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The use and potential applications of point clouds in simulation of solar radiation for solar access in urban contexts

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Abstract. High-performing architecture should be designed by taking into account the mutual dependency between the new building and the local context. The performative architecture plays an important role to avert any unforeseen failures after the building has been built; particularly ones related to the microclimate impacts that affect the human comfort. The use of the concept of solar envelopes helps designers to construct the developable mass of the building design considering the solar access and the site obstruction. However, the current analysis method using solar envelopes lack in terms of integrating the detailed information of the existing context during the simulation process. In architectural design, often the current site modelling not only absent in preserving the complex geometry but also information on the surface characteristics. Currently, the emerging applications of point clouds offer a great possibility to overcome these limitations, since they include the attribute information such as XYZ as the position information and RGB as the color information. This study particularly presents a comparative analysis between the manually built 3D models and the models generated from the point cloud data. The modelling comparisons focus on the relevant factors of solar radiation and a set of simulation to calculate the performance indicators regarding selected portions of the models. The experimental results emphasize an introduction of the design approach and the dataset visibility of the 3D existing environments. This paper ultimately aims at improving the current architectural decision of support environment means, by increasing the correspondence between the digital models for performance analysis and the real environments (context of design) during the conceptual design phase.

Keywords: solar envelope; point cloud data; microclimate impacts; environmental simulation; modeling environments

1. Introduction

1.1 General background

According to van Hove *et al*. (2011) in the Alterra report, the percentage of people living in urban areas will continually increase by more than 60% of the total world population in 2030. This trend indicates the impact of the urban density to an occupation of 40% of the energy consumption

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from the building sectors (Brophy and Lewis 2011). Having said that, the implementation of passive design strategy becomes of importance solutions, not only to maintain a quality of the built environment but also to achieve the optimized building performance during the conceptual design process. Analysis of the to-be-built environment, furthermore, allows averting the unexpected failures after the building has been built.

The concept of vernacular architecture was commonly designed and constructed by considering the interrelation between the new building and the plot of local context. In the case of contemporary architecture, unfortunately, the design implementation remains some concerns. As an example, the Walkie Schorcie building in the UK showcases some practical issues related to the lack of integration of the local context. Evidently, its building form caused numerous microclimate effects. The glazed and curved south façade reflects solar radiation over 70 Celsius degree into the surrounding environment. This situation has tremendously created wide impacts on the local context such as melting body of the car that parked at the surrounding buildings and eventually consuming the expensive cost-recovery for the building facade (Futcher and Mills 2015). It goes without saying that the building has been awarded as "the worst building of the year," Carbuncle Cup 2015 by RIBA. This case clearly points out the unexpected microclimate impacts caused by new building toward the local environment. Vice versa, the UCL Student Housing in Caledonian Road, North London, UK exemplifies the situation of the new building which may not fit its local context and therefore being harmed by that. In this case, around half of the 350 building rooms surprisingly do not gain direct sunlight access because of being obstructed by the existing façade built in the 19th century.

By focusing on solar radiation performance, the examples described above highlight a critical perspective of how architecture should approach the local context especially dealing with an early phase of the design process. The new building should develop a reciprocal relationship to its existing environment since the natural resources like sunlight, daylight, and wind are shared together. This paper specifically proposes an integration of the existing method of solar envelopes by making use of the detailed information extracted from the point cloud data. Further overview of solar envelopes and point clouds are addressed below.

1.2 Solar envelope

A solar envelope is an imaginary building mass determined by considering the amount of desirable sun access without obstructing the surrounding site during the critical time (Knowles 1974). Fig. 1 illustrates the basic mechanism of the solar envelope for the generation of daily and annual time limits, taking into account the Northern hemisphere. In a full day setting, the morning sun establishes the envelope shape of western limits and the afternoon sun generates the envelope shape of eastern limits (Knowles 1980). During the critical time between 9 am until 2 pm, the envelope limits will be steeper on the east than the west because the sun's altitude around at 2 pm is higher than at 9 am. In this case, the sun's rays hit the plot at the higher position between the selected hours. The same process applies to annual time patterns. The solar envelope is steeper in summer than in winter because the sun angle in winter is lower than in summer.

Following this basic set of the solar envelope, its concept was then evolved and elaborated into several identified generation techniques:

- Solar obstruction angle; it consists of the three main parameters such as solar planes, the perimeter of the site plot and the site orientation (Brandao and Alucci 2005, Pereira *et al*. 2001, Grazziotin *et al*. 2001, Amaral 2005, Paramita and Koerniawan 2013, Emmanuel 1993, Lobaccaro *et al*. 2012, DeKay 2012, Okeil 2010).

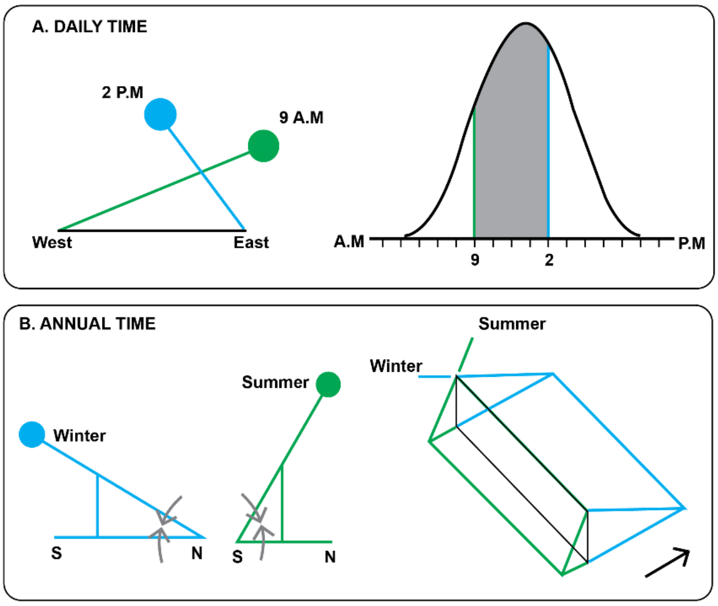


Fig. 1 Design mechanism of solar envelopes, generated from: A. daily time limits (Knowles 1980, p. 13) and B. annual time limits (Knowles 1981, p. 54)

- Descriptive method; it is based on the trigonometric calculation between sun altitude, sun azimuth and the cut-off times (Capeluto *et al*. 2005, Bruce 2008, Saleh and Al-hagla 2012, Noble and Kensek 1998, Camporeale 2013).
- Digital elevation modeling (DEM); it relies on the image processing technique and calculation of the shadow volume for the urban scale (Ratti and Morello 2005).
- Constructive solid geometry; it mainly based on the site extrusion and the solar vectors (Stasinopoulos 2001, Kensek and Henkhaus 2013, Vartholomaios 2015, Cotton 1996, Niemasz *et al*. 2011).

These studies propose different ways of dealing with the concept of solar envelope aligned with the technological development of design tools. However, these works were predominantly simulated without any consideration on the built environment. Consequently, the spatial relationship and the environmental impacts into the local context become a problem during the design process. Some literature has addressed the surrounding environment through the descriptive method (Capeluto and Shaviv 1997, Machacova *et al*. 2013, Martin and Keeffe 2007, Martin *et al*. 2011, Raboudi and Saci 2013, Dekay 1997, De Luca 2016, De Luca and Voll 2017). However, the existing environment (design context) in these works is modelled based on major simplifications. The representation of existing context is mostly constructed by using the basic geometric shapes. When it comes to the isolated site or complex building forms, the 3D modelling context becomes the real problem. In accordance to the simulation of solar radiation, furthermore, the exclusion of texture as the surface characteristic of the existing buildings will affect the interpretation of the simulation results; such that the simulation of solar radiation applies the same treatment to all the building surfaces which are in fact different in the real situation. As a part of the existing environment properties, the surrounding vegetation (Emmanuel 1993) should also be addressed further as it may influence the design configuration of the solar envelopes.

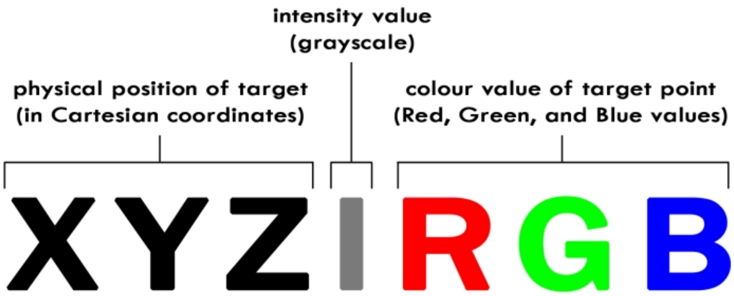


Fig. 2 Attribute information of point cloud data (Randall 2013)

In contrast, this study claims the importance of considering the aforementioned aspects to generate a solar envelope particularly related to the properties of the surrounding environment. The potential of point clouds as a 3D data scanning allows for mapping the spatial information of the existing context. The inclusion of a large accurate dataset and the real information contained in the point cloud can be used to generate a contextual model of the real environment. Further development of such accurate modelling permits to perform simulations and design analysis afterward. Besides, it helps to minimize the possible discrepancies between the environmental design simulations and the real phenomena.

1.3 Point cloud data

The rapid development of 3D laser data scanning technology has been widely implemented in various disciplines especially related the data visualization and data analysis such as civil engineering, geosciences, photogrammetry, and heritage. Conceptually speaking, Weinmann (2016) pointed out that the term “point” in geometry represents the specific unit location in a particular space and the term “cloud” describes the unorganized nature of the arrangement and its spatial coherence in a blurred boundary. Thus, the term point cloud is a set of points, Pi =1, . . .n, that is embedded in the three-dimensional Cartesian space (Otepka *et al*. 2013). As an entity of 3D data scanning, point cloud constitutes the discrete three-dimensional locations (points) that can have additional information associated with each record (White 2013). It is characterized by spatial XYZ coordinates as position information and is optionally be assigned by auxiliary information (see Fig. 2) such as color information (RGB) (Fujita *et al*. 2015) and intensity information (I) (Wand *et al*. 2008, Lichti *et al*. 2005, Weinmann 2016).

Furthermore, Randall (2003) described that point cloud data could support the following information:

- The position of the object with 3D coordinates in a global coordinate system.
- Geometrical features such as the length between points and the orientation of the objects.
- Visual information such as 2D and 3D digital image and 3D virtual model.
- Physical features such as textures, cracks and different object types by different density (Gressin *et al*. 2013).

The utilization of point cloud in several engineering domains shows potentials for high precision results for the simulation performance (Vahid 2017). It can also be used to perform numerous tasks in the early stage of architectural design in which various design scenarios can be analyzed during the decision-making process (Fujita *et al*. 2014). For example, the point cloud

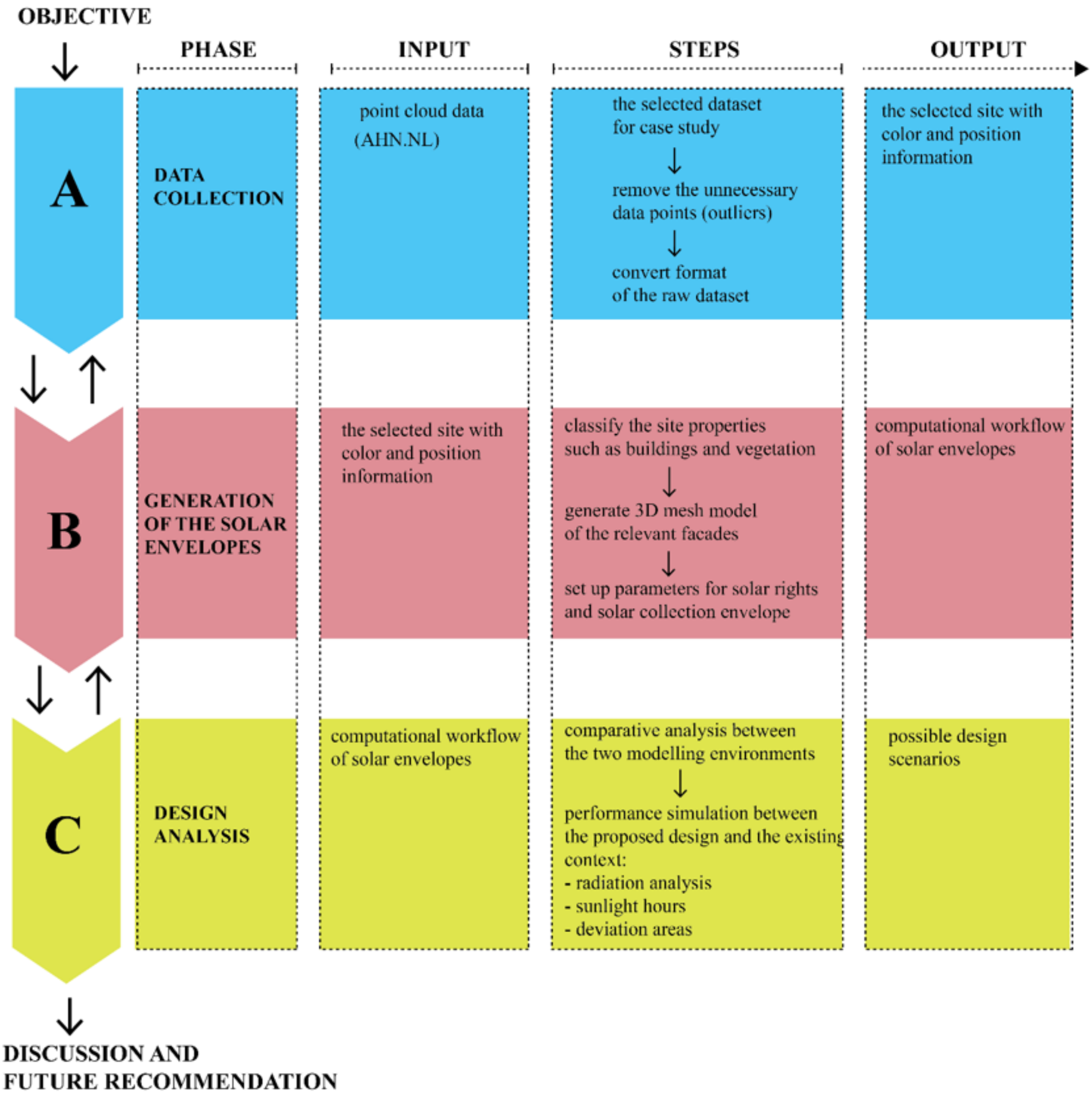


Fig. 3 Overview of the proposed procedure

data can be employed to generate the 3D model of the complex existing urban form (Babahajiani *et al*. 2015, Richter and Dollner 2014, Hackel *et al*. 2016). Besides, the point cloud allows for visualizing the whole construction process according to time-based transformation (Shih and Wu 2005) and captures the deformation of existing structures in the renovation process (Varady *et al*. 1997). Further, the surface attribute information contained in the point cloud is useful for detecting the solar potential at any existing building surfaces (Jochem *et al*. 2009, Santos *et al*. 2014, Martin *et al*. 2015). These prospective applications of point cloud offer great potential for analyzing the existing environment during the architectural design process. However, studies specifically investigating the solar envelope performance by making use of point cloud remain a blank spot in the solar radiation analysis.

This study ultimately aims at exploring the potential application of point cloud data in generating the solar envelope. In this case, a comparative analysis between the manually built 3D models and the models generated from point clouds is addressed; the following section illustrates further the process.

2. Proposed procedure: From point clouds to the solar envelopes and design analysis

Given an unstructured raw dataset of the point cloud, the proposed procedure allows simulating the solar envelope according to selected information from the existing context. Its procedure consists of three phases: (a) data collection, (b) generation of the solar envelope and (c) design process. The overview of the process is illustrated in Fig. 3.

2.1 Data collection

The data collection phase is useful not only for gathering the raw point cloud dataset but also for identifying the relevant information from the local context to be the input in the design simulation. During this phase, the source of dataset collection plays an important part as it considers the types of attribute information attached to the point cloud data. For example, the Terrestrial Laser Scanning (TLS) technique caters different robustness and attributes of point cloud dataset in comparison with Airborne Laser Scanning (ALS). Thus, the level of information properties should be determined in this phase. Specifically, the followings are required steps to distribute the selected point cloud dataset:

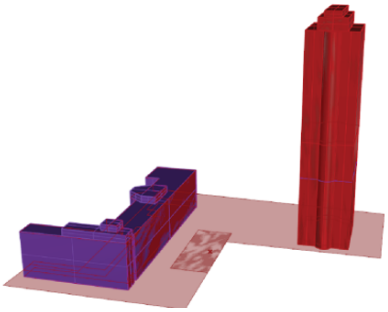
- Select the plot and the relevant site properties like vegetation and surrounding buildings.
- Remove the outliers to reduce the unnecessary information during the meshing process.
- Export the dataset into the designated format.

The output of this phase is the selected point cloud containing color (RGB) and position (XYZ) information. Therefore, we can identify the elevation of each point in the dataset according to its color scale.

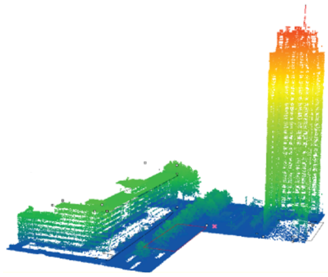
2.2 Generation of the solar envelope

This phase focuses on the development of computational workflow of the solar envelopes, based on which the output of the data collection is processed. In the proposed workflow, the point cloud data processing is established first to classify the site properties like vegetation and buildings, also to perform the mesh generation for the selected building's facade. As an extension of the solar envelopes method from Capeluto and Shaviv (1997), the workflow consists of two design principles "solar right envelope" and "solar collection envelope." Generally, this workflow attempts to tackle two main challenges. The first is to select the relevant parameters of the solar envelope according to the extracted information contained in the point cloud data. The second is to deal with the density of points in order to manage the time and storage of the computational process during the simulation. As a part of the improvement of the existing set of solar envelopes, the output of this phase endeavors to proposing a computational framework of selected solar envelope parameters with some relevant information extracted from the point cloud data.

(a) Google earth model



(b) Manual model



(c) Point cloud model

Fig. 4 Representation of selected site in different 3D models

2.3 Design process

The third phase constitutes of the design process and related analysis that can be performed by using the output models of solar envelopes. As this phase includes exploratory design techniques, a large variety of possible scenarios can be set depending on the intended design case.

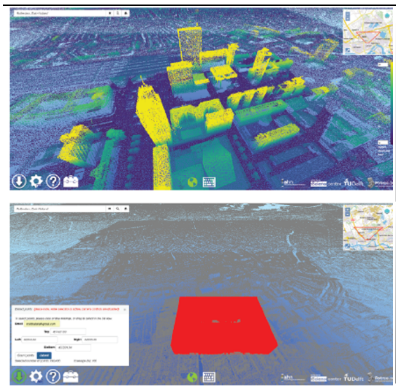
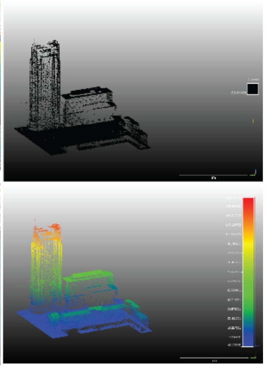
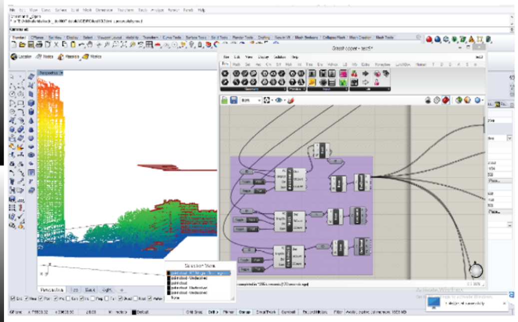
Furthermore, the comparative analysis is addressed by using two different modelling environments on the one specific case study. The aims are to investigate further design configurations produced by the same urban context and to identify the extent of simulation result discrepancies regarding the volume of the geometric envelope, the total radiation value and the total sunlight hours. These simulation results are performed by comparing the TIN (Triangulation Irregular Network) model from the point cloud and the 3D model manually generated based on the CAD-drawings.

3. Case study: The Kruisplein area in Rotterdam

The selected location is Kruisplein areas in Rotterdam, Netherlands (the latitude coordinate is 51.9244° N, and the longitude coordinate is 4.4777° E). As this area is the crowded district nearby the Rotterdam Central Station; so that many people frequently pass through the area for eating, shopping, and resting. The area also varies to functions and urban scales such as high-rise and wide-span building, large open space and vegetation in between of the buildings. By taking into account the urban quality in this area, the existence of a new building should preserve the mutual relationship to the surroundings. The case study focuses on guaranteeing appropriate solar access between the new design and the surrounding environment.

The Fig. 4 illustrates the selected buildings with multiple functions such as the hotel (high-rise building) and commercial areas (wide-span building). Understanding these specific functions allow setting the limit of sun access for the surrounding environment. For example, the commercial functions consist of the shop, restaurant, and cafes along the ground floor and offices on the upper floors. The commercial areas on the ground floor are preferably gaining a shadow rather than the direct sunlight because of the durability standard of the food located in the storefronts. The open space often becomes a mixed-use for temporal events such as live music, market, and other festivals. On the other hand, the direct sunlight is more suitable for the housing areas during a specific time.

Table 1 Data processing workflow of 3D point cloud data

Step 1	Step 2	Step 3
		
Site selection	Data conversion	Design space
AHN map	Cloud compare	Rhino + Grasshopper

The case study proposes a set of design scenario by designing a multifunction building for supporting activities in the open space areas. It consists of 16.5 x 42 m with commercial areas on the ground floor and offices on the upper floors. The proposed building is then expected to meet the requirement of the surrounding site by do not violate the sun access to the particular function of spaces and vice versa.

4. Data collection in the case study

In terms of data availability, this study attempts to use an open data platform for capturing the 3D point cloud. Architects can access and extract the selected context from the *Actueel Hoogtebestand Nederland*, AHN (retrieved from http://www.ahn.nl). This open dataset constitutes a digital altitude map of point cloud according to laser altimetry measurement (AHN 2017). During the data collection phase, three steps are performed as illustrated in Table 1: Site selection, data conversion, and design space.

4.1 Site selection

As the first step, the site selection process involves several actions in capturing the 3D point cloud data. It starts from marking the 3D boundary of the plot, setting the color type of dataset, specifying density of points and importing the selected dataset. These actions may consider the following facets of the site selection:

- Point density, it contains the number of points per square meter. The number of points can affect the surface quality of the mesh model during the 3D modelling process.
- Size of points, it merely intends to show the sharpness of the visual representation of the data user.
- Color field of the dataset, this part can available be set to many variations such as height, depth, intensity, return number and so forth.

- The quality of dataset, this option is accessible in the AHN map. It also varies from different resolutions such as high, low, standard and ultra-resolution.

Another aspect that should be taken into account is that the AHN datasets cater potential drawbacks both of the measurement methods and tools regarding the generation of DTM (Digital Terrain Model). The AHN map contains limited attribute information and much less robust datasets in comparison with the TLS (Terrestrial Laser Scanning) techniques. Besides, the material properties of the environment like the real color of the building surfaces are not available yet in AHN map. This feature then affects the searching tasks for the user to capture the precise boundary in the selected areas. As an option, Google earth via satellite image can help the user to mark the precise location of the case study.

4.2 Data conversion

The data conversion aims at preparing the appropriate datasets in order to be readily used in the design space. The preparation process employs the Cloud Compare (CC) and related components as the supporting tools. The following steps highlight tasks for this phase:

- Activate the color field of the dataset. As the original dataset comes from the AHN map, the initial color remains monochrome. The color field is used for filtering the selected areas according to the scalar field value. The scalar field refers to the real number for each coordinate in a space such as 3D space $\phi = \phi\ (x,y,z)$ (Hirschfeld 2007), or a structure of the real values (scalar) (Girardeu-Montaut 2015). In CC, some of the scalar field functions are available such as density, curvature, roughness, intensity and so forth. As illustrated in Table 1 step 2, for example, the scalar field of coordinate Z is activated from the original dataset (monochrome). Attached to the scalar field, the gradient color in the coordinate Z represents the elevation of the areas. The red color means the highest position and the blue color shows the lowest position. Thus, we can use the color scale value to filter and identify a certain area according to their elevations. Unfortunately, the filtering feature in CC only can cut per areas, not per objects.
- Export the selected dataset. In order to be legible and interoperable in the parametric design space, the dataset should meet the suitable format. In this case, we export the original dataset (.laz file) into the .e57 file due to keeping the color field of datasets visible in the 3D modelling space.

4.3 Design space

This study considers the use of parametric design to enable the accessibility for architects in integrating the point cloud data into the environmental design platform. Because of the imported datasets from CC remains unclassified objects of points, the site properties like buildings, trees, and other objects constitute the same point entities. Therefore, the following actions are required to run before performing the simulation:

- The classification of the existing objects. Identifying the relevant objects are important to be included in the simulation process. For example, we employ only the relevant building facades for running the sunlight hour simulations.
- The generation of reference plans. It is useful to set the boundary of the selected building areas in particular for the threshold lines of the sun right access.
- The generation of the 3D mesh model from the point cloud data.

To execute the above tasks, this study specifically uses Rhinoceros as the 3D modelling platform in parallel with the Grasshopper (GH) for the visual programming environment. Besides, the environmental design simulations are supported by components from Ladybug (Roudsari and Pak 2013) for constructing the solar right and the solar collection envelope, Volvox (Zwierzycki *et al*. 2016) for the data processing of point cloud, and some customized components (Lin and Girot 2014) for supporting the 3D mesh model.

5. Development of design framework for solar envelopes

This paper particularly formulates the design framework of the solar envelope by considering two design mechanisms “the solar right envelope” and “the solar collection envelope.” The intersection of these envelopes generates a maximum developable volume of building design according to the solar access criteria.

The solar right envelope stands for a maximum height of the envelope surface corresponding to the proposed design. To achieve the solar right envelope, we should regulate the sun access level that affects the adjacent buildings during a desirable period. The main rule is to keep sun access to the surrounding buildings without any obstruction from the mass of new building design. In so doing, the height level of sun right access from the surrounding buildings should be marked first. This level refers to the bottom border (minimum level of gaining sun access) of surrounding buildings. For example, by setting the height level on the 1st floor, we compensate the sun right access of neighboring buildings on top of the 1st floor. Consequently, the surrounding areas located below this level will get a shadow.

Meanwhile, the solar collection envelope refers to the lowest possible envelopes in obtaining the sun access (for the proposed design) without being violated by the adjacent buildings during a desirable period. The height limits of the solar collection are determined by considering the top border of the surrounding buildings. As a result, the areas in the proposed design located beneath the surface of solar collection envelope will not get direct sun access. The mechanism of solar collection envelope may also be useful to identify the potential areas of the solar collector in the proposed design. In this case, the solar collector refers to the instrument of solar panels to absorb the sunlight as a source of energy for the buildings.

Furthermore, this study identifies many variations of solar envelope parameters as described in the previous literature. The inclusion of point cloud data permits formulating additional parameters in the existing workflow of the solar envelopes. This study particularly considers two principal components for the generation of solar envelopes. First, the climate aspects consist of the weather data, longitude coordinate, latitude coordinate, azimuth and altitude angle. It also corresponds with the sun path (useful for running the analysis period and radiation analysis by inputting the location contained in the weather file), sky components (generate the matrix of sky patch based on the Perez weather model, sky density and connect the analysis period for the radiation analysis), and insolation periods. In this case, we set a scenario of cut-off times by testing a half year of the insolation period from June 1st to December 31st in 2017 between 9 am to 10 pm. Second, the site rules and the environmental aspects. These aspects consider the plot areas, set back, height restriction and the inclusion of vegetation and the 3D mesh model from the part of point cloud data. Last, the simulation results consist of comparative analysis between performance indicators by using different 3D modelling platforms. The overview of selected parameters is illustrated in Fig. 5.

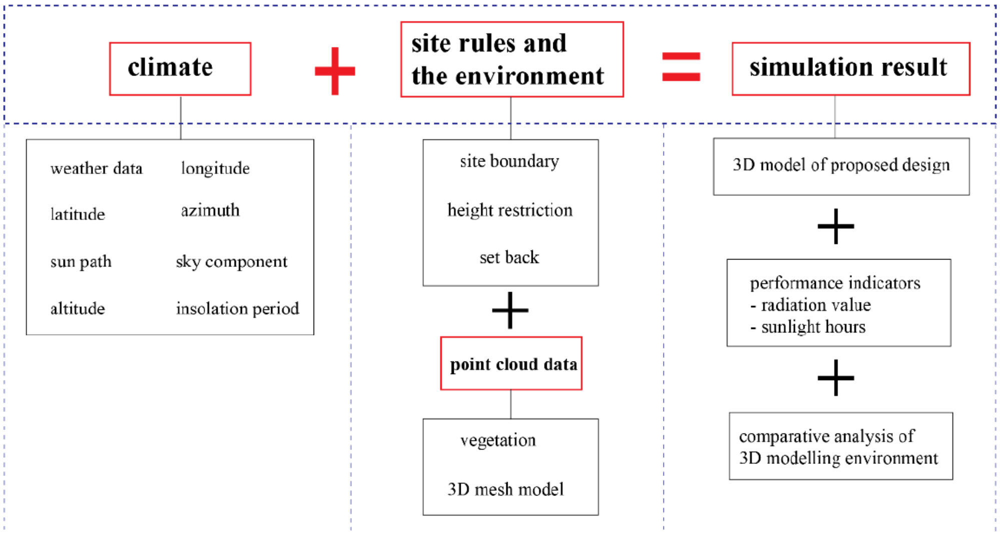


Fig. 5 Selected parameters for solar envelope

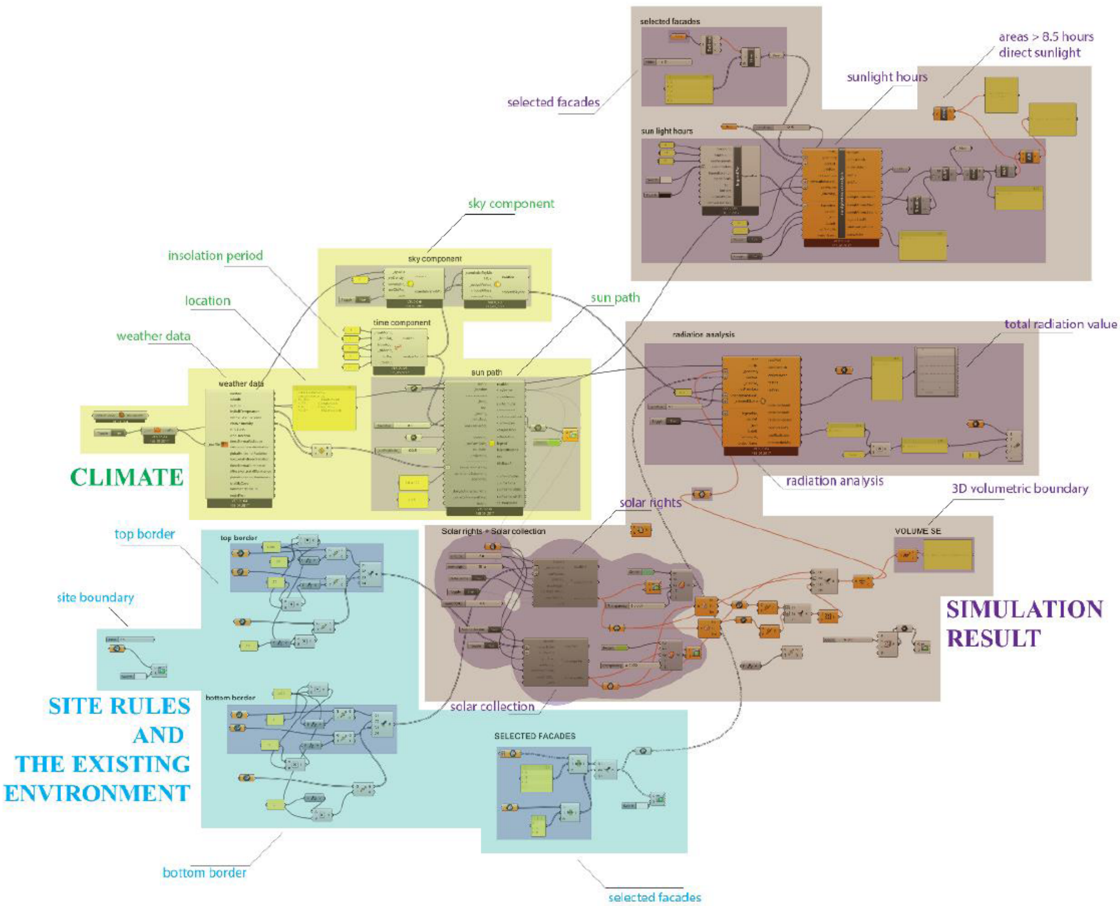


Fig. 6 Digital workflow of solar envelope

According to digital workflow of the solar envelope (see Fig. 6), the use of 3D point cloud data indicates several of the following impacts on the geometric envelopes:

- The role of vegetation in the proposed workflow affects the shape and volume of the solar envelopes. The proposed scenario sets the sun access protection to the intended design without being blocked by the surrounding vegetation. In this case, the vegetation acts as a part of the site obstruction. Thus, we put the height level of the vegetation into the border of the solar collection parameters.
- The ability of 3D point cloud to capture the complex building geometry may fulfill the gaps of manually built 3D model related the surface building properties. For example, the point cloud data can be used to construct the 3D model of under construction buildings around the plot or areas located in the dense environment like alleys or natural environment properties. Therefore, the modifications happened on the building facades due to renovation or others can always be modelled as it is and included in the simulation of solar radiation analysis.
- Having considered the relevant facades of surrounding buildings allows generating different results of the solar radiation simulation. In particular, the total radiation value and the sunlight hours create an obvious comparison by accounting the entire surfaces of the surrounding buildings. In this case, we consider only the relevant facades are facing toward the plot to be considered for the simulation.
- The inclusion of sunlight hour analysis allows detecting the most accessible areas received the solar radiation in the building facades and the plot areas during a certain time. As a result, we can identify the potential areas of solar collectors in the solar envelopes. The simulation results exemplify the different values of sunlight hours produced by two different 3D models.

6. Result and discussion

In order to construct an in-depth analysis of the simulation result, this research investigates two comparative aspects that intersect each other (see Fig. 7):

- The simulation context is divided into two parts which are the proposed design and the existing context. In the proposed design, two indicators are calculated: The envelope's volume and the radiation values. On the other hand, we consider three indicators for the existing context: The total sunlight hours, the potential areas that receive more than 8,5 hours of direct sunlight and the radiation values. The simulation mainly covers the areas included in the selected facades of the wide-span and the high-rise building and the plot.
- In the simulation process, the 3D site model compares two type of modelling techniques: The manually built 3D models and the models generated from the point cloud that refers to the TIN (Triangulation Irregular Network) model.

6.1 Simulation of the existing context

As illustrated in Fig. 7, the simulation assessment of the existing context consists of three indicators: Sunlight hours, radiation values, and residue areas. These indicators are evaluated by comparing two different 3D models, the manual 3D model, and the TIN model. When it comes to the surface generation, both models employ the polygon mesh as it contains vertices, edges, and

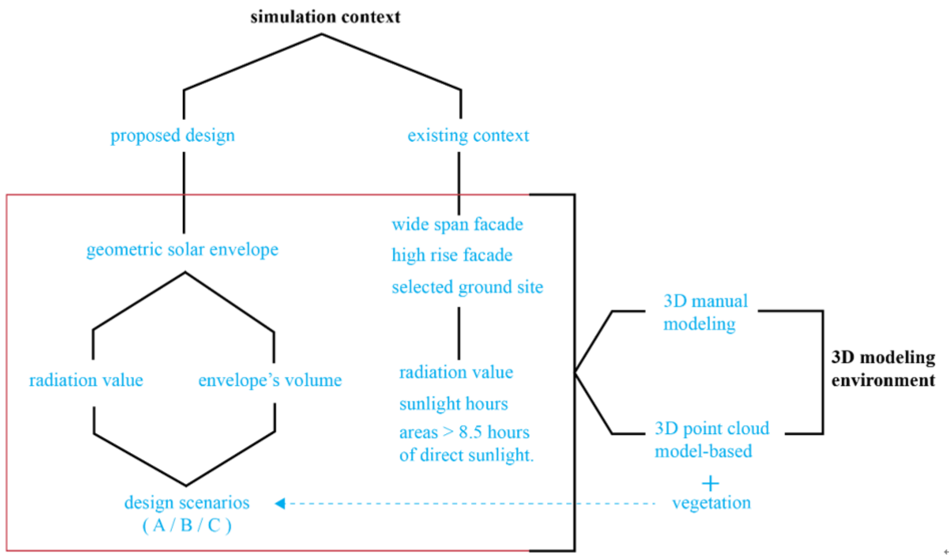


Fig. 7 Comparative indicators of the simulation context

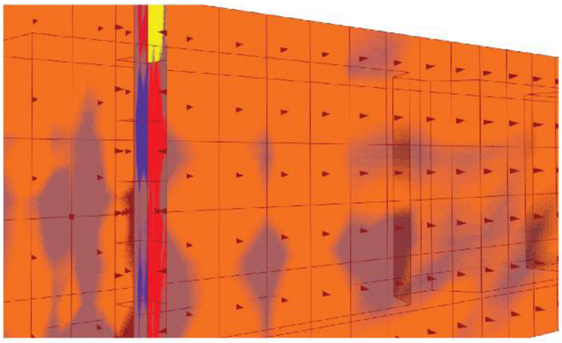
faces (Power 2012) and is easily transformed into any objects. However, the mesh generation techniques are constructed differently for both models. The manual 3D model exploits the quadrilateral type of cell shapes. Because of its 2D plan extrusion, the surface morphology of the buildings yields most often flat and plain. Besides, the manual modelling process requires a longer time than the TIN model because it should be dealing with the scale and proportion of each object contained in the real environment. On the other hand, the TIN model employs the triangle mesh for the surface generation according to the Delaunay triangulation method. This method generates a depth and an irregular structure on the surface morphology of the TIN model because the mechanism of Delaunay triangulation basically constitutes a proximal technique. In particular, the three nodes of a triangle are attempted to be maintained inside the imaginary circle boundary (Tchoukanski).

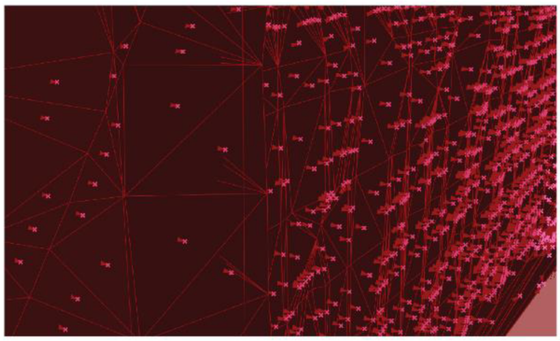
Table 2 illustrates a comparison of three indicators using two different 3D models. The calculation of total sunlight hours refers to the total hours of direct sunlight received at each test point in which being multiplied by the mesh areas of the test point attached to (Chauhan 2017). In this case, the simulation process considers only the relevant building surface (selected facades) and do not simulate the entire buildings to avoid unnecessary context information. We also calculate the potential areas that receive more than 8.5 hours of direct sunlight. A scenario has been set to employ 8.5 desirable hours from the total of 13 hours of the simulation period. The total areas for the simulations are then divided into the areas received the sunlight hours for fewer than 8.5 hours. Based on this calculation, we can identify the location of the PV panels on the building surfaces and locate the site plan on the plot areas.

According to the simulation results in Table 2, the manual 3D model averagely illustrates larger values for all performance indicators in comparing with the TIN model. In the case of total sunlight hours, although the test points of the TIN model are greater in quantity than the manual 3D model, the values of its test points are moderately small. It is affected by two factors. First, the mesh surfaces of the TIN model are generated unequal and unstructured between one triangle face

Table 2 Simulation results of the existing context

The manual model	Total sunlight hours (n hours)	Areas > 8.5 hours of direct sunlight (m²)	Total radiation (kwh)
Façade building A (wide span)	27.476,68	161,888	248.328
Façade building B (high rise)	129.187,77	12,627	207.756
Site area	29.324,46	5,879	724.274,11
The TIN model	Total sunlight hours (n hours)	Areas > 8.5 hours of direct sunlight (m²)	Total radiation (kwh)
Façade building A (wide span)	18.236,16	0,00785	51.822,194
Façade building B (high rise)	47.040,23	4,45021	114.613,314
Site area	17.387,45	0,9853	45.552,12





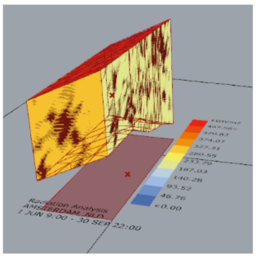
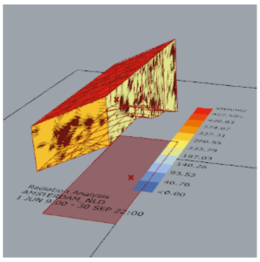
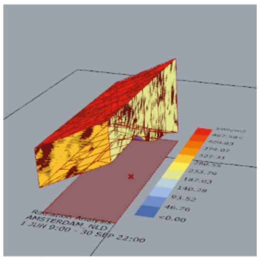
(a) Surface of the 3D manual model (b) Surface of the TIN model

Fig. 8 Comparison of the solar point vectors

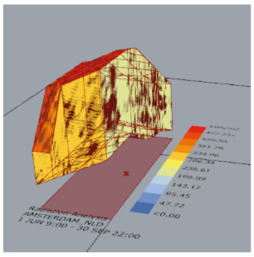
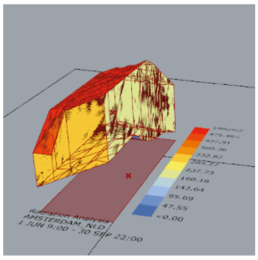
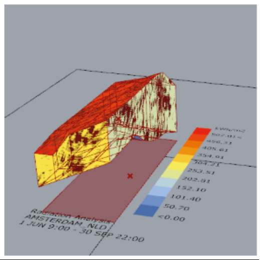
to another. Then, the shape of these triangle faces is constructed by the interpolation factor between the control points (refers to the Delaunay Triangulation method). The robustness of triangle meshes and test points shows a trade-off with the density of points from the original datasets because it ultimately affects the grid distribution of the final mesh surfaces. In contrast, by zooming into the mesh surfaces of both models (see Fig. 8), the faces generation of the manual 3D model illustrates a flat and continuous surface which affects the equal grid distribution for the test points.

Second, the direction of the triangle mesh surfaces in the TIN model demonstrates the irregular position. It means that the test point vectors follow the orientation of their triangle meshes due to the normal perpendicular position. Consequently, these point vectors respond differently to the incoming sunlight and yield various values in the simulation results. In connection with the surface position, the idea of reflection behavior also affects the significant impacts on the surface properties of both models. The flat surface of the manual 3D model demonstrates the equivalent angle between the reflection and the illumination. According to the reflection law, the reflection of the incoming lights is directly pointed into the specular path from the reflection process (Kigle-Boeckler 1995) which refers to the regular reflection. This mechanism indicates that either reflected light is parallel or converged at a point, the accumulation of the radiation values gathers in the same direction. In the meanwhile, the distribution of the reflected light from the TIN model illustrates "the orange-peel effect" because of the reflection pattern from the wavy surfaces.

Table 3 Simulation results of the proposed design

The manual model	Scenario A (m) Top: 50/20 Bottom: 3/2	Scenario B (m) Top: 60/15 Bottom: 7/5	Scenario C (m) Top: 80/10 Bottom: 1/1
The envelope's volume (m^3)	13485,30	7691,60	7508,46
Radiation value (kwh)	98790,36	75291,73	74324,64
Solar envelopes			

*top = high rise building / wide span building (meter)
bottom = high rise building / wide span building (meter)

The TIN model	Scenario A (m) Top: 50/20/14 Bottom: 3/2	Scenario B (m) Top: 60/15/4 Bottom: 7/5	Scenario C (m) Top: 80/10/14 Bottom: 1/1
The envelope's volume (m^3)	11996,63	9920,10	7252,89
Radiation value (kwh)	86736,44	79270,82	71444,75
Geometrical envelope			

*top = high rise building / wide span building / vegetation (meter)
bottom = high rise building / wide span building (meter)

As this condition is highly reliant on the structure of surface morphology, the distribution of solar reflection scatters unequally which then affect the collection numbers of the radiation value during the simulation.

6.2 Simulation of the proposed design

The second simulation discusses the results of the proposed design. Three different scenarios are applied in the simulation of solar envelopes. Each scenario consists of sun access criteria that correspond to the solar rights and the solar collection envelopes. The criteria for sun access refer to the top and the bottom border of the context properties. As described in Section 5, the top border indicates the height limit of surrounding environment properties corresponding to the solar collection surface. The bottom border marks the minimum level of sun right access of the adjacent buildings in which corresponding to the generation of the solar right envelope. The objective of these scenarios is to investigate the geometric configurations of the solar envelopes following the sun access settings of the surrounding environment. Further, the geometric of solar envelopes are then evaluated by using two indicators: The envelope's volume and the radiation values (see Table 3). The assessment of the solar envelopes geometry aims at testing the geometric performance of the solar envelopes by considering the use of different 3D models of the surrounding environment.

According to simulation results in Table 3, several following items are discussed:

- The geometric envelopes for all the scenarios illustrate nearly flat with the inclined surface on the top envelopes. The spatial arrangement of the context (see Fig. 4b) shows that only the wide-span building locates side by side to the edge of the plot area. Besides, due to the long and continuous shape of the wide-span, it covers the dimension of the plot edge. Thus, the plot edge facing the wide-span illustrates a flat curve. Although on the other side, there was a high-rise building, unfortunately, it is almost out of reach from the plot edges. Therefore, the solar envelopes geometry do not fully consider the site obstruction from the high-rise. The higher curve (facing to the high-rise) is ultimately affected by the height limit of the top border parameter. Further, the inclusion of the trees as the site obstruction in the TIN model shows the non-flat surfaces of the top envelopes.
- Scenario A demonstrates the largest volume of the solar envelope in comparing with other scenarios in both 3D models. This result indicates that the maximum volume of the solar envelope can be generated by setting a small discrepancy between the top and the bottom border values. The same rule applies to the distance between the high-rise and the wide-span building. The smaller discrepancy values assigned at the top borders, the greater volume of the solar envelope can be produced (scenario A for both models).
- Vegetation has successfully confirmed the alteration of the solar envelope's volumes and shapes to all scenarios. Scenario A and C demonstrate the decreasing volume of the solar envelopes and the radiation values from the manual 3D model to the TIN model. However, the different trends are illustrated in Scenario B, the volume of the solar envelopes and the radiation values slightly increased in the TIN model. By focusing on the height level of vegetation (top border values = 14 m) and the values of bottom border, as stated in the previous point that small distance between these settings can increase the volume of the solar envelopes for a certain extent.
- The scenario C illustrates the least values of the solar envelope's volumes compared to the others. This result simultaneously indicates the minimum buildable volumes of the solar envelopes that can be considered for architects in the design exploration.

7. Concluding remarks

The simulation results summarized in Table 2 and Table 3 illustrate that the use of point cloud not only contributes to the generation of the solar envelopes but also offers further possibilities in analyzing the existing environment. The proposed method confirms a positive procedure in achieving the main objective of this study. The data collection allows architects to capture and filter the important information from the point cloud of data context. However, a different workflow may appear by the usage of data processing tools and level of the detail information.

Furthermore, the comparative analysis of the manual 3D model and the TIN model demonstrates a significant discrepancy related to the simulation of radiation values and the sunlight hours. The use of some customized components in Grasshopper also provides great assistance in the development of digital workflow, particularly related to the data processing of point cloud and 3D mesh modelling.

Although some progress has been made during this study, the incremental approach provides only a partial answer due to acknowledged limitations. For example, the accuracy of the surface generation of the TIN model as it deals with the density of points from the original datasets and the unstructured polygon surfaces during the mesh generation process. This study does not also consider further the material properties during the simulation process because of the dataset availability from the AHN map. Consequently, the calculation of the radiation values focuses on the surface morphology of the buildings.

Further study related the aforementioned constraints needs to continue. Of great importance through this study includes the concept of "metabolism" of Knowles by having the broad impact quality into the built environment. The followings are some potential development areas for future recommendations:

- The inclusion of multiple performance indicators into the simulation framework such as shadow analysis, daylight factors, thermal comfort, and so forth. These indicators allow further environmental assessments of the solar envelopes that can be useful during the conceptual design stage.
- The integration of current solar envelopes workflow into the multi-objective optimizations. It aims at exploring the geometrical solutions of the solar envelopes according to certain objectives such as maximizing the energy distribution of the solar envelopes and the use of space efficiency inside of the solar envelopes.
- Adjustment of different climates into the workflow of the solar envelopes. For example, most of the tropical countries like South East Asian countries will require a different objective of the solar envelopes in comparing with the European countries. The shading areas are preferably suitable for the tropical countries instead of the direct sun access for the building's room.

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