a predefined simulation period (Knowles, 1974). This method principally permits architects to adapt the geometric model of new buildings into the local context so that it results in a maximum volumetric shape that guarantees adjacent buildings have direct solar access (Knowles & Berry, 1980) (see Figure 1). Figure 1 illustrates further the basic mechanism of solar envelopes based on daily and annual time settings. For a daily time, the geometric envelope can be generated by using two settings: sun vectors at the morning sun (i.e., 9 a.m.) will regulate the western envelope while the afternoon sun (i.e., 3 p.m.) will set the eastern shape. The combination of these envelopes yields a symmetrical daily-based solar envelope due to the similarity of solar altitude between morning and afternoon sun angles. This mechanism principally applies to annual time settings. Figure 1 shows that the annual-based solar envelope is steeper toward the north-facing

FIGURE 1. A basic principle of solar envelopes constructed based on A. Daily time limits and B. Annual time limits. These figures have been elaborated further from a book of Sun, Rhythm, and Form, authored by Knowles (Knowles, 1981).



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surfaces due to the greater sun altitude in summer. This concept was further computationally elaborated into various design methods such as descriptive geometry, solar obstruction angle, and constructive solid geometry (Alkadri, et al., 2020). However, these current methods pose several barriers that may result in missing information during contextual analysis. In most cases, for example, the existing 3D site modelling (e.g., solid modelling (Staneva, 2008) is deficient in storing the complex geometry of surrounding contexts especially when it comes to isolated and dense areas. Consequently, relevant site properties such as vegetation, material and other site elements are often neglected during the simulation of solar geometry.

Furthermore, advances in 3D laser scanning technology in capturing complex information from real contexts enable the features stored in point clouds (i.e., geometric and radiometric information (Kaasalainen, et al., 2009) (Kashani, et al., 2015) relevant to the aforementioned issues. Nevertheless, the application of 3D point clouds often partially applies to particular fields such as photogrammetry (Shih & Wu, 2005), cultural heritage (Andriasyan, et al., 2020) (Shanoer & Abed, 2018), and environmental engineering (Bornaz, et al., 2002) (Kassner, et al., 2008). Digital reconstruction as one of the major subjects in this area has yet to fully influence the architectural design process. In this case, existing works such as archaeology and heritage still predominantly employ massive mesh surfaces for the 3D model, which involves high costs for computational issues. This indeed matters when it comes to the simulation analysis of a complex architectural project in design practices.

Following up on the relevant aspects from the potential application of point cloud data and further consideration of current solar envelope methods, we specifically investigate an integrated computational approach of solar geometry based on attribute information stored in a point cloud data. Thanks to these attributes (i.e., position information—XYZ), color information—RGB, and reflection intensity—I), currently, environmental performance analysis can be performed more efficiently. This simultaneously compensates for missing features in the current method of solar envelopes. This paper, therefore, proposes a new generation of solar envelopes by making use of point cloud data. Through a 3D subtractive mechanism, our proposed method involves the simulation of solar radiation based on point cloud data. In this case, a point cloud-based solar simulation can effectively handle geometric concerns related to the 3D modelling context. In particular, the solar simulation method can be performed without necessarily converting a complex dataset of point clouds into a massive 3D mesh model.

This study develops a new computational framework of integrated solar envelopes on the basis of previous works conducted by the authors (Alkadri, et al., 2020) (Alkadri, et al., 2019). While prior studies primarily employ single data scans, the contribution of this study is specifically weighted in the use of the unstructured point cloud data retrieved from merged data scans. This provides great relevance to standard practice when architects receive existing datasets from other sources such as engineers or 3D scanning companies. The datasets often come in the format of merged data scans and as such their radiometric information is difficult to occupy.

Similarly to Szokolay (1996), Bruce (2008), and Alread and Leslie (2007), the term solar geometry in this paper not only covers geometrical relationship of thermal aspects but also includes a comprehensive discussion of desirable lighting condition. Accordingly, this term will regularly be used to describe the concept of solar envelopes in this paper. This study contributes at least to three particular aspects:

- To have a better comprehension of the existing context before starting the design exploration. Thanks to the attribute information of point cloud data, a comprehensive site

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analysis can be carried out based on real contextual datasets, not only identifying micro-climatic conditions of the existing site, but also highlighting the potential impacts that may occur between new buildings and local contexts.

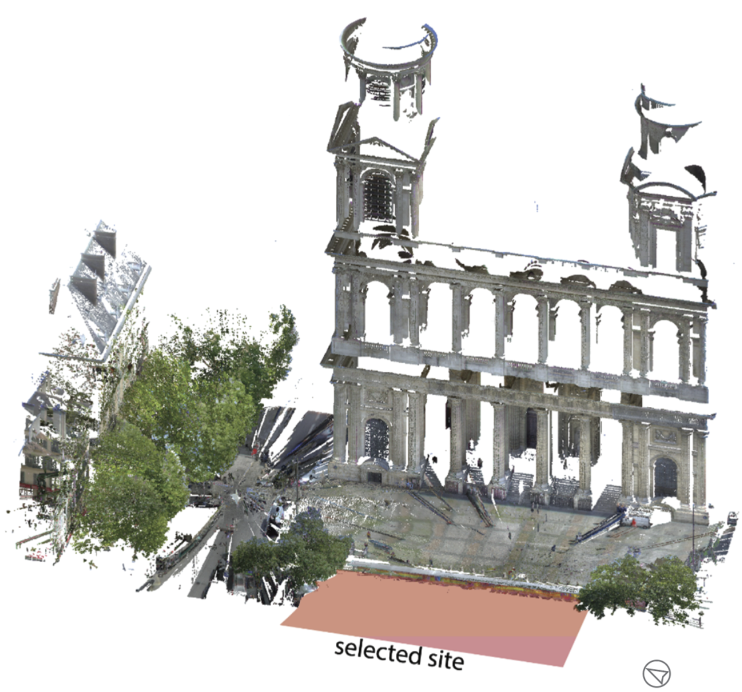
- To assist architects in producing informed-design decisions towards high-performed building massing. In this regard, insolation analysis plays a crucial part as a design feature, serving as both a performance evaluator and a form generator for the final configuration of solar geometry.
- To demonstrate a collaborative and interdisciplinary approach between remote sensing and the architectural design field. This can bring further opportunities for both disciplines to explore new features of 3D point cloud data, not only for 3D reconstruction bu5t also for environmental performance simulation.

2. DATASET COLLECTION

In principle, the main criteria for the dataset collection contain at least two aspects. *First*, the collected point cloud should be coming from TLS (terrestrial laser scanning) datasets so as to provide more accurate geometry and visual representation in comparison with ALS (airborne laser scanning) datasets. Moreover, it can cover a wide range of surrounding properties such as vegetation, site properties and other elements that may be relevant for the simulation of solar envelopes. *Second*, attribute information stored in point cloud data should at a minimum include XYZ (position information), RGB (color information), and I (reflection intensity). These attributes are used to correct the "true" value of datasets from the scanning.

More specifically, this study demonstrates a sample of 3D point cloud data (see Figure 2) that is collected from the open data source, project Terra Mobilita (http://www.libe57.org/data.

FIGURE 2. A 3D point cloud of the selected context.



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html). The initial purpose is to allow interested users to test a similar dataset to the workflow developed in this study. The location of the dataset is in Saint-Sulpice Square, Paris (latitude 48.8510 and longitude 2.3350). The dataset was collected using a Trimbel TX8, supporting with Nikon 7100 and a fish eye Sigma 10 mm for capturing color properties. The selected dataset consists of two single scans merged, containing around 3.8 million points. Due to highly dense datasets, the sub-sampling method is then applied to limit the density of points by setting the distance between points to 10 cm. This approximately results in a total of 806.775 points.

3. METHOD

In order to simulate new solar geometry, this study proposes three steps of computational workflows (see Figure 3): (a) calculation of optimal normal values, (b) simulation of solar radiation, and (c) generation of solar geometry. In general, the proposed workflow employs several supporting tools to cater to specific tasks in each step (see Figure 4). Furthermore, Cloud Compare (CC) is used not only to clean outliers (unnecessary cloud of points) but also to segment the selected areas and convert the dataset into any designated formats. Matlab supports the dataset correction, especially in calculating surface normal of the dataset. As a 3D modelling tool, Rhino coupled with Grasshopper (GH) is employed to run solar radiation and generate solar envelopes by using the plug-in of Ladybug. The detailed process of the workflow is described as follows:

1.1 Calculation of optimal normal values

In principle, this step aims at calculating optimal normal values of the dataset to be used later in the simulation of solar radiation. For the condition of unstructured point clouds, surface normal of the points is first calculated by using the Hough Normal plugin (Boulch & Marlet, 2016). Then, several tolerance angles are applied to the raw dataset, ranging from 10° to 90°. The main issue with this case is to register the surface normal of each point from the original

FIGURE 3. Overview of the computational workflow.

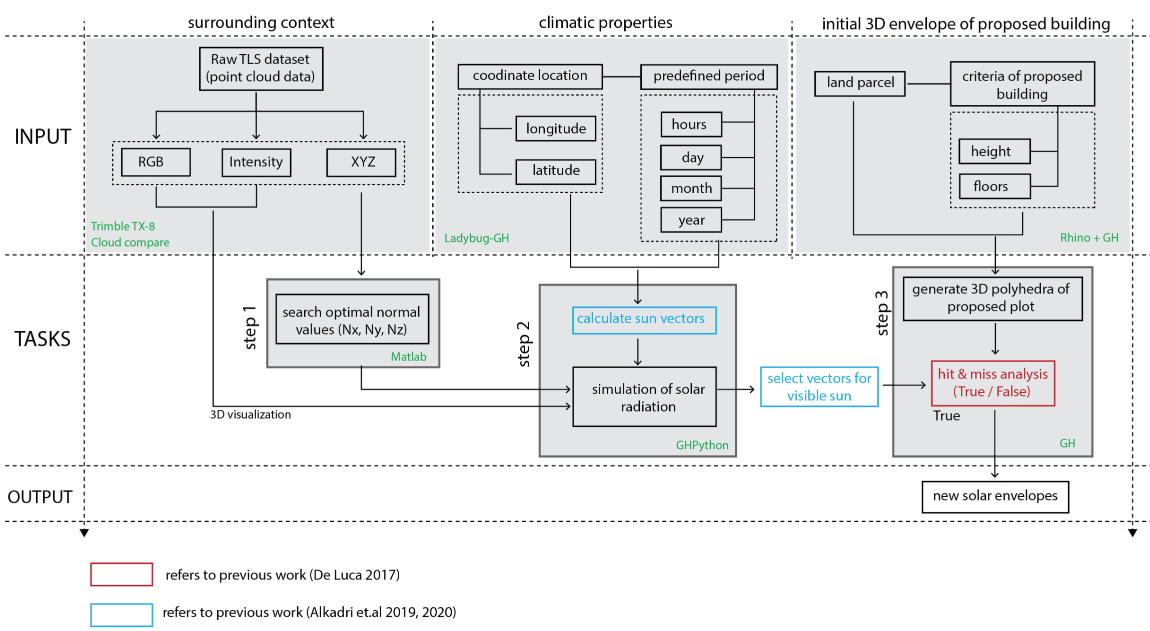

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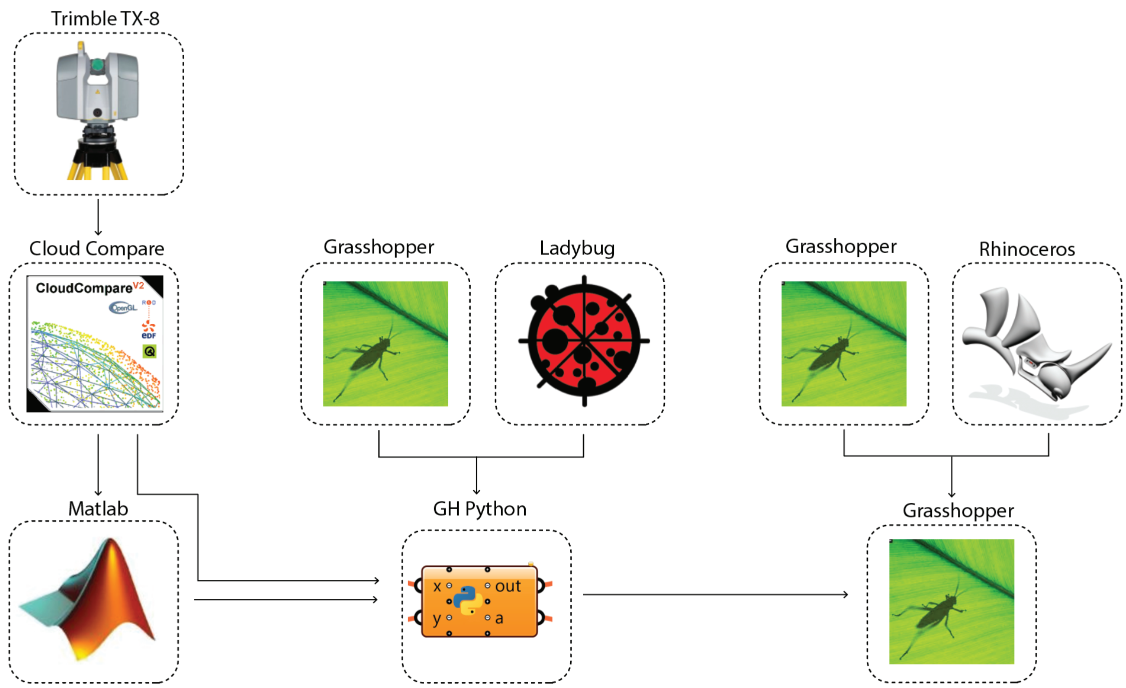
FIGURE 4. Digital tools used for the computational workflow.



reference coordinate of the scanner because the initial raw dataset consists of a merged scan between two clouds. Alternatively, we need to find the normal average of each formerly applied angle and calculate the angle of incidence (i). This calculation essentially aims to find the smallest angle from different ranges of *sin* products so as to identify the reliable surface normal on each applied angle. Accordingly, the optimal normal values of the dataset can be obtained from a different range of angles.

Figure 5 illustrates that the majority of points are at *sin* values between 0 and 0.1 or between 0° and 10°. This is because the projection of the laser beam from the scanner corresponds very well at a certain angle on the surface of the dataset during scanning. The next step is to search optimal values from the dataset by truncating the densest *sin* values (see Figure 6). This step is conducted based on equation (1). The equation is formulated from further elaboration on single processing data scanning proposed by Sasidharan (2016). Afterward, the dataset truncation is set to a range of 0–0.01, taking into account the densest point distribution at that range. The truncation process results in approximately 260.394 points or 32.2% of the total points. Having set the truncated points, the dataset becomes ready to be used for the next procedure.

$$i = \sin^{-1}\left(\frac{\overline{dn}.\,\overline{dl}}{\left|\overline{dn}\right|\left|\,\overline{dl}\,\right|}\right) \tag{1}$$

Where i = incidence angle

$\overline{dn}$ = direction of the surface normal

$\overline{dl}$ = direction of the laser pulse

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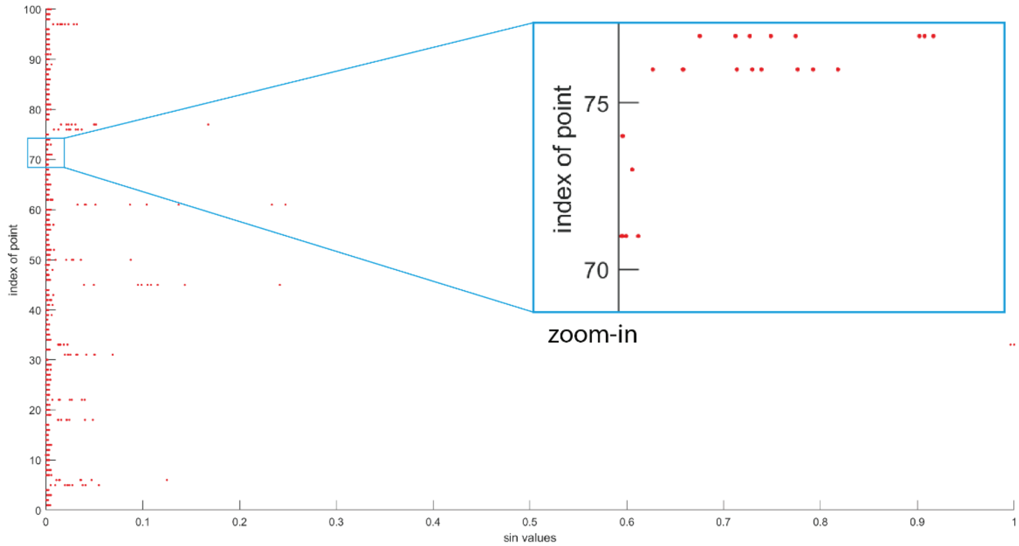
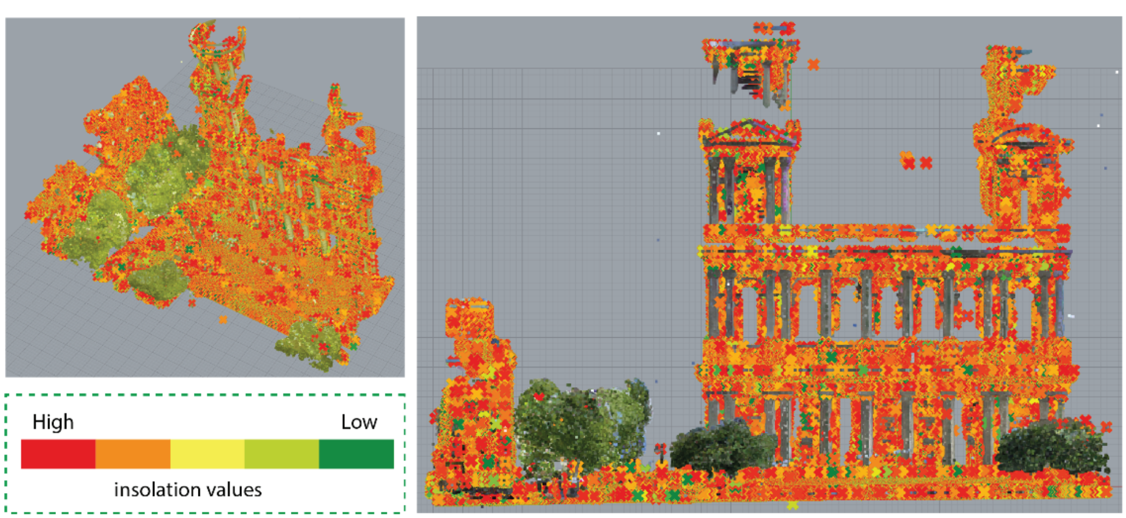
FIGURE 5. Distribution of points according to the angle of incidents.



1.2 Calculation of optimal normal values

Through an insolation (incident solar radiation) analysis, this part specifically contributes to substituting a feature of sun visibility in the existing work (De Luca, 2017), which primarily relies on the number of hours of visible sun. In this case, a section of sun visibility remains obscure to capture areas with blocked sun because it merely includes the self-blocking mechanism from existing buildings and then neglects the blocked areas caused by surrounding properties. Thus, a point cloud-based solar simulation plays an important role to identify the most and least exposed surfaces to the sun in existing contexts. In this case, high insolation values can be kept for ray tracing analysis between 3D plot (polyhedra) and surrounding buildings. Thus, the lowest one can be directly removed as it principally denotes areas shaded by surroundings.

FIGURE 6. Simulation of solar radiation



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In principle, simulation of solar radiation contains two main inputs, which are sun vectors acquired from sun hours analysis and normal vectors of the selected dataset (existing context). In this case, the simulation samples three months of the summer period from June to August (from 9 am to 6 pm Central European Time). The insolation values of each point within the dataset are calculated by using trigonometric principles from the normal irradiance (solar irradiance on a plane facing the sun position) multiplied by the cosine of incident angle. A detailed procedure of this part has been addressed in the previous works (Alkadri, et al., 2020) (Alkadri, et al., 2019).

1.3 Generation of solar geometry

Before constructing solar geometry, the ground level of datasets needs to be eliminated first as it is not relevant to the input of solar envelopes. This step also aims to decrease the unnecessary computational resource during the simulation process. The following Table 1 describes various inputs for generating solar geometry.

Furthermore, Figure 7 illustrates the procedure for generating solar geometry. It starts by establishing the plot plan in the selected site. The next step is to generate 3D polyhedra that consists of 2000 voxels. In this case, each voxel consists of 3 × 3 × 3 m, representing one typical room in the building. These voxels are then inputted into the step of hit and miss analysis to evaluate the total voxels that meet the criteria of solar geometry. Afterward, visible sun vectors are calculated based on the input from climatic properties. In total, it yields around 72 sun vectors. The quantity of these sun vectors has been improved from the previous existing method (De Luca, 2017) that predominantly relies on centroid points of surrounding windows. Instead, this study considers each point within the dataset of surrounding buildings to correspond to

TABLE 1. Input for generating the solar geometry.

No	Input & Criteria	Values
	Climatic properties	
1	Latitude	48.8510
2	Longitude	2.3350
3	Hours	7 hours (9 a.m. to 6 p.m.)
4	Day	31 days
5	Month	June to September
6	Sun vectors	72
	Proposed building	
7	Voxels	2000
8	Size of voxel	1.5 × 5.5 × 3 m
9	Dimension of 3D polyhedra	15 × 55 × 60 m
	Point cloud of existing context	
8	Original points	3.8 m
9	Subsampling points	806.775
10	Truncating points	260.394

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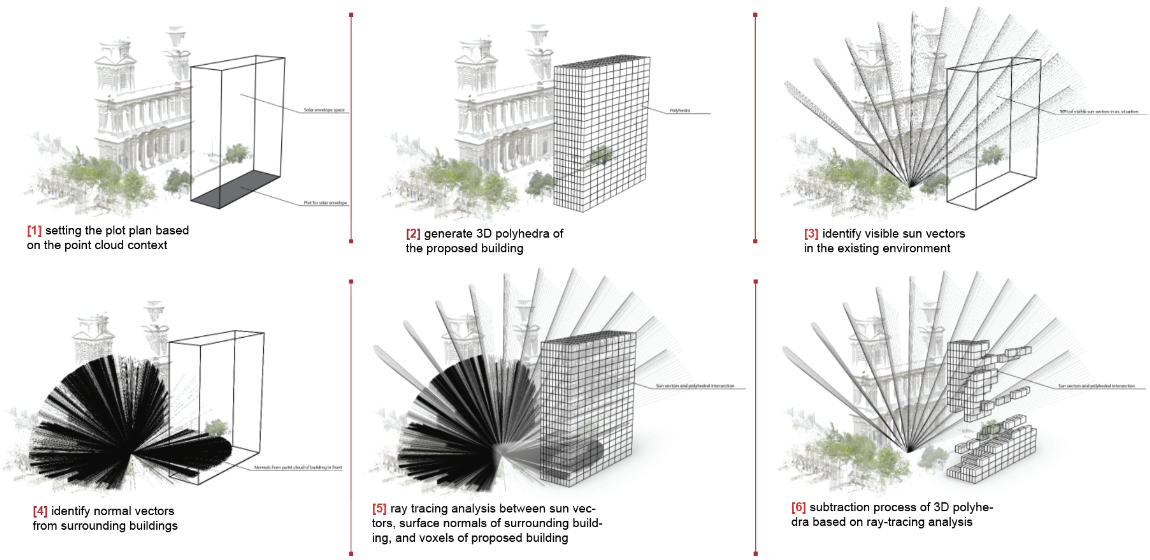
FIGURE 7. Steps to construct solar geometry.



72 sun vectors and 2000 voxels of the proposed building during the ray tracing analysis. These voxels will be counted as the geometric core of solar envelopes.

4. RESULTS AND DISCUSSIONS

This section focuses on discussing the simulation results and further possibilities of the proposed method in generating solar geometry. In order to provide comprehensive results, this study conducts a comparative analysis between solar geometry using surrounding buildings based on a point cloud model and without a point cloud dataset. In this regard, the surrounding buildings without point clouds in the Rhino 3D environment are created using Non-Uniform Rational B-Splines (NURBS) surfaces based on a simplified point cloud geometric model. The NURBS surface in general can be described as a form of mathematical representation that can be shaped into a 3D model from simple 2D lines, planes, curves, and free-form surfaces (Associates, 2023). Furthermore, a simulation of solar radiation is also performed on both models to identify the total incident solar radiation received by the geometric envelope of solar geometries.

According to the simulation results of both solar geometric models (Figure 8), some analysis can be further discussed as follows:

- There is a significant difference in the total intersection line produced during the ray tracing analysis between the point cloud-based context and the NURBS model. The trends in Figure 8-A illustrate further that the point cloud-based context yields approximately 29 million denser intersections compared to the NURBS model context, which only generates around 138 thousand intersections. This is because *first*, each point stored in the point cloud model produces one normal vector that is then used to evaluate each proposed building voxel and each resulting sun vector. In contrast, the NURBS model only produces limited normal vectors based on a simplified surface division of the proposed building façade. According to the proposed scenario in this study, the existing building facade is divided into 30 surfaces, and this means that each surface can only

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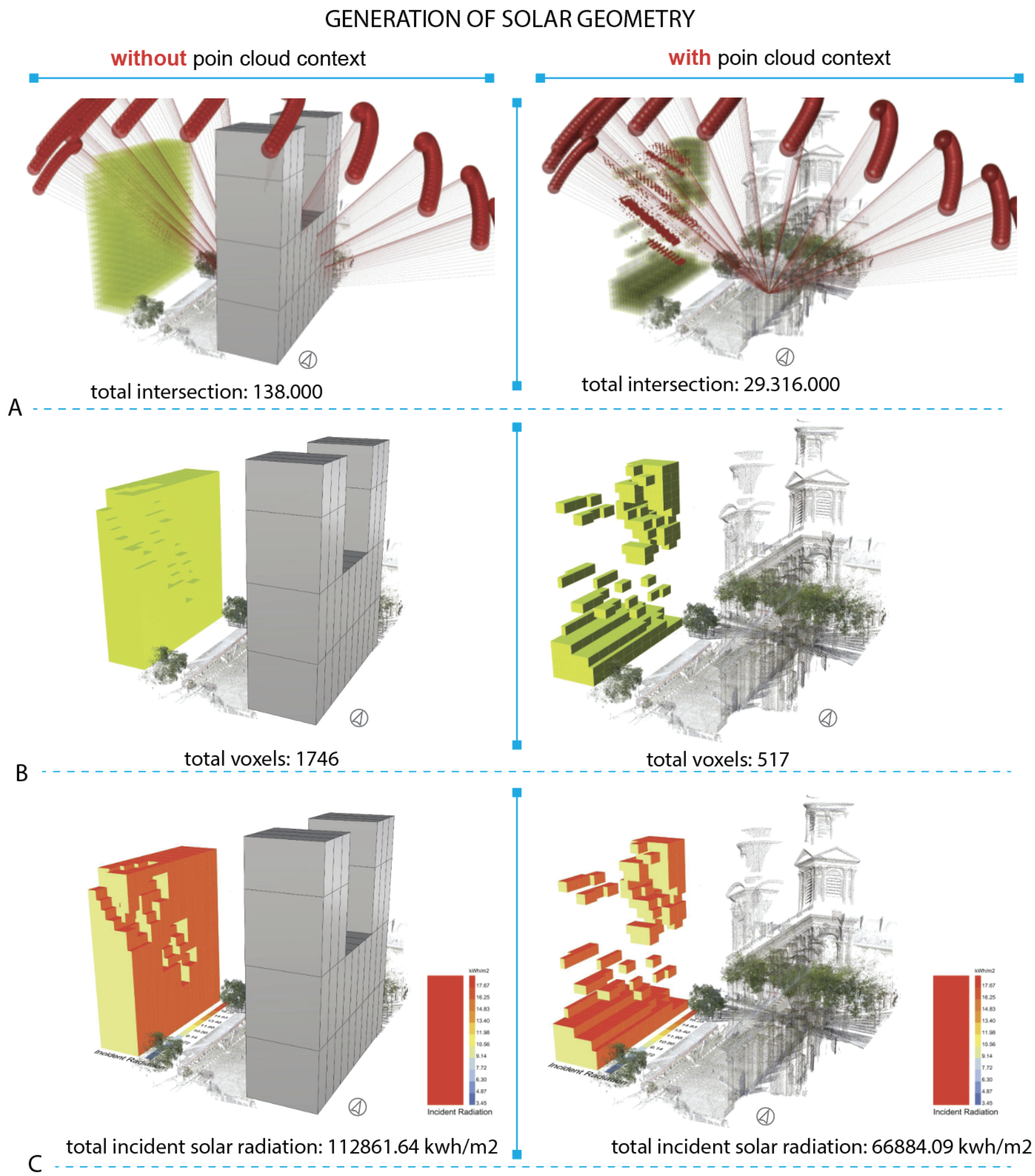
FIGURE 8. A comparative analysis of solar geometry based on two different modelling approaches.



produce one normal vector. *Second*, the point cloud-based context allows for the capture of more existing site properties during the simulation compared to the NURBS model. This can be seen from the inclusion of vegetation and other relevant geometric elements of the site during the simulation process.

- The remaining voxels in Figure 8-B principally can be considered as a geometric core of solar envelopes that may be used for the main program of the building. Accordingly, any related activities that need direct solar access to a certain period can be placed in

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these voxels, such as the living room for the housing or apartment functions, meeting room in offices, and so forth. Other possibilities are regarding the transparency level of the building form. The remaining voxels can be indicated as the less transparent form because those receive direct sun access while the reduced one should allow as much as possible sun access to surrounding buildings. In this case, a functional program for the reduced voxels can be allocated for open spaces such as a courtyard or garden. Figure 8-B further shows that the NURBS model yields more voxels remaining (i.e., 1746 voxels) than the point cloud-based context (i.e., 517 voxels). In other words, the point cloud-based context only has 25% of the total initial voxels which results from intersection lines that are denser than the NURBS model. According to Figure 8-B, most of the remaining voxels are located at ground level (i.e., 1st-3rd floor) of the polyhedra and its mid part is observed to have the greatest impact by the obstructing lines. This is because the highest insolation value from solar radiation is also specifically detected in the middle area of existing buildings. That is why voxels in the middle and top left corners of the polyhedra are significantly reduced.

- Figure 8-C shows that the east-facing voxels receive the most solar radiation than the other polyhedra during the predefined simulation period. Due to the significant difference of the total remaining voxels, the point cloud model only receives approximately 66884.09 kwh/m^2 of solar radiation value, which is around 60% lower than voxels with the NURBS model. This condition is also affected by the site characteristics during the generation of solar geometry. As Paris consists of a moderately high latitude location, the resulting solar elevation angle is low and accordingly many voxels are identified as inaccesible to receive direct sun access. In other words, the polyhedra in the point cloud model experience a massive reduction in voxels during the ray tracing analysis process due to the low solar elevation angle, especially when the proposed building is in close proximity to surrounding buildings. Nevertheless, having identified the solar potential for both models, it can be assumed that the resulting geometries present great capabilities to harvest solar energy as a solar collector from the building façade. This can simultanously illustrate to designers not only the importance of integrating environmental performance analysis durign the conceptual design stage but also the awareness for considering the microclimatic conditions of the design context between proposed and existing buildings.

After applying the proposed method into the case study, this research confirms favorable outcomes regarding the simulation workflow and the viability of incorporating it into architectural design practices. The proposed solar geometry not only provides architects with feedback from the new building to the existing context but also the environmental performance responses from surrounding buildings to the proposed design. In design practices, the Dutch Architecture and Urban Design Firm, MVRDV, has applied a similar concept of solar geometry into their projects based on solar-oriented design. One of these is a speculative research project called SolarScape (Mass, 2016) (MVRDV, 2021). These cases clearly illustrate relevant examples regarding the awareness of architects in implementing the concept of solar geometry to support their sustainable environmental designs. In this regard, 3D scanning technology (i.e., point cloud dataset) can be used to support architects in making better design decisions during the conceptual design stage.

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5. CONCLUSION

This study investigates the potential application of point cloud data in supporting contextual settings of solar envelopes. In particular, the proposed workflow has confirmed the feasibility of constructing a new method of solar envelopes based on a subtractive mechanism using TLS datasets. In general, this work may draw some concluding remarks as follows:

- Attributes information of point cloud data supports not only the capture of surrounding site properties of the real environment but also contributes to the development of new solar envelopes.
- Simulation of solar radiation plays an important role in improving the procedure of sun visibility in existing contexts. In this case, the proposed method can perform solar simulation without converting the dataset into the mesh model.
- The ray tracing analysis based on point cloud provides more robust results to identify the obstruction index between surrounding contexts and the 3D polyhedra.

The proposed method, however, presents several limitations that need to be considered further such as dataset correction of the raw point cloud data that consists of merged scans. In this case, although optimal normal values have been successfully obtained from the correction procedure, the resulting dataset remains roughly inconsistent after the truncation process. A major concern also comes from the computational issue, especially when dealing with mesh ray analysis between point cloud, 3D polyhedra, and solar vectors. Due to the highly dense dataset, computational processing takes a relatively long time. As an alternative, the quality of dataset or quantity of solar vectors should be reduced to accelerate the simulation run time.

For a further study, some possibilities can be explored through the inclusion of material aspects during the generation of solar envelopes. This simultaneously investigates an extended function of radiometric information of point cloud data. It is also recommended to implement the proposed method into the larger urban context with multiple building functions so that a variety of solar envelopes criteria can be further explored. Furthermore, in order to cater to the unfamiliarity of some designers when dealing with point cloud datasets in the future, the development of our proposed method into a single computing component that may potentially be embedded into existing tools can be proposed.

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Declaration of Interest

The authors declare that there is no conflict of interest regarding the publication of this article. Authors confirmed that the paper was free of plagiarism.

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