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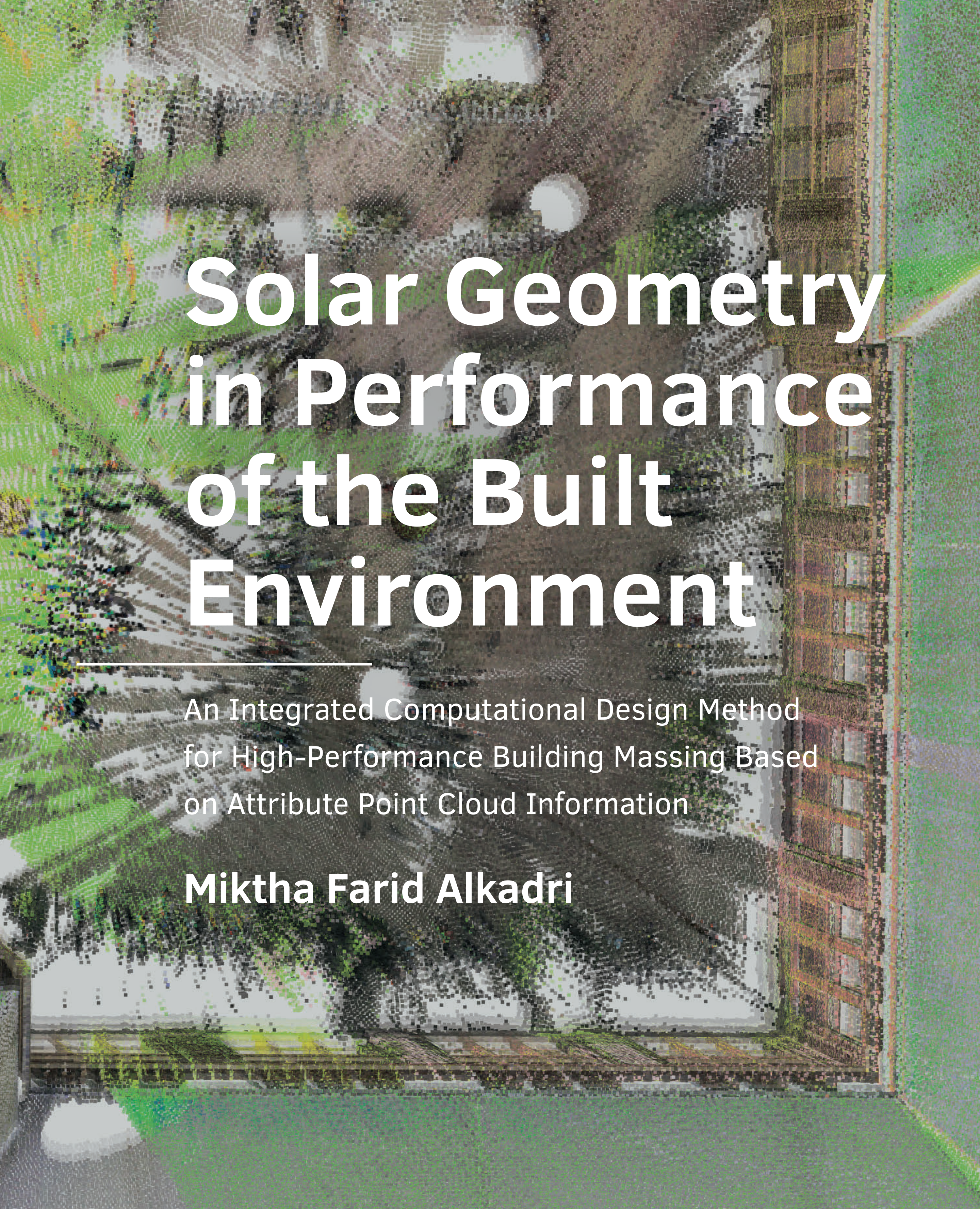

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Solar Geometry in Performance of the Built Environment

An Integrated Computational Design Method for High-Performance Building Massing Based on Attribute Point Cloud Information

Dissertation

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at Delft University of Technology,
by the authority of the Rector Magnificus Prof.dr.ir. T.H.J.J. van der Hagen,
chair of the Board for Doctorates
to be defended publicly on
Monday, 14 June 2021 at 15.00 o'clock

by

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Prof. dr. -Ing. ir. Widjaja Martokusumo	Bandung Institute of Technology
Dr. F. De Luca	Tallinn University of Technology, other member

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Not having learned it is not as good as having learned it;
having learned it is not as good as having seen it carried out;
having seen it is not as good as understanding it;
understanding it is not as good as doing it.

Xunzi

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Thank you – Dank u wel – Terima kasih.

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Summary

In recent years, urban population growth has increased rapidly in parallel with the escalation of energy consumption from the building sector. The UN SDGs (United Nations Sustainable Development Goals) play an important role in driving strategies such as green building technology and high-performance envelope to manage and calculate the efficiency of energy intensity in buildings. Although these approaches promote promising technical solutions, attempts to improve the environmental quality of the built environments have often been neglected, especially with regard to passive design strategies in the conceptual design phase. This is crucial for architects not only to prevent unexpected failures after a new building is built in a new context but also to understand comprehensively the microclimatic conditions from the design context. Through the computational development of solar geometric models, this thesis explored a new method for designing and analyzing existing environments by making use of attributes point cloud information, and solar and shading envelopes. The developed method not only helps further architects to construct interdependencies between the new building and the local context but also to make informed-design decisions towards high-performed building massing.

However, a state-of-the-art computational method for generating solar geometries poses a major challenge in understanding site characteristics of existing environments. Existing methods predominantly construct 3D digital contextual models based on basic architectural geometric shapes (i.e., solid modelling platforms), currently isolated from properties around the local context (i.e., vegetation, temporal site elements, materials). In addition, current methods also require labor and time-intensive to cover detailed site properties of complex projects, especially those located in remote and congested areas. Thus, it is clear that this condition may result in a fragmented understanding of local contexts during the design and simulation process.

Thanks to the potential application of attribute point cloud information, relevant features such as insolation analysis and material properties of the existing context can be used to address the aforementioned issues during the conceptual design stage. These features are essentials for architects not only to identify the specific characteristics and performances of the existing context but also to develop an integrated design method for simulating solar geometry based on real contextual datasets.

Furthermore, this research conducted a mixed-methods study using both deductive and inductive reasoning with qualitative and quantitative analysis. The research analysis was carried out based on the actions performed in three parts categorized into the research structure, namely theoretical framework, methodological frameworks, and case studies. In parallel, each of these frameworks contains a different research objective that corresponds to each chapter in this thesis. First, theoretical frameworks specifically addressed two main aspects of the research, namely solar envelopes and point cloud data. The first step was conducting a systematic review on computational solar envelopes based on design methods, parameters, digital tools, and design implementation (chapter 2). This chapter aims to review state-of-the-art computational solar envelopes and identify knowledge gaps as well as future directions of the study. Recommendations from the review study were followed up with a preliminary simulation of solar envelopes based on geometric properties of ALS (Aerial Laser Scanning) point cloud data (chapter 3). The goal of this preliminary simulation is not only to test the feasibility of integrating point clouds in the solar envelope simulation, but also to gain critical feedback on relevant and potential attribute point cloud information. For example, exploring radiometric information of the TLS (Terrestrial Laser Scanning) dataset allows one to compute material properties (i.e., thermal and optical) and perform insolation analysis on the surface of the contextual dataset (chapter 4).

Second, the methodological framework focuses on the development of computational workflows for the two proposed models, namely subtractive-solar envelopes (SOLEN) (chapter 5-Part A) and subtractive-shading envelopes (SHADEN) (chapter 5-part B). In this regard, the SOLEN model aims to generate solar envelopes based on a specific amount of direct sunlight from the surrounding context while the SOLEN model was developed to generate an appropriate building mass based on the shading performance criteria. Although these models were established based on the integration of the environmental performance features from the point cloud and subtractive design principles of solar envelopes, both models used these features differently in computational workflows. In SOLEN model, environmental features were used to assess the potential and impact of the final geometry of subtractive solar envelopes while the SHADEN model used it to generate the final geometry of subtractive shading envelopes.

The last part is case studies, in which the SOLEN and SHADEN model were applied in different contextual and climatic settings. The SOLEN model was applied in Delft, The Netherlands using a hypothetical case study and temperate climate settings while the SHADEN model was applied in Bandung, Indonesia, incorporated with an architectural firm using tropical climatic settings.

As an exploratory study, this research aimed at demonstrating the proposed computational method into design practices by conducting an interview with design practitioners (i.e., architects, developer, local government) (chapter 6). This is important not only to identify the feasibility and practicality aspect of the models developed into the existing architectural design scheme but also to gain technical and conceptual feedback comprehensively for future implementation. The interviews began with a brief presentation from the researcher about the background of the study, then continued with a booklet containing procedural steps for computational workflows. As a result of this interview, three main aspects such as computational environments, project cost, and local regulations require further attention to architectural design practice in design method implementation.

To sum up, the research developed an integrated computational method for establishing solar geometry based on attribute information stored in point cloud data, and solar and shading envelopes. The method presented in this thesis contributes to assisting architects not only in understanding the existing context comprehensively before starting the design exploration but also in supporting better design decisions during the conceptual design stage. In addition, this thesis also encourages a collaborative and interdisciplinary approach between the research field of remote sensing and architectural design. As for further considerations, this thesis acknowledges some critical aspects such as the requirement of a prerequisite knowledge for the dataset processing, especially for organizing and selecting relevant information from large datasets, the cost of tool affordability that is currently still expensive for small architectural design firms, and improvements to computational workflows to address factors such as dataset correction parameters, simulations from dense datasets, and design implementation using a variety of urban settings.

Samenvatting

In de afgelopen jaren is de groei van de stedelijke bevolking snel toegenomen, parallel met de escalatie van het energieverbruik van de bouwsector. De UN SDG's (United Nations Sustainable Development Goals) spelen een belangrijke rol bij het stimuleren van strategieën zoals groene bouwtechnologie en high-performance envelop om de efficiëntie van energie-intensiteit in gebouwen te beheren en te berekenen. Hoewel deze benaderingen veelbelovende technische oplossingen bevorderen, zijn pogingen om de milieukwaliteit van de gebouwde omgevingen te verbeteren vaak verwaarloosd, vooral met betrekking tot passieve ontwerpstrategieën in de conceptuele ontwerpfase. Dit is cruciaal voor architecten om niet alleen onverwachte storingen te voorkomen nadat een nieuw gebouw in een nieuwe context is gebouwd, maar ook om de microklimatologische omstandigheden vanuit de ontwerpcontext volledig te begrijpen. Door de computationele ontwikkeling van geometrische modellen voor zonne-energie, onderzocht dit proefschrift een nieuwe methode voor het ontwerpen en analyseren van bestaande omgevingen door gebruik te maken van attributen puntwolkeninformatie en zonne- en schaduw-enveloppen. De ontwikkelde methode helpt niet alleen andere architecten om onderlinge afhankelijkheden tussen het nieuwe gebouw en de lokale context te construeren, maar ook om geïnformeerde ontwerpbeslissingen te nemen voor een hoog presterende gebouwmassa.

Een state-of-the-art computationele methode voor het genereren van zonne-geometrieën vormt echter een grote uitdaging bij het begrijpen van locatiekenmerken van bestaande omgevingen. Bestaande methoden construeren voornamelijk 3D digitale contextuele modellen op basis van architecturale geometrische basisvormen (d.w.z. solide modelleerplatforms), momenteel geïsoleerd van eigenschappen rond de lokale context (d.w.z. vegetatie, tijdelijke site-elementen, materialen). Bovendien vergen de huidige methoden ook arbeids- en tijdintensief om gedetailleerde locatie-eigenschappen van complexe projecten te dekken, vooral die in afgelegen en drukke gebieden. Het is dus duidelijk dat deze voorwaarde kan resulteren in een gefragmenteerd begrip van lokale contexten tijdens het ontwerp- en simulatieproces.

Dankzij de mogelijke toepassing van attribuut-puntenwolkeninformatie kunnen relevante kenmerken zoals analyse van de instraling en materiaaleigenschappen van de bestaande context worden gebruikt om de bovengenoemde problemen aan te pakken tijdens de conceptuele ontwerpfase. Deze kenmerken zijn essentieel voor architecten om niet alleen de specifieke kenmerken en prestaties van de bestaande context te identificeren, maar ook om een geïntegreerde ontwerpmethode te ontwikkelen voor het simuleren van zonnegeometrie op basis van echte contextuele datasets.

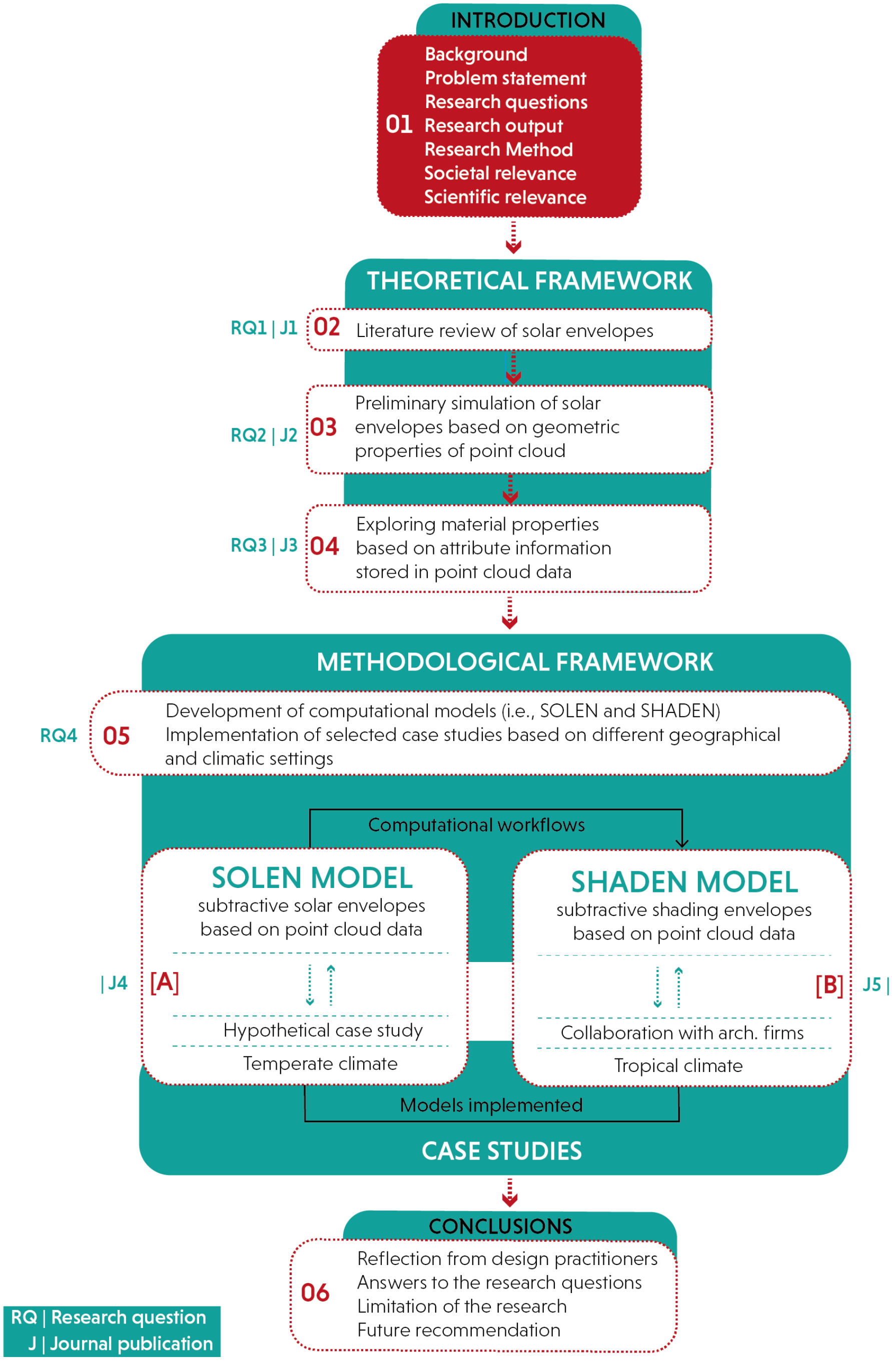
Bovendien heeft dit onderzoek een studie met gemengde methoden uitgevoerd met behulp van zowel deductief als inductief redeneren met kwalitatieve en kwantitatieve analyse. De onderzoeksanalyse werd uitgevoerd op basis van de acties die werden uitgevoerd in drie delen onderverdeeld in de onderzoeksstructuur, namelijk theoretisch kader, methodologische kaders en casestudy's. Tegelijkertijd bevat elk van deze raamwerken een andere onderzoeksdoelstelling die overeenkomt met elk hoofdstuk in dit proefschrift. Ten eerste behandelden theoretische kaders specifiek twee hoofdaspecten van het onderzoek, namelijk zonne-enveloppen en puntenwolken. De eerste stap was het uitvoeren van een systematische review van computationele zonne-enveloppen op basis van ontwerpmethoden, parameters, digitale tools en ontwerpimplementatie (hoofdstuk 2). Dit hoofdstuk beoogt een overzicht van de modernste computationele zonne-enveloppen en het identificeren van hiaten in de kennis en toekomstige richtingen van het onderzoek. Aanbevelingen uit de reviewstudie werden opgevolgd met een voorlopige simulatie van zonne-enveloppen op basis van geometrische eigenschappen van ALS (Aerial Laser Scanning) puntenwolkgegevens (hoofdstuk 3). Het doel van deze voorlopige simulatie is niet alleen om de haalbaarheid te testen van het integreren van puntenwolken in de simulatie van de zonne-envelop, maar ook om kritische feedback te krijgen over relevante en potentiële attribuut-puntenwolkeninformatie. Door bijvoorbeeld radiometrische informatie van de TLS-dataset (Terrestrial Laser Scanning) te onderzoeken, kan men materiaaleigenschappen (d.w.z. thermisch en optisch) berekenen en een analyse van de instraling uitvoeren op het oppervlak van de contextuele dataset (hoofdstuk 4).

Ten tweede richt het methodologische raamwerk zich op de ontwikkeling van computationele workflows voor de twee voorgestelde modellen, namelijk subtractieve zonne-enveloppen (SOLEN) (hoofdstuk 5-deel A) en subtractieve-schaduw-enveloppen (SHADEN) (hoofdstuk 5-deel B). In dit opzicht beoogt het SOLEN-model zonneschermen te genereren op basis van een specifieke hoeveelheid direct zonlicht uit de omringende context, terwijl het SOLEN-model is ontwikkeld om een geschikte bouwmassa te genereren op basis van de prestatiecriteria voor zonwering. Hoewel deze modellen werden opgesteld op basis van de integratie van de milieuprestatiekenmerken van de puntenwolk en subtractieve ontwerpprincipes van zonne-enveloppen, gebruikten beide modellen deze functies op verschillende manieren in computationele workflows. In het SOLEN-model werden omgevingskenmerken gebruikt om het potentieel en de impact van de uiteindelijke geometrie van subtractieve zonne-enveloppen te beoordelen, terwijl het SHADEN-model het gebruikte om de uiteindelijke geometrie van subtractieve schaduw-enveloppen te genereren.

Het laatste deel is casestudy's, waarin het SOLEN- en SHADEN-model werden toegepast in verschillende contextuele en klimatologische omstandigheden. Het SOLEN-model werd toegepast in Delft, Nederland met behulp van een hypothetische casestudy en gematigde klimaatomgevingen, terwijl het SHADEN-model werd toegepast in Bandung, Indonesië, opgenomen met een architectenbureau dat gebruik maakte van tropische klimatologische omgevingen.

Als verkennend onderzoek had dit onderzoek tot doel de voorgestelde computationele methode in ontwerppraktijken aan te tonen door een interview te houden met ontwerpdeskundigen (d.w.z. architecten, ontwikkelaar, lokale overheid) (hoofdstuk 6). Dit is niet alleen belangrijk om het haalbaarheids- en praktische aspect van de modellen die zijn ontwikkeld in het bestaande architectonische ontwerpschema te identificeren, maar ook om technische en conceptuele feedback te krijgen voor een uitgebreide implementatie voor toekomstige implementatie.
De interviews begonnen met een korte presentatie van de onderzoeker over de achtergrond van het onderzoek, en vervolgden met een boekje met procedurele stappen voor computationele workflows. Als resultaat van dit interview vereisen drie hoofdaspecten, zoals computeromgevingen, projectkosten en lokale voorschriften, verdere aandacht voor architectonische ontwerppraktijken bij de implementatie van ontwerpmethoden.

Samenvattend, het onderzoek ontwikkelde een geïntegreerde rekenmethode voor het vaststellen van zonnegeometrie op basis van attribuutinformatie opgeslagen in puntenwolkgegevens en zon- en schaduwomhullingen. De methode die in dit proefschrift wordt gepresenteerd, helpt architecten niet alleen om de bestaande context volledig te begrijpen voordat ze met de ontwerpverkenning beginnen, maar ook om betere ontwerpbeslissingen te ondersteunen tijdens de conceptuele ontwerpfase. Daarnaast moedigt dit proefschrift ook een collaboratieve en interdisciplinaire benadering aan tussen het onderzoeksveld van teledetectie en architectonisch ontwerp. Wat verdere overwegingen betreft, erkent dit proefschrift enkele kritische aspecten, zoals de vereiste van een vereiste kennis voor de verwerking van de dataset, met name voor het organiseren en selecteren van relevante informatie uit grote datasets, de kosten van betaalbaarheid van tools die momenteel nog steeds duur zijn voor kleine architectenbureaus. , en verbeteringen aan computationele workflows om factoren aan te pakken zoals correctieparameters voor datasets, simulaties van dichte datasets en ontwerpimplementatie met behulp van een verscheidenheid aan stedelijke omgevingen.



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1 Introduction

1.1 General Background

The United Nations (UN) Population Division predicts a significant increase in world population growth of around 3.2 billion from 2019 to 2100 [1]. This trend simultaneously underlines the rapid urban growth which presents many challenges and opportunities in the future. One of them is the implementation of an urban development agenda which must meet the criteria of 11 Sustainable Development Goal (SDG) programs, namely, to make cities inclusive, safe, resilient and sustainable [2]. The integration between renewable energy and passive design strategies plays a crucial part for the development of future urban planning, not only to reduce the increase of annual energy consumption of the building sectors [3] but also to improve the quality of the built environment.

In order to maintain a reciprocal relationship between a new building and the local context, architects are responsible for ensuring that environmental performance aspects have been prioritized during the design process. It is an essential task during the conceptual design stage, where the most significant design decisions are taken [4]. Therefore, architects are expected to be able to avoid potential failures before new construction is carried out, especially related to the unexpected microclimatic impacts caused by a building and imposed on the surrounding context (and vice versa).

In the past, the concept of vernacular buildings played a crucial role when dealing with environmentally sustainable designs, especially those related to passive solar designs. They have effectively granted massive reductions in the unsustainable use of energy resources by considering relevant aspects such as building orientation, location, geometry, and material choices. To date, continuous improvements to passive solar design principles have attracted increasing attention, such as solar-form finding [5] [6], solar energy simulation for building facades [7] [8], and solar potential for the urban areas [9] [10]. However, these existing studies predominantly focus on context-oriented buildings and energy quantities that unfortunately lack a contextual analysis. In most cases, this issue occurs in architectural design practice due to some practical constraints such as project deadlines, computational skills, limited budgets, and outdated regulations [20].

On the other hand, one concept in architectural design practice that specifically considers solar performance aspects in a local context is related to solar envelopes. Initially introduced by Knowles [11], solar envelopes conceptually provide relevance in addressing solar accessibility between new buildings and existing contexts. It specifically results in a maximum volumetric shape or building massing that guarantees direct solar access to the surrounding buildings for a predefined period [12]. In other words, it is a solar access protection approach that accommodates the development potential of urban forms based on solar irradiation needs.

The basic concept of solar envelopes has significantly encouraged architects to explore a variety of envelope generation methods. Over the last few decades, several developments in computational solar envelopes have been explored, resulting in various advanced workflows, design parameters, digital tools, and a broad range of case studies [13]. These developments allow architects to understand specific computational methods and parameters that are relevant and applied to different contextual urban settings. Nevertheless, existing methods predominantly do not support an understanding of the site characteristics of an existing environment, especially in relation to the geometric properties of surrounding contexts (i.e., vegetation, surface properties, and materials) [14] [15]. The absence of these properties can lead to enormous discrepancies found during an environmental performance analysis such as misinterpretation of simulation results and so forth.

Thanks to major advances in technological developments, computational solar envelopes can now be implemented in various urban settings. In that respect, climate consideration becomes one of the pivotal aspects to pay attention to given that most of the existing methods merely focus on the temperate zone in countries found in the Southern and Northern Hemisphere which have different climatic conditions during the four-seasons. Therefore, when it comes to tropical countries or those located on the Equator such as Indonesia, the suitability of this context becomes less appropriate because the design objectives and parameters are different and require particular adjustments to the local climate [16]. For example, since buildings in Indonesia are typically designed to block direct sun access due to hot daytime temperatures, the goal of solar envelopes in guaranteeing sun access ultimately becomes less applicable.

Furthermore, with the advancement of 3D laser scanning technology in capturing complex information from real contexts, potential features stored in the point cloud such as geometric and radiometric information may include making information relevant to the aforementioned issues available. As a basis for creating an informed design context, the attribute information of point cloud (i.e., position – XYZ, color – RGB, and reflection intensity – I) enables architects not only to deliver a rapid and realistic contextual modeling but also to conduct environmental performance assessments that support the simulation of solar envelopes both as a performance evaluator and form generator.

Following up on relevant aspects from the potential application of point cloud data and further consideration of current solar envelopes methods, this research specifically explores an integrated computational design method for solar geometry based on attribute information stored in point cloud data. Similarly to Szokolay [17], Bruce [18], and Alread and Leslie [19], the term solar geometry in this research not only covers geometric relationships from thermal aspects but also includes a comprehensive discussion of the desired lighting conditions. Accordingly, this term will regularly be used to describe the concept of solar and shading envelopes as the main models of the research.

Ultimately, this research should be of interest to practitioners (e.g., architects, urban planners, building engineers), decision makers (e.g., local municipalities), and academics in the areas of architectural engineering, design simulation, energy sustainability, and remote sensing.

1.2 Problem Statement

As part of the passive design strategy, the development of computational solar envelopes plays a major role not only to improve the quality of the built environment but also to construct a cooperative performance exchange between new buildings and their local contexts. However, a state-of-the-art computational method of solar envelopes poses a great challenge in understanding site characteristics from the given context. Existing methods predominantly construct 3D context models based on basic architectural geometric shapes (i.e., solid modelling platforms [21]), which are currently isolated from the surrounding properties of local contexts (i.e., vegetation, temporal site elements [14] [15], materials [22]). In addition, computational methods of solar envelopes are currently a tedious and time-consuming task especially in covering the detailed site properties of complex projects located in isolated and congested areas. It is clear that this condition may result in a fragmented understanding of the local context during the design and simulation process.

With the potential application of attribute information of point cloud data, it is necessary to consider relevant parameters such as the surface and material properties of existing contexts during the simulation of solar geometries, which are currently absent in computational frameworks, especially to address the aforementioned issues in the conceptual design stage. As such, the new method is required to enable architects not only to measure specific performances of the local context but also to identify vulnerable areas that may affect the proposed design.

1.3 Research questions, aims and objectives

1.3.1 Research questions

Considering the discussion in the previous section, this research addresses the following research questions:

How can we develop a computational design method of solar geometries as a decision-making support for architects based on solar and shading envelopes and attribute point cloud information?

In order to answer this overarching question, the research investigates further five sub-questions in association with its objectives, which are addressed in different chapters of this thesis:

1. What is a state-of-the-art review of computational design methods for establishing solar envelopes? *(Chapter 2) – A comprehensive review of computational solar envelopes.*

2 How do geometric properties of point cloud data contribute to the simulation of solar envelopes? *(Chapter 3) – Preliminary simulation of solar envelopes based on geometric properties of the point cloud.*

3 What are potential features that can be developed further from attribute information of point cloud data? *(Chapter 4) – Exploring the potential applications of geometric and radiometric information stored in point cloud data.*

4 How can new computational models for constructing solar geometry in temperate and tropical urban contexts integrate attribute information stored in point cloud data (i.e., position-XYZ, color-RGB, and reflection intensity-I)? *(Chapter 5) – Computational models for constructing solar geometry based on attribute point cloud information.*

1.3.2 Aim

The aim of the research is to develop an integrated computational method to analyze and design solar geometry in the built environment during the conceptual design stage. The ultimate goal is to allow architects to make informed-design decisions towards high-performance building massing based on solar and shading performance criteria, as well as geometric and radiometric information from point cloud data.

1.3.3 Objectives

In association with the aforementioned aim, the research has formulated the following objectives:

1 To investigate a state-of-the-art review of solar envelopes in order to identify variations in computational methods, tools, and design applications.
2 To conduct a preliminary study that focuses on the use of point cloud geometric properties in the existing solar envelopes method.
3 To investigate the potential application of attribute information stored in point cloud data through material properties and solar radiation analysis of the existing context.
4 To develop and demonstrate a computational model for subtractive solar envelopes and subtractive shading envelopes based on geometric and radiometric information of point cloud data, considering the temperate and tropical climate, respectively.

1.4 Research output

As a final result, this research produces an integrated computational method for establishing solar geometries based on attribute information stored in point cloud data. This method consists of subtractive solar envelopes and subtractive shading envelopes that refer to the SOLEN and SHADEN model, respectively. Each model contains a series of computational workflows that are developed to generate geometric envelopes based on its design objectives, contextual settings, and climatic parameters. The SOLEN model aims to produce solar envelopes based on the specific amount of direct sunlight obtained from ray tracing analysis between the 3D polyhedra of the new building and the existing site's point cloud dataset. In this regard, radiometric point cloud information is used to conduct insolation analysis and to detect material behavior of the existing environment as part of the environmental performance assessment of the solar envelope's final geometry. The SOLEN model is particularly applied to temperate climates with selected case study in Delft, the Netherlands. Meanwhile, the SHADEN model is developed to generate the appropriate mass based on shading performance criteria obtained from the results of ray tracing analysis between the 3D polyhedra of the new building and the point cloud dataset from the existing site. In this part, radiometric point cloud information is used to investigate material properties and sun visibility of the given context as part of form generation process for establishing the final geometry of shading envelopes. This model is specifically applied to tropical climates with a case study in Bandung, Indonesia.

1.5 Research method

In order to answer the research questions and to address the main aims and objectives of the thesis, the research follows a mixed-methods study using both deductive and inductive reasoning with qualitative and quantitative analysis, depending on the action taken in each section. In particular, the research structure is formulated into three main parts (see Figure 1.1).

The first part contains theoretical frameworks (i.e., design parameters of solar envelopes, attribute information stored in point cloud data) incorporated with preliminary simulations of solar envelopes based on geometric properties of point cloud data. This part also simultaneously supplies the fundamental concept and relevant elements for the following sections. The second part deals with the methodological framework to develop the computational design workflow of proposed models (i.e., SOLEN, SHADEN). The third part focuses on design implementation, in which case studies are applied to each proposed model. Although the computational workflows presented for chapter 5–Part B were predominantly developed from chapter 5-Part A, the sequence of these parts does not need to be linear. This is because some tasks have the same input and output which can be performed in parallel in later steps. For example, the computational design workflows for both chapters 5–Part A and 5–Part B received similar input regarding material properties and design parameters from chapter 3 and 4. Nevertheless, the simulation process and the final output remain different due to the different design workflows and case studies.

Furthermore, the aforementioned parts contain different tasks that correspond to each research question, as follows:

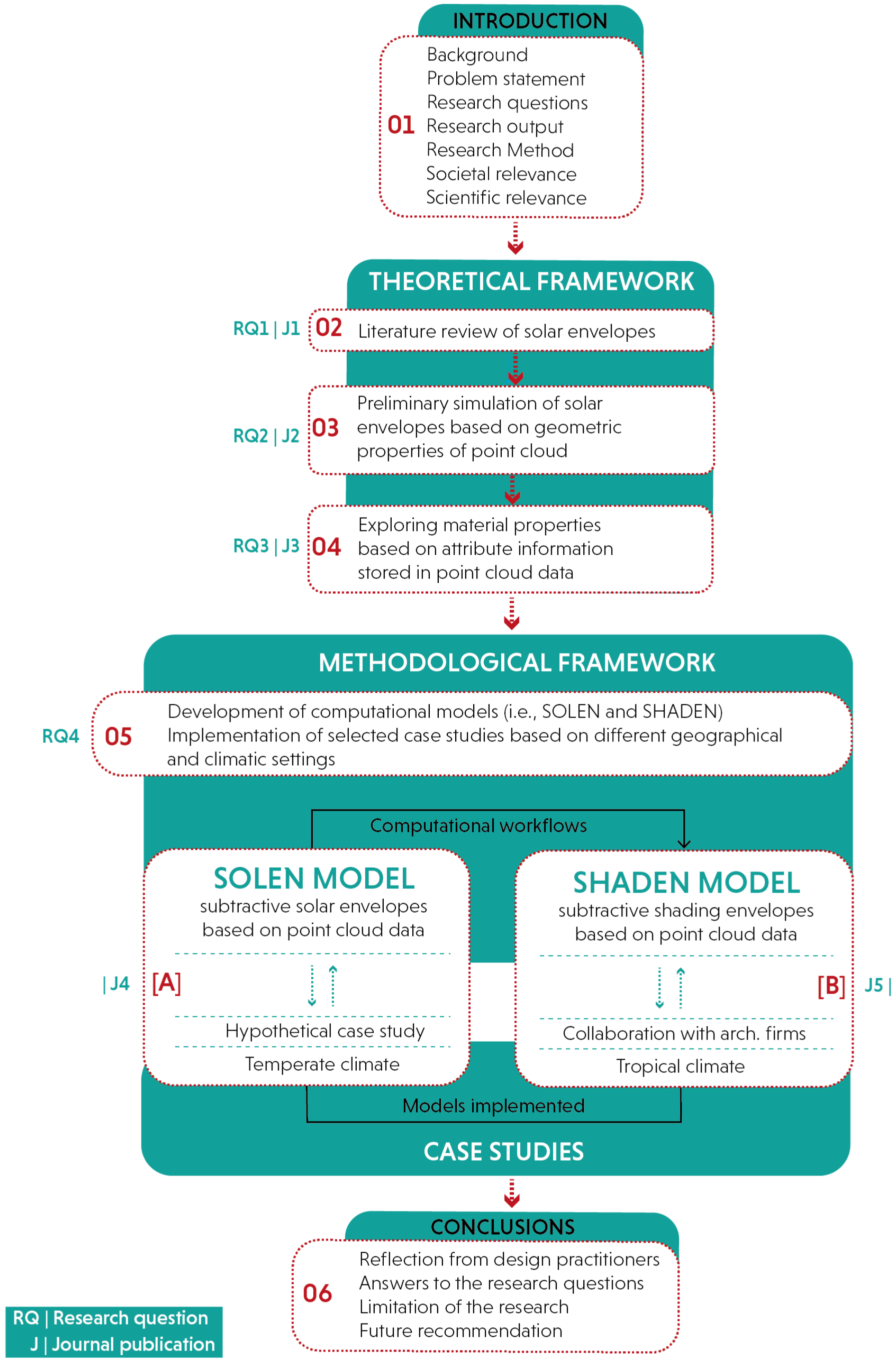

FIG. 1.1 Overview of research structure and methods

Part 1 – Theoretical framework

The first part specifically constructs a theoretical framework for the two main aspects of the research, namely solar envelopes and point cloud data. This framework is generated by first conducting a systematic review of computational solar envelopes based on design methods, parameters, digital tools, and case studies. It aims to map state-of-the-art methods for solar envelopes and identify knowledge gaps from existing studies. Recommendations from the review studies were followed up with a preliminary simulation to test the feasibility and relevance of point cloud data addressing with the current simulation of solar envelopes. This simulation allows for gaining critical feedback that is used to define *firstly*, further potential application of attribute information of point cloud data (i.e., radiometric information) by exploring the material properties of existing contexts and *secondly*, the design parameters for the subtractive method of solar envelopes.

This part has been published as follows:

- [13] M. F. Alkadri, F. De Luca and M. Turrin and S. Sariyildiz, “Understanding Computational Methods for Solar Envelopes Based on Design Parameters, Tools, and Case Studies: A Review,” *Energies,* vol. 13, no. 13, pp. 3302-3326, 2020.
- [23] M. F. Alkadri, M. Turrin and S. Sariyildiz, “The use and potential applications of point clouds in simulation of solar radiation for solar access in urban contexts,” *Advances in Computational Design,* vol. 3, no. 4, pp. 319-338, 2018.
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- [26] M. F. Alkadri, M. Turrin and S. Sariyildiz, “A computational workflow to analyse material properties and solar radiation of existing contexts from attribute information of point cloud data,” *Building and Environment,* vol. 155, no. -, pp. 268-282, 2019.

Part 2 – Methodological framework

The second part focuses on developing computational design method for the two proposed models, namely subtractive-solar envelopes (SOLEN) and subtractive-shading envelopes (SHADEN). Although these models address a similar workflow for calculating the material properties of existing contexts, the SHADEN model was principally established based on the further development of the SOLEN model. In particular, the SOLEN model was developed considering material properties as evaluation criteria for the resulting envelope, while the SHADEN model employed material properties as part of the generation criteria to establish the final envelope.

Part 3 – Case studies

The third part discusses the design implementation of SOLEN and SHADEN model. These models were implemented in selected case studies with different contextual and climatic settings. The SOLEN model was applied in Delft, The Netherlands using a hypothetical case study and a temperate climate setting while the SHADEN model was applied in Bandung, Indonesia, incorporated with an architectural firm using a tropical climatic setting. In parallel, reviews with design practitioners (i.e., architects) were conducted to gain feedback on the relevance of implementing the proposed models in their design workflows.

This part has been published as follows:

- [27] M. F. Alkadri, F. De Luca, M. Turrin and S. Sariyildiz, “Making use of point cloud for generating subtractive solar envelopes,” in *eCAADe SIGraDi 2019: Architecture in the Age of the 4th Industrial Revolution*, Porto, 2019.
- [28] M. F. Alkadri, F. De Luca, M. Turrin and S. Sariyildiz, “An integrated approach to subtractive solar envelopes based on attribute information from point cloud data,” *Renewable and Sustainable Energy Reviews,* vol. 123, no. -, p. 109742, 2020.
- [29] M. F. Alkadri, F. De Luca, M. Turrin and S. Sariyildiz, “A Computational Workflow for Generating a Voxel-based Design Approach Based on Subtractive Shading Envelopes and Attribute Information of Point Cloud Data,” *Remote Sensing,* vol. 12, no. 16, p. 2561, 2020.

1.6 Research relevance

1.6.1 Scientific relevance

The research scientifically expands on knowledge about passive solar design, especially as related to the new computational method of solar geometries in the conceptual design stage of the architectural design process. A systematic review of computational solar envelopes contributes not only to highlighting current possibilities and gaps for design methods, digital tools, and simulation parameters but also to further advocate for the implementation of solar envelopes in different contextual and climatic settings.

Furthermore, the exploration of attribute information stored in point cloud data enables the expansion of functional properties available in 3D scanning technology. In particular, radiometric information of point cloud (e.g., position, color, reflection intensity) makes it possible to identify material properties of an existing environment that are simultaneously relevant for performing environmental analysis from a design context.

With the integrated computational workflow between point cloud data and subtractive solar envelopes in chapter 5-A and subtractive shading envelopes in chapter 5-B, the method proposed in this research has confirmed the feasibility and contribution of new potential applications of 3D scanning into the design process of architectural projects. In other words, the research presents a multidisciplinary approach between architectural design and engineering that enlarges the scopes of development of remote sensing, computational design, and renewable energy.

1.6.2 Societal relevance

The research proposes a computational method for a passive solar design strategy that supports architects in making design decisions during the conceptual design stage. This method plays a key role not only to conduct environmental performance assessments between new buildings and existing contexts but also to understand comprehensively microclimatic conditions from the design context. Therefore, architects can avert the potential for unforeseeable failures that might occur before placing a new building into a real context.

The method proposed in this research also introduces new potential areas of 3D scanning technology for architects in design practice. For this reason, the community and industrial markets for 3D scanners are gradually being adapted and relevant for day-to-day architectural practices in terms of availability and cost-effectiveness. Therefore, further development of this technology can be affordable for architectural firms of all scales in the long term.

Lastly, the research allows decision makers (e.g., local municipalities, national government) and practitioners (e.g., architects, urban planners, building engineers, sustainability experts) to reflect upon and evaluate current regulatory parameters, especially those related to shadow fences, solar radiation analysis for the building facades, and solar access criteria. It is important to provide holistic guidance for architects regarding sustainable and green building policies that are currently missing in the conceptual design stage, especially in Indonesia. Most often, environmental performance assessments are carried out after design decisions have been taken, thus neglecting many crucial parameters in the early phase of design.

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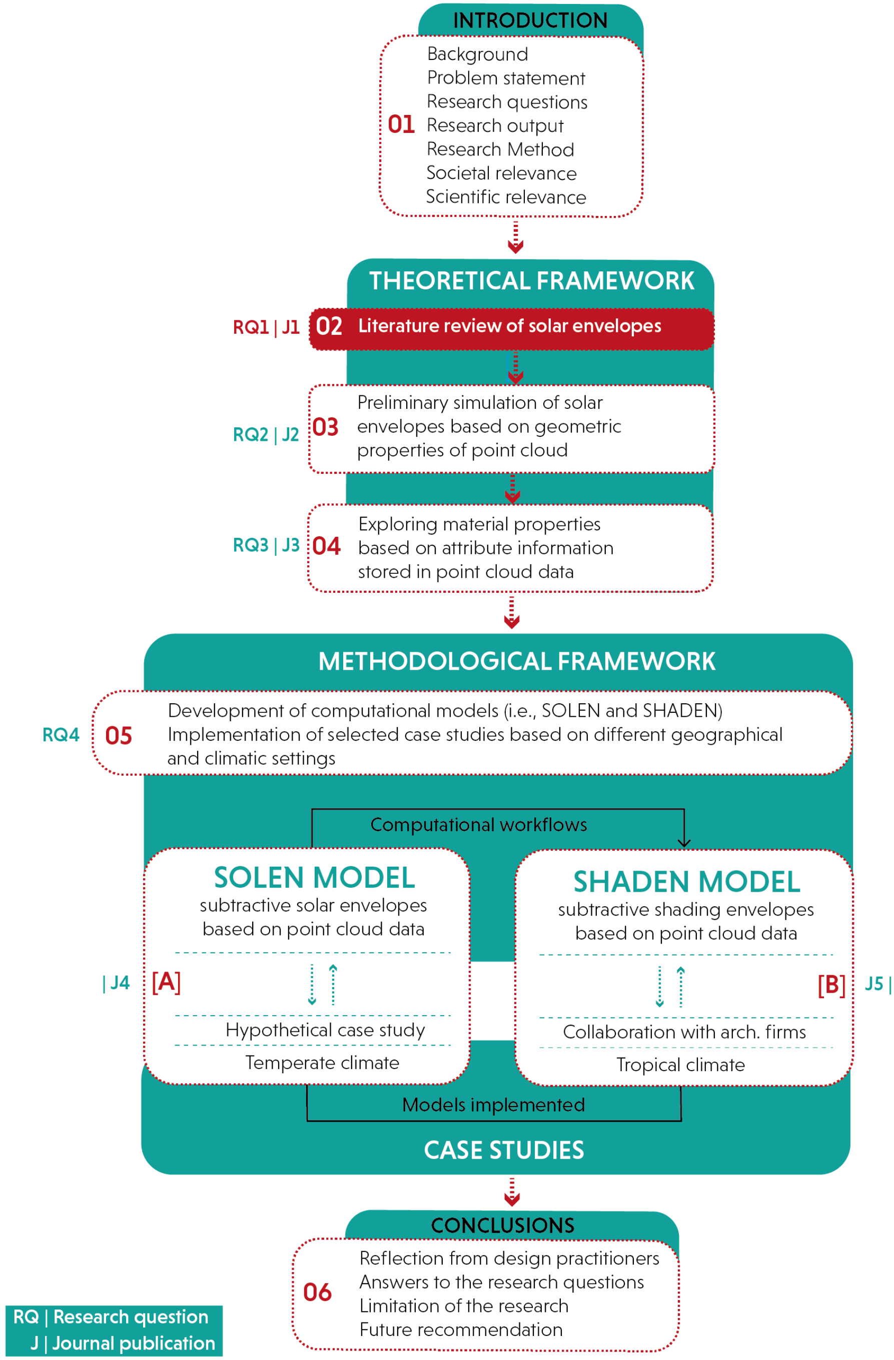
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J | Journal publication

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2 Review Of Computational Solar Envelopes

This chapter has been published as: Alkadri, M. F., De Luca, F., Turrin, M. and Sariyildiz, S., 2020. Understanding computational design methods of solar envelopes based on design parameters, tools, and case studies. *Energies*, 13(13), pp. 3302. The layout has been adjusted to fit the template of this thesis.

This chapter deals with a state-of-the-art review of computational solar envelope that specifically caters to the background study of the main topic in this research. In particular, a comprehensive investigation of the available knowledge of solar envelopes regarding computational methods, parameters, tools and design applications is presented. This review study aims to identify the different characteristics and levels of complexity for each categorized design method of solar envelopes based on 58 selected references. Under the three selected literature databases, namely, Web of Sciences, Scopus, and Google Scholar, specific topics are determined to stipulate the scope of reviews, which are conceptual themes (i.e., solar architecture, solar envelopes, and solar access), design workflow (i.e., computational design, solar design, and solar simulation), and contextual settings (i.e., urban planning, urban design, and architectural design). In addition, knowledge gaps and future developments of computational solar envelopes are discussed extensively to provide architects with an inclusive understanding of conceptual frameworks of solar envelopes as a passive design strategy. Ultimately, this literature review serves as a part of the theoretical foundation for the following section of the research presented. In particular, knowledge gaps and future directions of the study address potential features that will be considered for the development of new computational method of solar envelopes.

Understanding Computational Method of Solar Envelopes Based on Design Parameters, Tools, and Case Studies: A Review

ABSTRACT

The increasing population density in urban areas simultaneously impacts the trend of energy consumption in building sectors and UHI (urban heat island) effects of urban infrastructure. Accordingly, passive design strategies to create sustainable buildings play a major role in addressing these issues, while solar envelopes prove to be a relevant concept that specifically considers the environmental performance aspects of a proposed building given their local contexts. As significant advances have been made over the past decades regarding the development and implementation of computational solar envelopes, this study presents a comprehensive review of solar envelopes while specifically taking into account design parameters, digital tools, and the implementation of case studies in various contextual settings. This extensive review is conducted in several stages. First, an investigation of the scope and procedural steps of the review is conducted to frame the boundary of the topic to be analyzed within the conceptual framework of solar envelopes. Second, comparative analyses between categorized design methods in parallel with a database of design parameters are conducted, followed by an in-depth discussion of the criteria for the digital tools and case studies extracted from the selected references. Third, knowledge gaps are identified, and the future development of solar envelopes is discussed to complete the review. This study ultimately provides an inclusive understanding for designers and architects regarding the progressive methods of the development of solar envelopes during the conceptual design stage.

KEYWORDS

solar envelopes; passive design strategies; computational design methods

2.1 Introduction

By 2050, the UN (united nations) estimates that the world's population in urban areas will increase by approximately 68 % [1] with urban dwellers around 6.7 billion [2]. This trend is simultaneously followed by a continuous increase in energy consumption from the building sector, which will share 1.3 % of annual increment and reach 22 % in 2050 [3]. This means that a future urban planning requires sustainable strategies to deal with the energy use and building emissions [4]. Some strategies have been proposed to tackle these issues using the NDCs (nationally determined contributions) and UN SDG (sustainable development goal) programs. For example, many researchers have actively developed specific methods and tools to provide more practical guidance regarding sustainable buildings and construction technologies, such as the adoption of green building technologies [5] [6] and the enhancement of building energy efficiency [7] [8]. However, past surveys did not discuss the conceptual domain of passive design strategies but rather focused predominantly on the technical building operations such as, HVAC (heating, ventilation, and air conditioning) system [9] [10]. Consequently, a knowledge gap exists when addressing the environmental performances of building design especially at the conceptual design stage. In this case, this paper contributes by increasing the knowledge on passive design strategies. Specifically, it comprehensively reviews and examines computational methods, parameters, tools, and case studies related to solar envelopes.

This review is relevant in that it addresses a contextual design approach in which solar envelopes play a significant role in enhancing the quality of the built environment. Furthermore, this review integrates the environmental performance of a new building with the existing context and contributes to the most crucial design decisions made during the early design phase. In this respect, the concept of solar envelopes has made a relevant contribution by addressing the solar accessibility of new buildings and their existing contexts. By definition, solar envelopes are composed of the maximum volumetric container as determined by the amount of desirable or required sun access without considering the shadowing of adjacent buildings [6]. Accordingly, the envelope of proposed designs can be maximized without compromising the solar rights of surrounding buildings during the critical period. During the conceptual design process, this concept is useful for architects, as they seek to avert potential failures once a new building has been constructed, especially with respect to negative microclimatic impacts. In design practices, this approach has successfully been implemented by the Dutch architectural and urban design firm MVRDV through the project of P15 Ravel Plot, which is located in the Zuidas district, 1082 LC, Amsterdam [11] and the Grotius Tower II, which is

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located in the area of the Prince Bernard Viaduct, Den Haag [12]. These projects have similarly addressed the idea of solar-oriented design by integrating the optimal sightline for each housing unit with the terraces and greenery landscape. In so doing, proposed buildings have successfully presented high performing envelopes that fulfil both geometric and environmental performance quality.

Since the inception of the solar envelope, several methods for its determination have been developed. For example, Topaloglu [13] describes three simple techniques for establishing solar envelope, namely, the descriptive, profile angle, and 2D orthographic projection techniques. The descriptive technique adopts the initial solar envelopes concept introduced by Knowles [14]. As such, it intersects the vertical planes plotted on the selected site by using the trigonometric principles of the solar azimuth, altitude (α) and, cut-off times (i.e., daily and annual time limits). For example, given a full day setting, the morning sun governs the envelope's boundary of its western limits, while the afternoon sun establishes the envelope's shape of its eastern limits. This same mechanism applies to the annual time setting by calculating the sun's position during the winter and summer months. The profile angle technique consists of an intersection between inclined planes that are generated on each edge of the plot according to minimum solar angles as determined by a different orientation. In general, the profile angle is also employed to determine the geometric positions of the shading devices, the penetration of the sun's rays into a room, and the shading line on the building's facades. The orthographic projection technique employs a mechanism similar to that of the profile angle techniques but only applies to rectangular sites with two elevation planes within a two-dimensional projection. While these methods are valuable and convenient, further consideration of several aspects is required including the simulation time, range of input parameters, and accuracy of the 3D visualization, especially with respect to complex architectural forms [15]. In contrast to the above, this review investigates computational methods that offer several effective ways to address these challenges. Hence, ultimately, this study advances the work on the sustainable design approach by providing an overview on the current state of the computational environment of solar envelopes and exposing critical gaps for future consideration.

Having introduced the relevance and basic principles of solar envelopes, this paper is organized as follows. Section 2 describes the scope and procedure of the review, and Section 3 presents the results of the review and discusses the computational design methods for solar envelopes and related design parameters are presented. For each design method described in Section 3, Section 4 focuses on the aspects of the computational environment in parallel with the digital tools and the implementation of the case studies. Section 5 then addresses the knowledge gaps and new directions for future research on solar envelopes, and Section 6 presents the conclusions.

2.2 Scope and Method of the Review

This review addresses the main question that frames the survey of existing computational solar envelopes, i.e., What are the performance criteria and related computational methods for generating solar envelopes? This question simultaneously leads us to explore specific tasks and features of various design parameters, tools, and the implementation of case studies found in each design method of solar envelopes. The ultimate goals are to identify and understand the most basic and advanced parameters and computational methods for constructing solar envelopes and to analyze relevant factors that affect the complexity and flexibility of solar envelope methods from the perspective of the user. Explicit awareness of these issues is crucial for the comprehensive understanding of the current use of solar envelopes and to address the design needs and method gaps with respect to solar envelopes.

The articles for review are accessed through three selected literature databases, namely, *Web of Science (WoS), Scopus,* and *Google Scholar (GS).* Although there are many database searching that can be used for a literature review, this study focuses on employing Scopus, WoS, and GS because they are part of wide citation and bibliographic searching platform that have been designed to support scientific and research environment globally. To be more specific, Scopus and WoS similarly present substantial factual information that includes a number of peer-reviewed literature and article indexed through Elsevier and ISI citation database, respectively. On the other hand, GS has also been extensively utilized for a large interdisciplinary field coverage with a wide unique type of materials (i.e., PDF files, word docs, and technical reports), including indexed and non-indexed articles, especially for Master and PhD thesis that contains relevant information for the topic of solar envelopes [16] [17]. Accordingly, it can complement other databases such as Scopus and WoS that are predominantly based on indexed publication.

Furthermore, a new direction for the further development of solar envelopes is identified as a result of this review, which considers three main topics and sub-topics, namely, conceptual themes (i.e., solar architecture, solar envelopes, and solar access), design workflow (i.e., computational design, solar design, and solar simulation), and contextual settings (urban planning, urban design, and architectural design). The scientific findings of the reference databases are narrowed by setting the timespan to range between 1960 and 2019, given that the term "solar envelopes" was initially introduced in the scientific literature by Knowles around 1970 [18] although some authors, such as Giacomo [19], Galton [20], and

Atkinson [21] implicitly discussed related topics regarding solar access prior to Knowles' work. The detailed parameters used for reference databases are shown in Table A.1 in Appendix 2A.

Given that the resulting search remains extremely broad, the screening process is then weighted on references that only investigate the concept of solar envelopes within the domain of passive design strategy. To do so, some irrelevant references resulting from a discrepancy in research objectives are eliminated. For example, studies related to solar-form finding that focuses only on a generative architectural form [22] [23] [24], solar performance simulation that merely addresses the quantification of solar energy for existing building facades, 2D plans and new development areas [25] [26] [27], and studies related to solar radiation analysis that examine solar potential for the urban contexts [28] [29]. These references are consequently not further included in the main discussion of the review. In addition, this study identifies one previous review of solar envelope properties authored by Stasinopoulos [30]. However, this recent study focuses on the construction of solar envelopes based on solid modeling techniques [31], an area that can benefit from further consideration in our review that systematically addresses (1) a comprehensive study of computational solar envelopes based on various methods, tools, and contextual settings of various case studies, (2) an in-depth investigation of design parameters that correspond to different computational methods and the identification of relevant parameters for each method, and (3) several criteria that enable the further analysis of current gaps and future directions of the study. Therefore, the present review can be a very useful companion to the researchers involved in studying new methods and computational tools for generating solar envelopes. Due to the presented potentialities of solar envelopes, the expected impact of this review at large, is that to help in developing new design tools to increase sustainability, resource efficiency, and livability of our buildings and cities.

After having selected the relevant references that meet the screening criteria, this study proposes a conceptual framework for the review as presented in Figure 2.1.

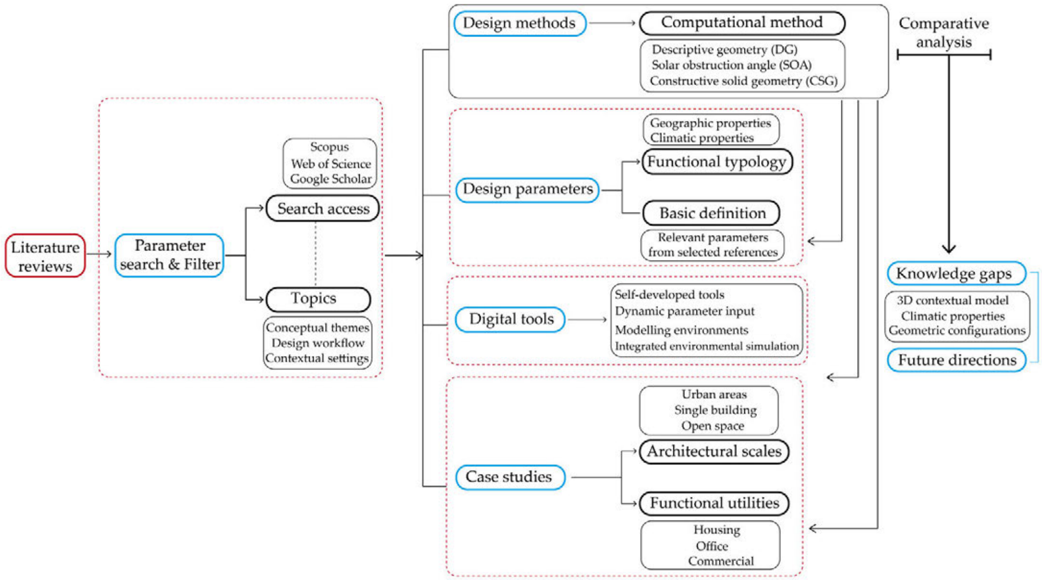

FIG. 2.1 General framework of the review

2.3 Review findings: Computational methods and parameters of solar envelopes

This section presents the results of the review by investigating the computational methods and the parameters for solar envelopes obtained from the 58 selected references. The computational methods based on design procedures when establishing solar envelopes are first categorized. This is followed by extracting and mapping the parameters from the selected references into the database and then, drawing a comparative analysis among the methods and parameters based on their frequency of use. These actions facilitate the identification of additional characteristics of the parameters and the performance aspects of each design method.

2.3.1 Design methods

By examining the basic computational procedures of each collected reference, this study identifies three methods of computational solar envelopes, namely, descriptive geometry (DG), solar obstruction angle (SOA), and constructive solid geometry (CSG).

Descriptive geometry (DG)

As a derivative approach from the descriptive mechanism, the DG method employs basic parameters such as latitude, a closed boundary of selected site, sun vectors, cut-off-times, and obstruction geometry of surrounding buildings, to generate solar envelopes. However, the use of these parameters is highly dependent on the type and objective of the projects. When simulating, for example, no-obstruction solar envelopes, such as parks and open spaces, the relevant parameters only require a closed curve of the site, the latitude and/or sun vectors, and the maximum height of the intended envelope given that the aim is to maximize solar access of the proposed envelope within a specific period. Moreover, solar envelopes that incorporate the surrounding context must consider the geometric obstacles from the existing context. This is pertinent when developing solar rights and solar collection, as the proposed envelopes cannot violate the solar access of neighboring buildings (solar rights) and the surrounding buildings cannot obstruct the sun access of the proposed envelopes (solar collection) [32].

Solar obstruction angle (SOA)

The SOA method simulates the projection of the minimum profile angle on each side of the plot through shadow lines and shadow angles. In this approach, the reference lines refer to the horizontal property lines of the North and the vertical axis, i.e., where the existing building stands in relation to the Cartesian space [33]. Due to daylight and the different orientation on each side of the plot, the resulting geometry of the SOA varies. Higher settings regarding the angle of solar obstruction produce shorter periods of shading and minimum shading conditions. Therefore, each side of the plot should be treated differently because of the shading conditions unique to each side. For example, it is important to minimize solar obstruction in designated areas within a range of $\pm 30°$ for southern facades due to passive solar gains while taking into account latitude position in the UK [24].

Constructive solid geometry (CSG)

The CSG method refers to a solid modeling approach [31] based on the Boolean operations of subtraction and intersection between the 3D plot and the initial shapes of new buildings. These initial shapes are usually generated from two settings of solar vectors. For example, the first solar vector, which may correspond to a solar access constraint or sun position is calculated by using latitude, longitude, and cut-off times. Furthermore, the second solar vector refers to the vectors that are generated from the sun path diagram [34]. In principle, these settings can be used in either a full [35] [36] [37] or a partial way [38] [39] during the construction of solar envelopes depending on the design concept and the complexity of the surrounding contexts. The CSG method can also be complemented with a solar fan to adjust the height and width of the floors of surrounding buildings.

In general, these computational methods have successfully addressed various advanced simulation techniques for establishing solar envelopes. However, these same methods also create dissimilar computational behaviors during the construction of solar envelopes. For example, among the three methods, CSG exhibits the highest rate of generating an unpredictable model in terms of the final configuration of geometric solar envelopes. This is because the CSG method primarily involves the volumetric intersection between different shapes, which means that the probability of yielding unstructured envelopes is also moderately high. Furthermore, but consistent with this, the geometric configuration of CSG requires a high computational performance, especially with respect to the mesh modeling of the contoured plot in larger urban scales. In contrast to the CSG method, however, the DG and SOA methods establish solar envelopes based on the plane intersections that are generated from shadow fences or the obstacle curves of surrounding buildings. Accordingly, solar envelopes that are constructed based on DG and SOA are not generally computationally intensive.

To better understand the characteristics of each computational method when considering the design practices, it is also important to examine the specific elements relevant during the simulation process, such as the basic and advanced parameters of each method, the interrelations between design parameters, and the contextual settings of each method of each specific project. The following section will discuss these aspects based on the collected references.

2.3.2 Design parameters

Design parameters include various aspects that determine the geometric and spatial properties of solar envelopes during the simulation process. Hence, this section focuses primarily on identifying each type of parameter included in the selected references. According to its functional typologies on space-time constraints [14], this study further subdivides the parameters into geographic and climatic properties. **Geographic properties** includes a series of elements that constitute a spatial relationship between a selected plot and the surrounding environment whereas **climatic properties** refer to the non-geometric characteristics that are primarily considered when establishing the time for the construction of the geometric model of the solar envelopes. In total, this study identifies 18 parameters from the collected references; among these parameters, 11 are regarded as geographic properties (i.e., longitude, latitude, orientation, courtyard, surrounding facades, sidewalk, surrounding building's height, FAR (floor area ratio), setback, shadow fences, and street), and seven are regarded as climatic properties (i.e., profile angle, cut-off times, dry bulb temperature, sun path, solar azimuth, solar altitude, and sun access duration). Similar to space and time, these properties also involve an inverse construction mechanism when assessing the volumetric size of solar envelopes. For example, the greater the time interval (cut-off-time) of the solar envelopes, the less the space that is produced inside the envelope. Similarly, the more sun access duration there are, the less the volume of the constructed solar envelope. Regarding the site orientation, the long sides of building with an in EW (east-west) orientation are larger and have higher ridges in the geometric envelopes than the long-sided areas with a NS (north-south) orientation. In contrast, the widths of streets and courtyards on the EW (east-west) sides generate the minimum height for solar envelopes [39].

To draw an in-depth analysis among parameters and methods of solar envelopes, it is necessary to examine the distribution level of each parameter for each corresponding method with respect to quantity and priority.

2.3.3 Comparative analysis of design parameters in relation to design methods

This comprehensive analysis between the design parameters and computational methods of solar envelopes consists of three major tasks. First, each parameter and its corresponding references based on computational methods must be plotted (see Figure 2.2) to provide an overview of the distribution pattern regarding the method and the total number of references of each parameter. Second, the usage frequency

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between parameters and their corresponding methods must be plotted (see Figure 2.3). This facilitates the categorization of the parameters into three different groups, namely, high, medium, and low, according to their usage level during the construction of the solar envelopes. Third, the total number of parameters, i.e., geographic and climatic properties, registered for each computational methods are calculated based on the predefined categories discussed (see Figure 2.4). This allows us to identify the most basic and the most advanced parameters as well as the methods used to establish solar envelopes.

To perform these three tasks, Table 2.1 provides the necessary preliminary information regarding the distribution of design parameters and corresponding methods based on the selected references.

Table 1 displays a list of the selected references on computational solar envelopes that are plotted based on their design methods. Each of these references is then further investigated by marking its contextual settings and parameters through a binary operation. For example, the “True” condition is indicated with a bullet point, whereas the “False” condition remains empty. The results illustrate that some references nearly fulfill all of the listed parameters (e.g., [39] [67] [68]), while others require only six parameters ([30] [34] [71] [72]) to construct solar envelopes. This is because each reference is affected not only by the type of applied computational method but also by the design concept of the projects that often involve more parameters. With respect to the contextual settings, the plot condition for solar envelopes is divided into the inclusion and exclusion conditions of surrounding site properties (e.g., vegetation, adjacent buildings, open spaces, and other relevant elements). Accordingly, the solar envelope simulations that include site properties create spatial negotiations between the proposed building and the existing context, while the exclusion condition focuses on the given land parcel, and hence, the context implementations primarily correspond to new development areas. In general, all categorized methods contain both inclusion and exclusion conditions during the construction of solar envelopes. As the most-used method, DG considers site properties more often than SOA and CSG. However, the DG method cannot guarantee the number of involved parameters during the simulation because the input parameters of solar envelopes rely on design concept and project complexity. For example, Camporeale [58] and Saleh and Al-Hagla [55] employ more variations of design parameters than with Machacova et al. [44] and Martin and Keeffe [45], who take into account the surrounding site properties.

Having established the preliminary database regarding design parameters and solar envelope methods presented in Table 1, a comparative analysis of the two can now be performed.

TABLE 2.1 Database of design parameters and computational method of solar envelopes based on the selected references

Literature	Context*	Input Parameters																	
		Geographic properties											Climatic properties						
		Longitude	Latitude	Orientation	Court yard	Surrounding facade	Sidewalk	SBH**	FAR	Setback	Shadow fences	Street	Profile angle	Cut-off-times	DBT***	Sun path	Solar azimuth	Solar altitude	Sun access duration
No.		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Descriptive Geometry (DG)																			
[40] [41] [42]	+	●	●	●		●	●	●	●			●		●			●	●	●
[43]	+	●	●	●		●		●					●	●	●	●	●	●	●
[44]	+		●			●	●	●			●	●		●			●	●	
[45] [46]	+		●	●		●		●			●			●			●	●	●
[47]	+	●	●	●			●		●	●			●	●		●	●	●	
[48]	+	●	●	●		●		●			●			●		●	●	●	●
[49]	+	●	●	●		●		●			●			●		●	●	●	●
[50]	+	●	●	●		●		●						●			●	●	●
[51]	+	●	●	●		●		●						●			●	●	●
[52]	+	●	●	●		●	●					●		●			●	●	●
[53]	-		●	●					●		●			●			●	●	●
[54] [55]	-		●	●				●	●					●		●	●	●	●
[56]	-		●	●	●			●		●	●			●			●	●	●
[57] [58]	-		●	●				●	●	●		●		●			●	●	●
[59]	-		●	●							●	●		●			●	●	●
[60]	-		●	●					●					●			●	●	●
[61]	-	●	●	●				●	●		●	●	●	●		●	●	●	●
[62]	-	●	●	●							●			●		●	●	●	●
Solar Obstruction Angle (SOA)																			
[63]	+		●	●			●	●	●			●	●	●			●		●
[33]	-	●	●	●		●		●		●			●		●		●	●	●
[64] [65] [66]	-			●		●		●		●		●	●	●	●	●			●
[67] [68]	+	●	●	●		●	●	●	●	●	●		●	●	●	●	●	●	●
[69]	+		●	●		●		●					●	●	●	●			●
[70]	-	●	●	●				●	●		●		●	●			●	●	●
[71] [72]	+/-		●	●							●		●	●					●
[73] [74]	-					●		●	●	●	●		●	●		●	●	●	
[75] [76]	-					●	●	●	●	●	●		●	●	●	●	●	●	●

>>>

TABLE 2.1 Database of design parameters and computational method of solar envelopes based on the selected references

Literature	Context*	Input Parameters																	
		Geographic properties											Climatic properties						
		Longitude	Latitude	Orientation	Court yard	Surrounding facade	Sidewalk	SBH**	FAR	Setback	Shadow fences	Street	Profile angle	Cut-off-times	DBT***	Sun path	Solar azimuth	Solar altitude	Sun access duration
No.		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Constructive Solid Geometry (CSG)																			
[35] [77] [78]	+/-		•					•	•	•		•	•	•			•	•	•
[34] [30]	-		•										•	•			•	•	•
[36]	-		•	•				•		•	•		•	•			•	•	•
[39]	-		•	•	•	•	•	•		•	•	•	•	•		•	•	•	•
[37] [79]	-		•	•				•					•	•			•	•	
[38] [80]	+		•	•			•					•	•	•					•
[81]	+	•	•	•		•		•			•			•		•	•	•	•
[82]	+	•	•	•		•		•			•			•		•	•	•	•
[83]	+	•	•	•		•		•			•			•		•	•	•	•
[84] [85]	+	•	•	•		•		•			•	•	•	•			•	•	•
[86] [15]	+		•	•		•		•			•	•	•	•		•	•	•	•
[87]	-		•	•							•			•		•	•	•	•
[88]	+	•	•	•	•	•				•				•		•	•	•	•

* *Context = (+) include site properties, (-) exclude site properties; **S.B.H = Surrounding building's height; ***D.B.T = Dry Bulb Temperature*

Task 1 – Design parameters, methods, and total references

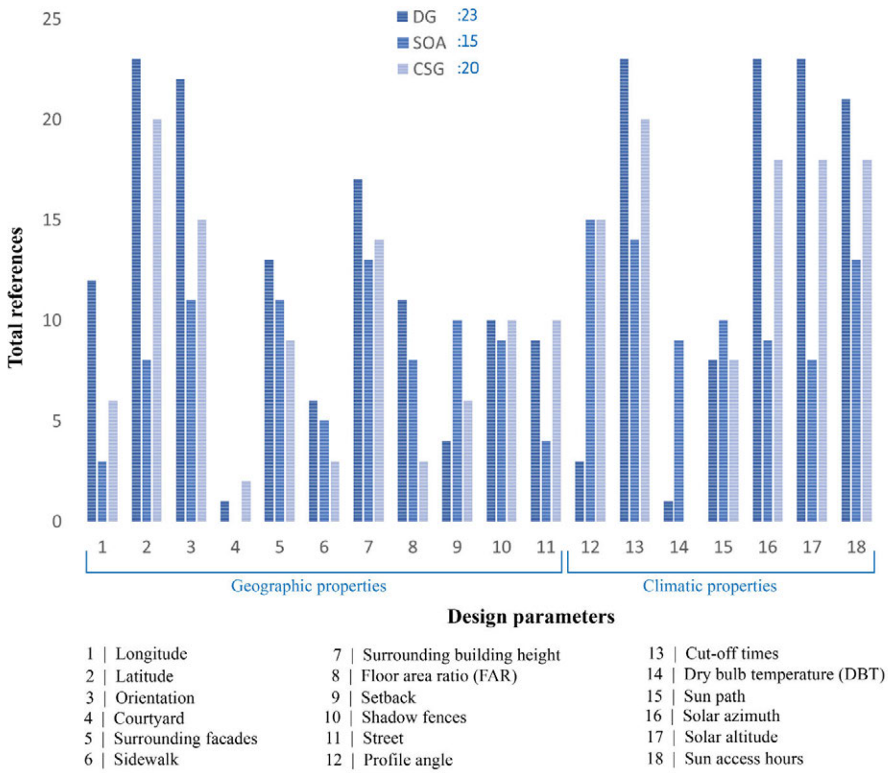

FIG. 2.2 Distribution of design parameters according to corresponding computational methods and selected references

Figure 2.2 illustrates the pattern of computational solar envelopes based on the registered parameters and the number of references for each method. In general, the trend indicates that, with respect to using the parameters of solar envelopes, DG is referenced in more studies that the other two methods. Specifically, DG is referenced in 23 studies, followed by CSG with 20 and SOA with 15. This provides an early indication that DG is the most-used technique for constructing solar envelopes. Additionally, DG includes four parameters, i.e., latitude, orientation, cut-off times, and solar altitudes, thus nearly satisfying all selected references, while SOA and CSG consist of one (profile angle) and two (latitude and cut-off times) parameters, respectively. Moreover, an interesting pattern is observed regarding parameters 4 (courtyard) and 14 (dry bulb temperature). Specifically, these parameters are similarly registered only in two methods for parameter 4, i.e., DG and CSG, and two methods for parameter 14, i.e., DG and SOA. Hence, it can be argued that courtyard and dry bulb temperature are rarely used parameters and are thus irrelevant properties for SOA and CSG, respectively. This condition also indicates the relevance of parameters that may only be employed in certain context during the construction of solar envelopes.

Task 2 – Usage frequency of parameters and corresponding methods

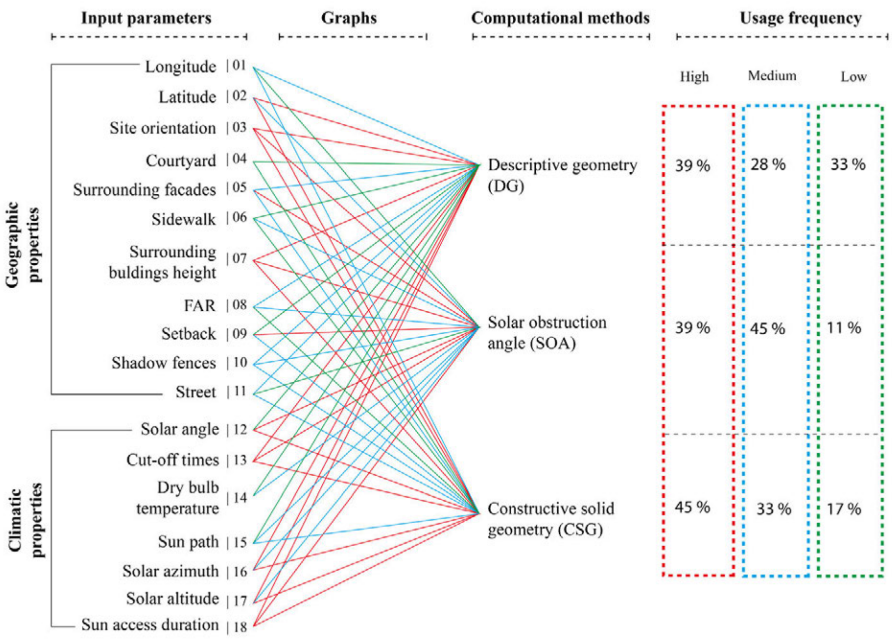

FIG. 2.3 Categorization of design parameters and corresponding methods based on usage frequency

After quantifying the total references for each parameter and corresponding method in Figure 2.2, the usage frequency of the parameters is divided by the total references for each method into three groups with each group comprising a certain range of references that indicate the usage frequency level of the parameters. Accordingly, the higher the number of references is for one parameter, the higher the frequency of that parameter's use during the construction of solar envelopes. For example, DG contains 23 references that correspond to 18 parameters. One parameter may consist of a different number of references depending on the type of parameters and how many studies that use that parameter. It is worth to note that some parameters may also look identical such as “solar angle” and “solar altitude”. In this regard, “solar angle” is not an independent parameter. It is retrieved based on the projection of solar altitude perpendicularly to the border of the plot. Thus, some references may not mention explicitly certain parameters they used. Furthermore, these 23 references are then divided into three range groups, whereby each group represents a different level of frequency; e.g., the high category consists of nine references, followed by the medium and low categories with eight and six references, respectively. To identify the category for each parameter, the specific ranges of total references for each category should be defined first. Specifically, the high category ranges from 15 to 23 references, while the medium and low categories range from 7 to 14 and from 1 to 6 references, respectively. Hence, a specific category for each parameter can be identified and similar approach can now be applied to other methods.

As illustrated in Figure 2.3, the general trend reveals a fluctuating pattern in the percentages for each category of each method. For example, the greatest percentages for each category are identified by different methods. For example, the high category is fulfilled by CSG with 45 %, whereas SOA and DG dominate the medium and low categories with 45% and 33%, respectively. These highest numbers simultaneously represent the priority usage of parameters when constructing solar envelopes, which means that the parameters listed within the high and medium categories serve as basic parameters for establishing solar envelopes. Moreover, the low category, due to its lowest usage values, especially for SOA and SCG is a list of the advanced and complementary parameters, and accordingly, only a few parameters can be used in this category such as longitude and street for SOA and courtyard, sidewalk, and FAR for CSG. An exception applies to DG because it contains more assigned parameters and references, i.e., nearly 18 % above the other values. Based on these data, it is concluded that DG is the most-used method, as evidenced by its wide range of options for complementary parameters. Moreover, the small discrepancies in the values between each category in DG results in greater flexibility with respect to switching parameters when establishing solar envelopes.

Task 3 – Quantity of geographic and climatic parameters for each corresponding method

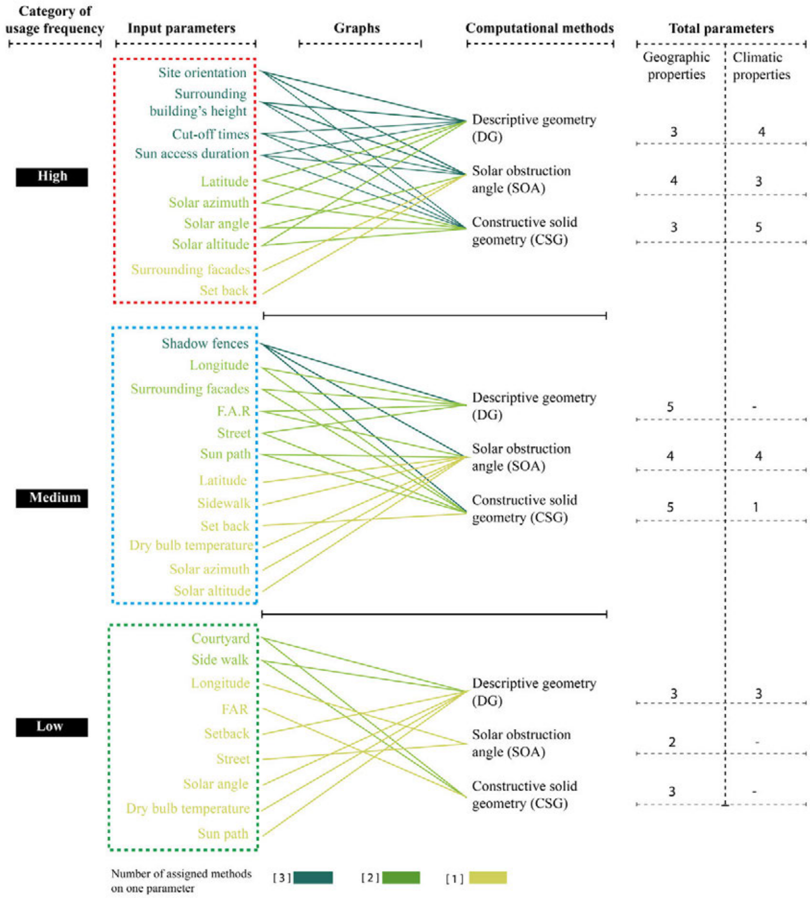

FIG. 2.4 Specific distribution of design parameters (geographic and climatic properties) based on the group usage frequency and corresponding methods

The plot of the parameters illustrated in Figure 2.4 requires further explanation. First, denoting the highest usage frequency, the high category confirms the greatest numbers of parameters that are incorporated in all methods. This category consists of four parameters (i.e., site orientation, surrounding building height, cut-off times, and sun access duration), whereas the remaining parameter, shadow fences, is found only in the medium category. Based on the similarity of the three methods, these shared parameters can be further defined as global parameters. However, there are several parameters, such as surrounding facades, set back, latitude, sidewalk, dry bulb temperature, solar azimuth, solar altitude, longitude, and street, that are included only in particular methods. As these parameters specifically correspond to SOA, they are defined as local parameters. To some extent, these local parameters act as basic parameters when they are located in the high-frequency use category (red dashed box) while at the same time, they are considered nonstandard parameters when implemented in other methods. For example, setback is a regular parameter for SOA, but it is regarded as an advanced or nonstandard parameter for DG. This is because SOA requires different daylight conditions on each side of the plot and is therefore influenced by the setback and plot orientation, whereas DG treats the same condition based on the whole boundary of the plot. Another interesting trend is the DG's local parameters (i.e., setback, solar angle, dry bulb temperature, and sun path), which simultaneously become advanced parameters because they are in the low-frequency use category. As a the most frequently-used method, this trend indicates that DG exhibits a higher degree of complexity, especially when comparing the quantity of DG's local parameters to those of the other two methods. Thus, it is worth noting that the specific parameter of a solar envelope plays a great role in determining the computational workflow of the simulation method.

Second, after plotting the parameters based on the usage frequency, the number of geographic and climatic properties for each method can be determined. The general trend indicates that only the parameters from both categories are found in the high category while only parameters that satisfy the geographic properties are assigned to the other two methods. Specifically, climatic properties are absent from the medium (DG) and low categories (SOA and CSG). This is not only because the total number of assigned parameters in the high category is greater than that in the others but also because the medium and low categories are populated with rarely-used parameters.

2.4 Discussion: digital simulation tools and case studies

An investigation of the computational environment of solar envelopes focuses on two qualities, namely, digital simulation tools and implementation of case studies (see Table 2.2), which are specifically investigated based on computational criteria and typologies of the projects, respectively. To conduct this investigation, each selected reference is evaluated by using a similar binary operation, as in the previous section, and the evaluation is conducted based on predefined computational parameters. For example, the digital tools of each selected reference are first investigated, and the evaluation criteria are then established based on four relevant factors i.e., self-developed tools, dynamic-parameter input, modeling environment, and integrated environmental simulation. The project implementations (case studies) are then specified according to two aspects, namely, architectural scales (i.e., urban, open space, and single building) and functional utilities (i.e., housing, offices, and commercial). The distributions of these qualities are subsequently plotted onto the bar graph, as illustrated in Figure 2.5. The purpose is to identify the performance of each computational method in relation to the number of corresponding references for each criterion. In so doing, a better overview regarding the computational workflow of solar envelopes is developed, especially with respect to the context of design practices available for architectural use.

TABLE 2.2 Database of the computational environment parameters of solar envelopes based on the selected references

Literature	Digital tools	Computational criteria				Case studies								
						Architectural scales			Functional utilities					
									Housing					
		A	B	C	D	E	F	G	H	I	J	K	L	M
Descriptive Geometry (DG)														
[40] [41] [42]	SustArc	●		●	●	●		●			●			
[43]	Rhino, Grasshopper (Ladybug)		●	●	●			●				●	●	
[44]	-			●		●		●			●	●		
[45] [46]	CAD			●		●		●				●	●	●
[47]	-						●					●		
[48]	Rhino, Grasshopper (Ladybug, Octopus)		●	●	●			●		●				
[49]	Rhino, Grasshopper (Ladybug)		●	●	●			●		●				
[50]	T4SU, Sketchup, GIS	●	●	●				●					●	
[51]	AutoCAD			●				●	●				●	●
[52]	Heliodon, Ecotect		●	●	●	●		●	●				●	●
[53]	TAS (EDSL v. 9.09)		●	●	●			●		●				
[54] [55]	Rhino, Grasshopper, Diva, Ecotect, Vasari		●	●	●	●					●			
[56]	CalcSolar (Autolisp)- Autocad	●		●			●	●			●			
[57] [58]	Rhino, Grasshopper, Ecotect, Galapagos		●	●	●	●					●			
[59]	-				●	●		●		●				
[60]	AutoCAD, Sketchup, 3D Max		●	●				●	●					
[61]	-				●		●	●	●				●	●
[62]	Autodesk			●		●					●			
Solar Obstruction Angle (SOA)														
[63]	-	●			●	●	●			●			●	●
[33]	The Obstrucao 1.0	●		●	●			●	●					
[64] [65] [66]	MascaraW	●		●	●	●		●			●			
[67] [68]	CityZoom (Block magic 3D)	●		●	●	●		●				●		●
[69]	-					●		●					●	
[70]	Envi-met (thermal analysis), PMV		●	●	●		●	●	●					
[71] [72]	CAD-Microstation			●	●		●	●			●			
[73] [74]	BRADA	●		●	●	●		●			●			
[75] [76]	City SHADOWS, Envi-met	●		●	●	●		●		●				

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TABLE 2.2 Database of the computational environment parameters of solar envelopes based on the selected references

Literature	Digital tools	Computational criteria				Case studies								
						Architectural scales			Functional utilities					
									Housing					
		A	B	C	D	E	F	G	H	I	J	K	L	M
Constructive Solar Geometry (CSG)														
[35] [77] [78]	Solar envelopes tools + BSK			•	•	•		•			•			
[34] [30]	AutoCAD 2000			•		•		•				•		•
[36]	CalcSolar (Autolisp)-Autocad	•		•				•				•		
[39]	GIS, EnergyPlus 8.1			•	•	•		•		•				
[37]	Form.Z			•				•				•		
[79]	SolCAD	•		•			•	•				•		
[38] [80]	Rhino, Grasshopper, EnergyPlus		•	•	•			•				•	•	
[81]	Rhino, Grasshopper, Ladybug		•	•	•			•	•				•	
[82]	Rhino, Grasshopper, Ladybug		•	•	•			•	•			•	•	
[83]	Rhino, Grasshopper, Ladybug		•	•	•			•	•				•	
[84] [85]	PIRAMIDA	•		•	•			•		•				
[86] [15]	Autodesk's 3dsmax™			•	•	•		•				•	•	
[87]	AutoCAD			•	•			•		•				
[88]	Rhino, Grasshopper, Ladybug		•	•	•			•	•				•	•

A: Self-developed; B: Dynamic parameter input; C: Parametric modeling environment; D: Integrated environmental simulation; E: Urban; F: Open space; G: Single building; H: Discontinued collective; I: Continued collective; J: Dense individual; K: Dispersed individual; L: Offices; M: Commercial.

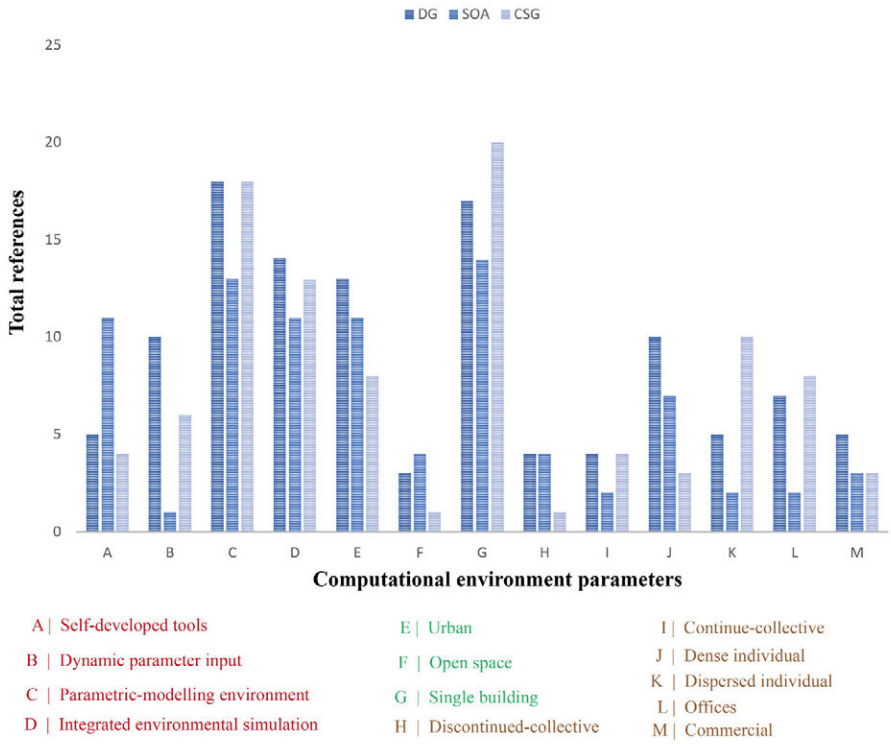

FIG. 2.5 Distribution of computational environment parameters according to the corresponding computational methods

2.4.1 Digital tools

The simulation tools in each selected reference to construct solar envelopes are examined. According to Anderson [89], in *Design Energy Simulation for Architects*, the minimum requirement for design tools to run performance simulations consists of three components, specifically, a user interface, three-dimensional modelers, and an engine. Accordingly, several criteria are established to identify a general pattern of simulation platforms in relation to the computational methods of solar envelopes. simulation method.

Self-developed tools

Self-developed refers to the ease of access of the tools during the creation of solar envelopes. These tools are then defined according to three specific criteria. The first category of tools includes those preferred by authors who use popular CAD-related platforms to run the simulations of solar envelopes (e.g., [45] [46] [51] [60] [71] [72] [34] [30] [87]). The second category consists of a custom-built module that is generated from a particular function of existing digital tools such as T4SU in SketchUp [50], SolCAD [79] and Calcsolar [56] in Autocad, solar envelope tools in Revit [36], and the Solar Toolbox plugin in Grasshopper [90]. Third, a tailor-made supporting tools that perform specific tasks related to solar envelopes. Among these tools are MascaraW [66], SustArc [40], CityZoom [68], Calcsolar-AutoLISP [56], The Obstrucao 1.0 [33], CitySHADOWS [94,95], form Z [37], and PIRAMIDA [84] [85]. Note that some references are found to be incomplete due to limited information during the review process, i.e., [44] [47] [59] [61] [63] [69].

When these criteria are plotted with their corresponding methods and references in Figure 2.5 (see point A), it is evident that SOA exhibits the higher number of references, followed by DG and CSG given that SOA consists of the greatest number of local parameters. As previously elucidated in Figure 2.4, local parameters represent a series of parameters that only attach to a particular method due to their scarcity and complexity of use. Accordingly, SOA requires particular tools to formulate the appropriate parameters when constructing solar envelopes.

Dynamic parameter input

This criterion emphasizes the flexibility between the fixed and adaptable-parameter algorithms. The fixed-parameter algorithm often includes both a static and a limited number of parameters due to the default system of design tools. Consequently, the end user of the tool can only follow the simulation procedure and input the dataset on the basis of the given parameters [36]. Some design tools, however, consist of adaptable or dynamic parameters that permit additional tasks, such as the reduction in the number of and generation of relevant parameters. These tasks provide a direct interaction between the users and the tools when developing a solar envelope simulation.

To create a legible representation, Figure 2.5 (see point B) specifically illustrates a bar graph of references that corresponds to the dynamic parameter inputs. The graph indicates that DG has the highest number of dynamic parameter input references, followed by CSG and SOA. This trend is relevant to all methods, however, as DG simultaneously also consists of the largest quantity of references. As the most frequently-used and flexible method (see Figure 2.3), DG provides great accessibility for using the existing digital tools during the construction of solar envelopes. Table 2.2 (see the digital tools) illustrates that DG predominantly uses a well-known tool with a wide input of parameters.

Modelling environment

According to the geometric representation, the modeling environment of the selected references is predominantly generated based on NURBS (non-uniform rational B-spline) models that range from the organic free-form surface to the 3D solid model [31]. The NURBS models are further divided into parametric and direct modeling approach models. These approaches not only differ with respect to design rule and process but also in the complexity of geometrical parameters. Accordingly, the geometric configuration of solar envelopes is dependent on the applied algorithm of the modeling approach. For example, the surface representation of the 3D model can geometrically vary when generated from the TIN (triangulation irregular network) of the point cloud compared to one that is manually created based on the CAD platform [91].

According to Figure 2.5 (see point C), the total number of references for the DG and CSG methods are equally proportioned and outnumber the studies the reference for the SOA method. This trend represents the total selected references for all methods, except some references for unidentified tools. This is because all methods use design tools with parametric functions during the construction of solar envelopes. Nonetheless, further research is required to identify the geometrical behaviors generated by the interaction of parameters.

Integrated environmental performances

Interoperability plays an important role during the design process, especially when dealing with various simulation tools and multiple dataset sources. While this can create, to some extent, a computational issue due to different algorithmic operations, a comprehensive analysis for optimal design solution can be achieved. With an integrated environmental simulation, the computational functions of certain design tools, such as solar thermal exposure [61], wind analysis [42], daylight availability, solar photovoltaic exposure, ventilation enhancement, and water surface catchment and flow [92], can be extended during the construction of solar envelopes.

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In general, the trend in Figure 2.5 (see point D) illustrates high percentages regarding the use of environmental performances in all methods. This results means that most of the selected studies performed one or more environmental simulation during the construction of solar envelopes. According to the stage of use during the simulation process, these environmental performances can be categorized into three functions, namely, generator, evaluator, and generator, as well as evaluators that are operated in the same workflow. For example, *first*, the performance generator is used to support the main parameter to establish the final geometry of solar envelopes. Some example of performances can be observed in DG that includes direct sun access duration, temperature [43], annual space heating demands, daylight, thermal performances, solar renewables [53], wind analysis [59], visual assessment, street network [55] [54], and solar irradiation [58] [57], while in SOA urban heat islands [71] [72] and daylight [73] [74], and CSG consists of sun hours availability [88]. *Second*, the performance evaluator is employed to assess the final geometry of solar envelopes. In other words, this process measures the environmental impacts of new envelopes and compares those impacts to previous and existing conditions. Examples of these criteria are found in DG with performances that involve urban density, direct sun access duration [49], and solar irradiation [52], SOA with energy consumption [33], temperature, wind, albedo, thermal comfort [70], urban heat island, and daily direct solar radiation [76] [75], CSG with aeshthetics, solar access, lighting, ventilation, public safety [35] [78] [77], solar access hours, annual energy consumption, cost, CO2e [38] [80], urban density [15] [86], and sunlight and shading simulation [87]. *Third*, the performance generator and evaluator consist of a combination of two types of performances that are operated simultaneously in one workflow. For example, some studies on DG use performances such as urban density, energy consumption [32] [41] [42], temperature, wind, climate, and energy [61], while references in the SOA category consider insolation hours, urban density [63], comfort issues and wind flows [67] [68], and those in CSG involve more performances related to air temperatures, global radiation, passive solar gains, heating loads, insolation values [39], sun access duration [81], building density [82], and sphere view factors [83].

2.4.2 Case studies

To identify the contextual settings of computational solar envelopes in design practices, this study separates and plots the selected references in two functions, namely, architectural scales and functional utilities. According to Figure 2.5 (see points E-G), case studies of solar envelopes are predominantly implemented in single buildings since the building-oriented context requires fewer geographic parameters

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than do urban scales. For example, the CSG method has the greatest number of references with a single building context (see Figure 2.5 point G), but it receives the lowest rate for implementation in urban contexts (see Figure 2.5 point E) because the modeling construction of CSG is more appropriate for building contexts than for urban-scale contexts due to the high cost of computational issues. The context of open space, however, has received less attention. In fact, open space only seems to play an essential role during the construction of solar envelopes, particularly in highly dense areas such as metropolitan cities.

The functional utilities of the projects are divided into three types, namely, housing, offices, and commercial. The housing category includes those typologies proposed by Maizea et al [93] and thus, consists of the *discontinued collective*, *continued collective*, *dense individual*, and *dispersed individual*. In general, the trend of this housing category suggests that the 'individual' groups are referenced more frequently than the 'collective' groups due to the complexity of the projects and scale of the plots. Accordingly, the DG and CSG method are referenced more often in the dense individual and dispersed individual groups, respectively.

With respect to the comparison of housing group and other functions, such as offices and commercial properties, Figure 2.5 illustrates that of all the functional utilities, housing is the one most referenced, even though most people who live in big cities or dense areas spend far more time in offices during the day. Accordingly, solar envelopes are crucial to providing sunlight penetration to the working space to reduce energy consumption during working hours. Consistent with this fact, solar envelopes also play an important role in determining specific conditions of commercial areas. For example, as direct sunlight can affect food and product durability issues, especially when located in ground floor level storefronts, shading becomes a critical factor. However, as some references do not include a specific function for the implementation of a case study, it is challenging to understand the relationship between the contextual settings of these references and performance criteria of the solar envelopes.

2.5 Knowledge gaps and new directions

Based on the understanding of the computational methods of solar envelopes presented in the previous sections, this study identifies several gaps that may drive further research for new approaches to the generation of solar envelopes (see Table 2.3). These gaps are formulated into three aspects, namely, 3D contextual model, climatic properties, and geometric configuration. The proposed directions are also discussed in relation to each gap.

TABLE 2.3 Knowledge gaps and new directions for solar envelopes

No.	Qualities	Knowledge gaps	Future directions
1	**3D contextual model**	Limited discussion on covering contextual geometries	DEM (digital elevation modeling) Point cloud data
		Limited understanding of site characteristics information	
2.	**Climatic properties**	Predominantly based on four-season countries	Tropical countries
		The objective is to collect direct sunlight	The objective is to avoid direct sun access
		Predefined period only relies on cut-off times	Consider sun visibility on each period
3.	**Geometric configuration**	Limited results on final geometry of solar envelopes	Multi objective optimization
		Limited performance criteria	Integrate multi performance criteria (e.g. material)
		Focuses only on 3D mass of solar envelopes	Explore performance configuration of the layout of the building’s interior.

3D contextual model

As previously described, most of the current methods employ solid modeling as a platform of the 3D contextual model. Most important when considering this approach is the challenge to comprehensively understand the characteristics of the existing contexts, especially when dealing with complex sites. The current approach to 3D site modeling often not only fails to preserve geometric aspects of existing context but also fails to sufficiently address the surrounding site properties, such as vegetation or other temporal site elements that may be relevant for further analyses of solar envelopes. Moreover, the surface characteristics of the existing environment, such as the material of surrounding facades, have also received less attention to date. That said, it is argued that the calculations of solar energy within solar envelopes should take into account the surface characteristics of the surrounding environment.

An alternative to the aforementioned issues is DEM (digital elevation modeling). In comparison with other solar envelope methods that are created primarily by CAD drawings, the DEM platform employs image processing techniques to obtain and quantify a solar exposure map by means of shadow volumes ([94] [95]). This approach includes iso-solar rights and iso-solar collection surfaces to implement energy-oriented shapes in urban environments. As the current DEM method predominantly focuses on the urban scale, it remains challenging to identify and calculate specific geometric parameters, such as building scales. Another consideration is the 3D laser scanning technologies that offer opportunities to capture the physical properties of the environment. As a product of laser scanner, potential applications of point cloud data may counterbalance relevant information within the surrounding context using geometric and radiometric properties.

Climatic properties

With respect to the climatic parameters found within the collected literature, the existing studies are based primarily on four-season countries. This means that their objectives focus on minimizing sun access duration during summer while maximizing it during winter so that the sunlight can penetrate the main activity room. In fact, these objectives differ significantly from those of tropical countries, especially for those countries located on the equator. Since tropical countries consist of annual wet and dry seasons, these climatic factors affect the objectives and mechanisms of solar envelopes, and accordingly, solar envelopes should be able to minimize the sunlight coming into the house due to high temperatures. For example, building constructions in Indonesia prefer shaded conditions to lower the hot temperatures inside the building. Accordingly, the concepts and existing parameters of solar envelopes require further adjustments for tropical contexts.

Geometric configuration

During the schematic design phase, it is often important to analyze the solar access of new buildings when selecting the optimal layouts for massing that fulfils the volumetric shape of solar envelopes. Accordingly, the solar collection envelope (SCE) [32] and solar collection multi-isosurface [49] have been developed. However, solar collection surfaces can only be used for single buildings with rectangular or convex

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footprint layouts. Thus, further research is needed to identify optimal massing and layouts for articulated buildings and clusters in urban environments. Hence, the concept of multi objective optimization is useful for exploring geometric design configurations of solar envelopes to identify the optimal solution.

2.6 Conclusion

This study presents a conceptual review of solar envelopes by investigating the qualities of design methods and computational performance aspects in relation to parameters, digital simulation tools, and implementation of the case studies. In particular, 58 selected references of solar envelopes are extensively examined as the basis idea to perform comparative analysis between each categorized method and predefined criteria. This study ultimately allows architects not only to identify different characteristics and levels of complexity for each design method but more importantly also to address the concept of solar envelopes in design practices such as the projects of P15 Ravel Plot and Grotius Towers II by the Dutch architectural and urban design firm MVRDV. As a research framework, the present study may also benefit further for urban planner and related municipality to update the current parameters of local regulation especially related to solar energy building performances and environmental design assessments between proposed building and existing environment. Specific remarks on each section in this review are presented as follows:

- By categorizing the contextual setting of solar envelopes into the inclusion and exclusion of surrounding properties (e.g., vegetation, adjacent buildings, open spaces, and other relevant elements) enables architects to identify the types of methods that predominantly focus on new or existing contexts. Given that urban densities may have scarcity of wide areas, DG plays an essential part to deal with the future scenarios as it considers more site properties than other methods.

- Categorization of design parameters into geographic and climatic properties allows us to identify specific parameters that affect volumetric size of solar envelopes for each design method.

- The comparative analysis among methods and parameters indicates that DG is the most frequently-used method of the three. This is because DG has the greatest number of registered references and thus, it contains more basic parameters (latitude, orientation, cut-off times, and solar altitudes) as compared to other methods. In addition, DG has the greatest flexibility to switch parameters during the establishment of solar envelopes because of its wide range of complementary parameters.

- This study categorizes SOA and CSG method as a group with the low category parameters and thus, it refers to local parameters because their parameters can only apply to particular cases when establishing solar envelopes.

- This study investigates the geometric performance of each solar envelope method with respect to the predefined criteria of the digital tools. For example, SOA is identified as the method with the greatest use of self-developed tools since it has the greatest number of local parameters. In contrast, DG is the most flexible for constructing solar envelopes due to its great accessibility, its ability to use the existing digital tools, and its wide range of dynamic parameter inputs.

- This study identifies that CSG is predominantly implemented in a single building rather than on an urban scale due to the high cost of computational modeling and the mesh generation procedures. Moreover, this study reveals that housing remains a predominant case study of solar envelopes, even though offices and commercial sectors consume a greater portion of urban functions, especially in dense areas.

Furthermore, although the conceptual framework of computational solar envelopes is extensively addressed in this review, there is still a need for an objective evaluation approach to provide a quantitative analysis of different methods. By using a similar set of predefined parameters, digital tools, and case study, volumetric shape and performance criteria of geometric solar envelopes on different methods can be further measured more precisely.

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Appendix 2A

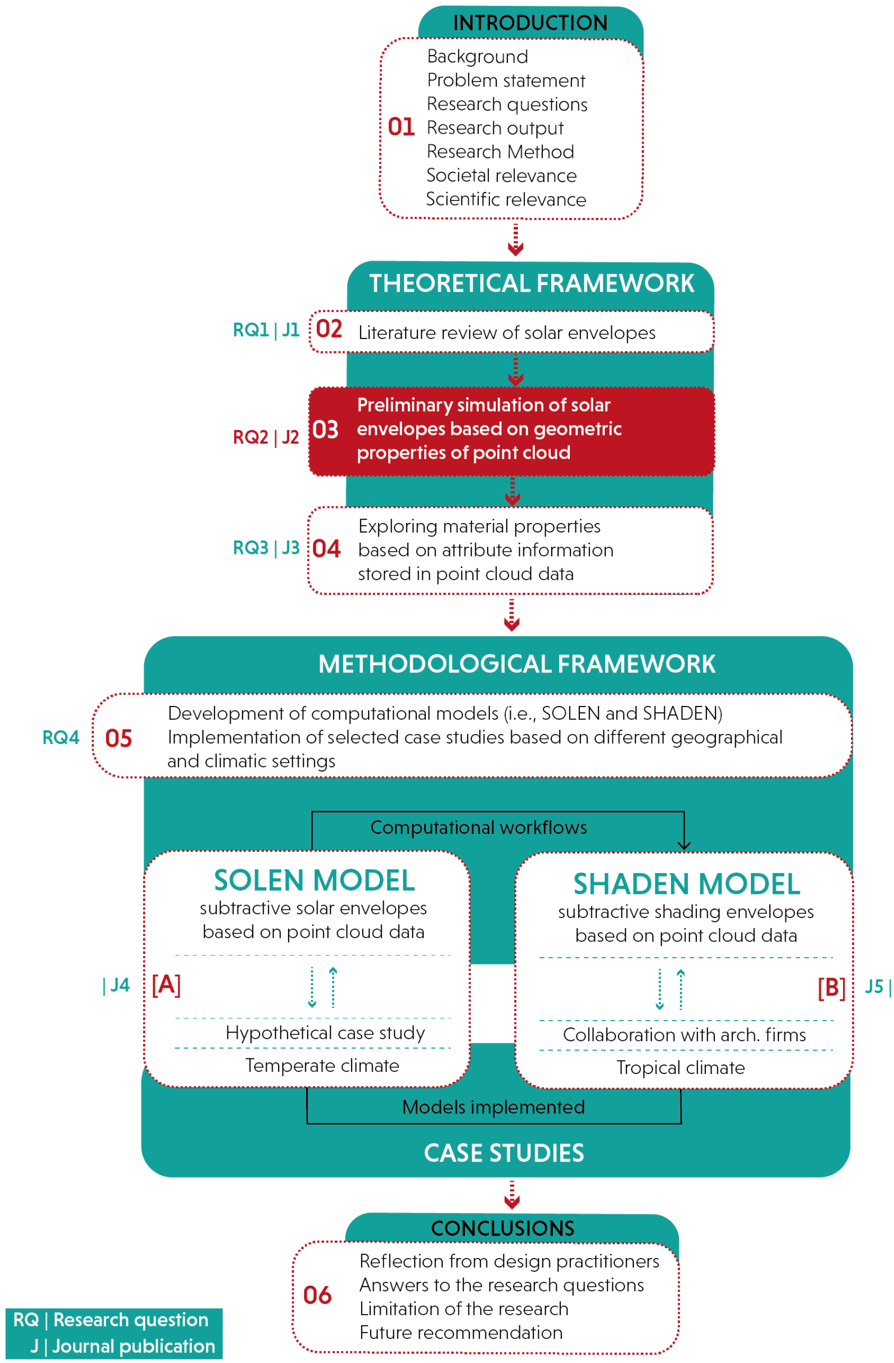
TABLE A.1 Parameters selection for reference databases

Operation	Sources	Topics		
		Conceptual themes	Design workflow	Contextual settings
		Solar architecture	Computational design	Urban planning
		Solar envelopes	Solar design	Urban design
		Solar access	Solar Simulation	Architectural design
OR	WoS	TOPIC: ("solar architecture" OR "solar envelopes" OR "solar access") Refined by: WEB OF SCIENCE CATEGORIES: (CONSTRUCTION BUILDING TECHNOLOGY OR ARCHITECTURE OR GREEN SUSTAINABLE SCIENCE TECHNOLOGY OR ENGINEERING CIVIL OR URBAN STUDIES OR COMPUTER SCIENCE INTERDISCIPLINARY APPLICATIONS OR ENGINEERING MULTIDISCIPLINARY) AND DOCUMENT TYPES: (ARTICLE OR BOOK CHAPTER OR PROCEEDINGS PAPER) AND RESEARCH AREAS: (CONSTRUCTION BUILDING TECHNOLOGY OR ENGINEERING OR ARCHITECTURE OR URBAN STUDIES) Timespan: 1960-2019. Indexes: SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC	TOPIC: ("computational design" OR "solar design" OR "solar simulation") Refined by: WEB OF SCIENCE CATEGORIES: (COMPUTER SCIENCE INTERDISCIPLINARY APPLICATIONS OR ARCHITECTURE OR ENGINEERING MULTIDISCIPLINARY OR CONSTRUCTION BUILDING TECHNOLOGY OR ENGINEERING CIVIL OR GREEN SUSTAINABLE SCIENCE TECHNOLOGY) AND DOCUMENT TYPES: (ARTICLE OR BOOK CHAPTER OR PROCEEDINGS PAPER) AND RESEARCH AREAS: (COMPUTER SCIENCE OR ENGINEERING OR ARCHITECTURE OR CONSTRUCTION BUILDING TECHNOLOGY OR URBAN STUDIES) Timespan: 1960-2019. Indexes: SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC	TOPIC: ("urban planning" OR "urban design" OR "architectural design") Refined by: WEB OF SCIENCE CATEGORIES: (URBAN STUDIES OR ARCHITECTURE OR REGIONAL URBAN PLANNING OR ENGINEERING CIVIL OR CONSTRUCTION BUILDING TECHNOLOGY OR GREEN SUSTAINABLE SCIENCE TECHNOLOGY) AND DOCUMENT TYPES: (ARTICLE OR PROCEEDINGS PAPER OR BOOK OR BOOK CHAPTER) AND RESEARCH AREAS: (URBAN STUDIES OR ARCHITECTURE OR ENGINEERING OR CONSTRUCTION BUILDING TECHNOLOGY) Timespan: 1960-2019. Indexes: SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC
Total		**139**	**846**	**10.196**

>>>

TABLE A.1 Parameters selection for reference databases

Operation	Sources	Topics		
		Conceptual themes	Design workflow	Contextual settings
		Solar architecture	Computational design	Urban planning
		Solar envelopes	Solar design	Urban design
		Solar access	Solar Simulation	Architectural design
	Scopus	TITLE-ABS-KEY (“solar architecture” OR “solar envelopes” OR “solar access”) AND PUBYEAR > 1959 AND PUBYEAR < 2020 AND (LIMIT-TO (DOCTYPE , “ar”) OR LIMIT-TO (DOCTYPE , “cp”) OR LIMIT-TO (DOCTYPE , “ch”) OR LIMIT-TO (DOCTYPE , “bk”)) AND (LIMIT-TO (SUBJAREA , “ENGI”) OR LIMIT-TO (SUBJAREA , “ENER”) OR LIMIT-TO (SUBJAREA , “COMP”) OR LIMIT-TO (SUBJAREA , “ARTS”)) AND (LIMIT-TO (LANGUAGE , “English”))	TITLE-ABS-KEY (“computational design” OR “solar design” OR “solar simulation”) AND PUBYEAR > 1959 AND PUBYEAR < 2020 AND (LIMIT-TO (DOCTYPE , “ar”) OR LIMIT-TO (DOCTYPE , “cp”) OR LIMIT-TO (DOCTYPE , “ch”) OR LIMIT-TO (DOCTYPE , “bk”)) AND (LIMIT-TO (SUBJAREA , “ENGI”) OR LIMIT-TO (SUBJAREA , “COMP”) OR LIMIT-TO (SUBJAREA , “ENER”)) AND (LIMIT-TO (LANGUAGE , “English”))	TITLE-ABS-KEY (“urban planning” OR “urban design” OR “architectural design”) AND PUBYEAR > 1959 AND PUBYEAR < 2020 AND (LIMIT-TO (DOCTYPE , “ar”) OR LIMIT-TO (DOCTYPE , “cp”) OR LIMIT-TO (DOCTYPE , “ch”) OR LIMIT-TO (DOCTYPE , “bk”)) AND (LIMIT-TO (SUBJAREA , “ENGI”) OR LIMIT-TO (SUBJAREA , “COMP”) OR LIMIT-TO (SUBJAREA , “ARTS”) OR LIMIT-TO (SUBJAREA , “ENER”)) AND (LIMIT-TO (LANGUAGE , “English”))
Total		**388**	**2.548**	**61.900**
	GS	Sort by date: “solar architecture” OR “solar envelopes” OR “solar access”	Sort by date: “computational design” OR “solar design” OR “solar simulation”	Sort by date: “urban planning” OR “urban design” OR “architectural design”
Total		**43**	**674**	**8.530**
AND	WoS	TOPIC: (“solar architecture” OR “solar envelopes” OR “solar access” AND “computational design” OR “solar design” OR “solar simulation” AND “urban planning” OR “urban design” OR “architectural design”) Refined by: WEB OF SCIENCE CATEGORIES: (ARCHITECTURE OR URBAN STUDIES OR CONSTRUCTION BUILDING TECHNOLOGY OR ENGINEERING CIVIL OR REGIONAL URBAN PLANNING OR GREEN SUSTAINABLE SCIENCE TECHNOLOGY) AND DOCUMENT TYPES: (ARTICLE OR PROCEEDINGS PAPER OR BOOK CHAPTER OR BOOK) AND RESEARCH AREAS: (ARCHITECTURE OR URBAN STUDIES OR ENGINEERING OR CONSTRUCTION BUILDING TECHNOLOGY) Timespan: 1960-2019. Indexes: SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC		
Total		**5.592**		
	Scopus	TITLE-ABS-KEY (“solar architecture” OR “solar envelopes” OR “solar access” AND “computational design” OR “solar design” OR “solar simulation” AND “urban planning” OR “urban design” OR “architectural design”) AND PUBYEAR > 1959 AND PUBYEAR < 2020		
Total		**13**		
	GS	Sort by date: “solar architecture” OR “solar envelopes” OR “solar access” AND “computational design” OR “solar design” OR “solar simulation” AND “urban planning” OR “urban design” OR “architectural design”		
Total		**1050**		


INTRODUCTION
01
Background
Problem statement
Research questions
Research output
Research Method
Societal relevance
Scientific relevance
THEORETICAL FRAMEWORK
RQ1 | J1
02
Literature review of solar envelopes
RQ2 | J2
03
Preliminary simulation of solar envelopes based on geometric properties of point cloud
RQ3 | J3
04
Exploring material properties based on attribute information stored in point cloud data
METHODOLOGICAL FRAMEWORK
RQ4
05
Development of computational models (i.e., SOLEN and SHADEN)
Implementation of selected case studies based on different geographical and climatic settings
Computational workflows
SOLEN MODEL
subtractive solar envelopes based on point cloud data
| J4
[A]
Hypothetical case study
Temperate climate
SHADEN MODEL
subtractive shading envelopes based on point cloud data
[B]
J5 |
Collaboration with arch. firms
Tropical climate
Models implemented
CASE STUDIES
CONCLUSIONS
06
Reflection from design practitioners
Answers to the research questions
Limitation of the research
Future recommendation
RQ | Research question
J | Journal publication

3 Preliminary Simulation Of Solar Envelopes Based On Geometric Properties Of Point Cloud

This chapter has been published as: Alkadri, M. F., Turrin, M. and Sariyildiz, S., 2018. The use and potential applications of point clouds in simulation of solar radiation for solar access in urban contexts. *Advances in computational design,* 3(4), pp. 319-338. The layout has been adjusted to fit the template of this thesis.

The previous chapter introduced a conceptual review of solar envelopes based on various aspects such as computational methods, parameters, tools, and design applications. It also presented several knowledge gaps and future directions of the study such as 3D contextual models (e.g., limited understanding of site characteristic information), climatic properties (e.g., limited use of the four-season countries and cut-off-times parameters), and geometric configurations (e.g., limited performance criteria). In order to overcome these challenges, this study first focuses on the importance of the surrounding site elements in the existing context. Thus, it proposes the use of point clouds, especially with regard to the geometric properties, not only to capture relevant information for 3D contextual modeling but also to support a comprehensive site analysis before the simulation takes place. As a reality-based dataset, point cloud data enables one to include vegetation and other geometric aspects of the existing context that have not been addressed yet by current methods of solar envelopes. This chapter specifically investigates this aspect using ALS (Airborne Laser Scanning) datasets gathered from the AHN (Actueel Hoogtebestand Nederland) for selected sites in Rotterdam, the Netherlands. As a preliminary study, the simulation includes a performance evaluation of the design context by comparatively analyzing a series of indicators such as sunlight hours, radiation values, and residual areas between 3D manual model and TIN (Triangulated Irregular Network) model generated from point cloud data. The findings from this chapter describe significant contributions made by geometric properties of point cloud data, not only to filter relevant information from the design context but also to improve the current performance analyses features for solar envelope simulations. Ultimately, these results provide a stepping stone to further explore the potential application of attributes information stored in a point cloud data especially related to surface characteristics and material properties of existing contexts.

The Use And Potential Applications Of Point Clouds In Simulation Of Solar Radiation For Solar Access In Urban Contexts

ABSTRACT

High-performance buildings should be designed by considering the interdependencies between the new building and its local context. This is important to avoid any unforeseen failures after the building has been built; particularly ones related to the microclimate impacts that affect human comfort. In this regard, the concept of solar envelopes helps designers to construct a developable mass of the building design, considering solar access and site obstructions. However, the current method of using solar envelopes lacks in integrating detailed information from the existing context during the simulation process due to the limitations of contextual modelling features in preserving the complex architectural geometry and surface characteristics information. To date, emerging point cloud applications offer a great possibility for overcoming these limitations through potential applications of attribute information, such as position (XYZ) and color information (RGB). This study presents a comparative analysis between manually-built 3D geometric models and digital geometric models generated from point cloud data. This geometric modelling comparison focuses on the relevant factors of solar radiation and a set of environmental performance simulations based on selected parts of the generated models. The experimental results emphasize an introduction of the design approach and the visibility of the dataset from existing 3D environments. This paper ultimately aims to improve the support of current architectural design decisions by increasing the correspondence between digital models for performance analysis and the real environment as a design context during the conceptual design phase.

KEYWORDS

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

3.1 Introduction

3.1.1 General background

According to [1] 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 that the impact of increased urban density will result in a 40% increase of energy consumption in the building sectors [2]. Having said that, the implementation of a passive design strategy is an important solution, not only to improve the quality of the built environment but also to achieve optimal building performance during the conceptual design process. The to-be-built environmental analysis, furthermore, avoids unexpected failures once 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 local context. In the case of contemporary architecture, unfortunately, there remain some concerns in the design implementation. For example, the Walkie Schorcie building in the UK presents some practical issues with the lack of integration into the local context. Evidently, its building form causes numerous microclimatic effects. The glazed and curved south façade reflects solar radiation of more than 70 Celsius degree to the surrounding environment. This situation has had a tremendously negative impact on the local context, where the heat produced from the reflected solar radiation melted the body of a car parked on the street below and the expensive adaptation of the building facade [3]. It goes without saying that the building was awarded as “the worst building of the year,” by RIBA and received the Carbuncle Cup in 2015. This case clearly points out the unexpected microclimatic impacts caused by a new building on the local environment. In another instance, the UCL Student Housing located on Caledonian Road, North London, exemplifies a situation in which a new building does not fit into the local context. In this case, around half of the 350 student rooms do not gain direct sun access because part of the building is being obstructed by the original 19th century façade.

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

3.1.2 Solar envelopes

A solar envelope is an imaginary building mass determined by considering the desired amount of sun access without obstructing the surrounding site during critical times [4]. Figure 3.1 illustrates the basic mechanism for the solar envelope to produce daily and annual time limits, considering sunlight patterns in the Northern hemisphere. In a full-day setting, the morning sun establishes the western boundary envelope while the afternoon sun generates the eastern boundary envelope [5]. During the critical time between 9 am and 2 pm, the envelope limits will be steeper in the east than in the west because the sun's altitude at 2 pm is higher than at 9 am. In this case, the sun's rays hit the plot at a 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.

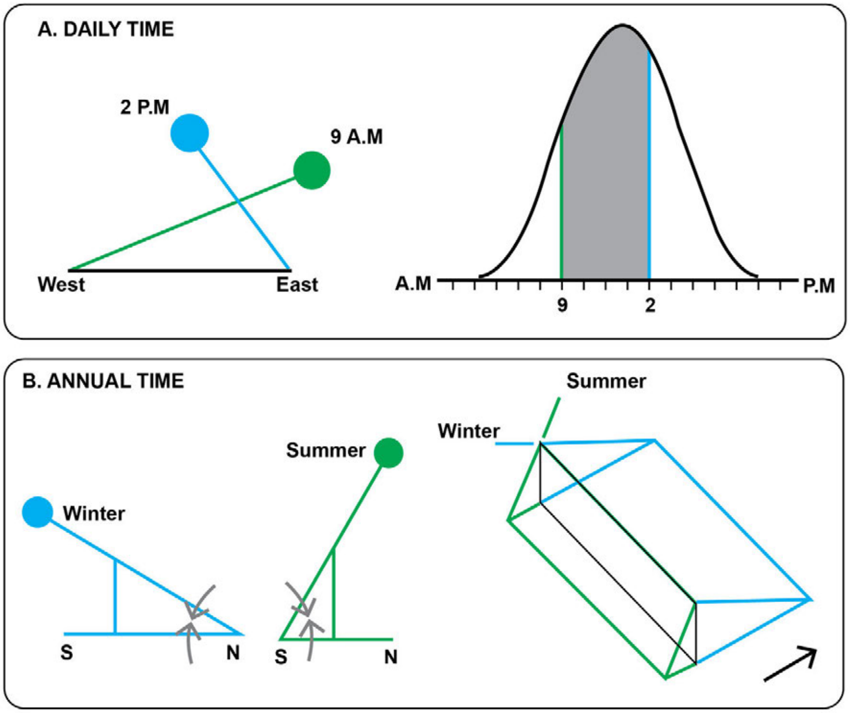


FIG. 3.1 Design mechanism of solar envelopes, generated from: A. daily time limits and B. annual time limits [6]

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

- Solar obstruction angle; consists of the three main parameters such as solar planes, perimeter of the site plan, and site orientation [7] [8] [9] [10] [11] [12] [13] [14].
- Descriptive method; is based on trigonometric calculations between sun altitude, sun azimuth and cut-off times [15] [16] [17] [18] [19].
- Digital elevation modeling (DEM); relies on image processing techniques and shadow volume calculations for urban scale [20].
- Constructive solid geometry; is mainly based on site extrusion and solar vectors [21] [22] [23] [24] [25].

These existing studies propose different ways of dealing with solar envelopes aligned with the technological development of design tools. However, their solar envelope simulations were predominantly performed without considering the actual environmental context. Consequently, the spatial relationship between the proposed building and the local context poses to some extent contextual issues associated with the microclimate during the design process. Some literature has discussed the role of the surrounding context when generating solar envelopes based on the descriptive method [26] [27] [28] [29] [30] [31] [32] [33]. However, the geometric model of existing environment (design context) in these works is generated on the basis of major simplifications. Currently, the geometric 3D representation of existing contexts is mostly constructed using the basic architectural shapes, especially when it comes to isolated sites with complex building forms. This can significantly affect the interpretation of the simulation results. For example, surface characteristics of existing buildings such as texture and material play an important role when simulating solar radiation. Overriding these characteristics makes solar radiation simulations apply the same treatment to all building surfaces, which in fact differ from the actual situation. In addition, the surrounding vegetation [12] should also be further addressed as a relevant parameter for contextual setting because it can influence the design configuration of the solar envelopes.

In contrast to existing research, this study points to 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 3D data scanning allows mapping of spatial information from the existing context. The inclusion of a large accurate dataset and attribute information contained in the point cloud can be used to generate contextual models of real environments. The further development of accurate modelling not only makes it possible to perform simulations and design analysis afterward but also to minimize any possible discrepancies between the simulated environmental design and the real context.

3.1.3 Point cloud data

The rapid development of 3D laser data scanning technology has been widely applied in various disciplines, especially in data visualization and data analysis such as civil engineering, geosciences, photogrammetry, and heritage. Conceptually speaking, Weinmann [34] 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 its spatial arrangement and coherence within blurred boundaries. Thus, the term point cloud is a set of points, Pi =1, . . .n, which is embedded in the three-dimensional Cartesian space [35]. As a 3D data scanning entity, point clouds are discrete three-dimensional locations (points) that can have additional information associated with each record [36]. It is characterized by spatial XYZ coordinates as position information and is optionally assigned by auxiliary information (see Figure 3.2) such as color information (RGB) [37] and intensity information (I) [38] [39] [34].

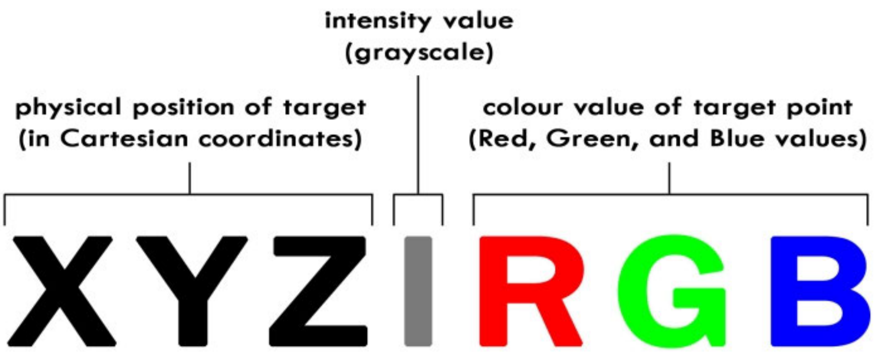


FIG. 3.2 Attribute information of point cloud data [40] quality.

Furthermore, Randall [40] described that point cloud data can support the following information:

- The position of the object with 3D coordinates in global coordinate system.
- Geometric features such as length between points and orientation of objects.
- Visual information such as 2D and 3D digital images and 3D virtual models.
- Physical features such as textures, cracks and different types of objects with different densities [41].

Utilization of point clouds in several engineering domains shows high-precision results for simulation performance [42]. It can be used to perform numerous tasks in the early stage of architectural design where various design scenarios can be analyzed to support the decision-making process [43]. For example, point cloud data can be employed to generate 3D models of existing complex urban forms [44] [45] [46]. Besides, it also allows one to visualize the entire construction process according to time-based transformations [47] and to capture the deformation of existing structures in the renovation process [48]. Furthermore, the surface attribute information contained in the point cloud is useful for detecting the solar potential on any existing building surfaces [49] [50] [51]. However, studies that specifically investigate the solar envelope performance based on point cloud data remain a blank spot in solar radiation analysis.

This study ultimately aims to explore the potential application of point cloud data in generating the solar envelope. In this case, a comparative analysis between manually-built 3D geometric models and digital geometric models generated from point cloud data is performed; the following section illustrates this process further.

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

Given the unstructured raw dataset of the point cloud, the proposed workflow allows simulating of 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 analysis. The overview of the process is illustrated in Figure 3.3.

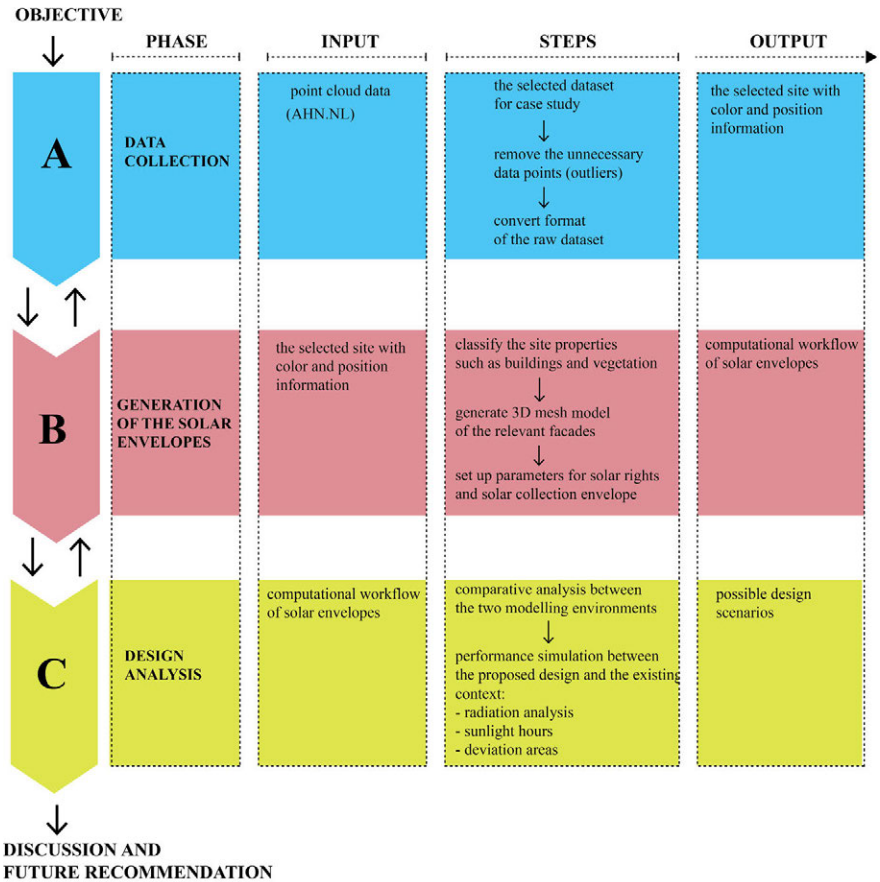


FIG. 3.3 Overview of the proposed procedure

3.2.1 Data collection

The data collection phase is useful not only for gathering the raw point cloud dataset but also for identifying relevant information from the local context as input in the design simulation. During this phase, the source of the dataset plays an important part because it considers the type of attribute information attached to the point cloud data. For example, the Terrestrial Laser Scanning (TLS) technique caters to different levels of robustness and attributes of point cloud dataset compared to Airborne Laser Scanning (ALS). Specifically, the following are steps needed to distribute the selected point cloud dataset:

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

The output of this phase is a selected point cloud that contains color (RGB) and position (XYZ) information. This attribute information enables one to identify the elevation of each point in the dataset according to its color scale.

3.2.2 Generation of the solar envelopes

This phase focuses on developing a new computational workflow of the solar envelope. In the proposed workflow, point cloud data processing aims not only to classify site properties such as vegetation and buildings but also to perform the mesh generation for the selected building’s facade. The mesh model is used to support the environmental performance simulation. As an extension of the solar envelope method from Capeluto and Shaviv [26], the proposed workflow consists of two design principles “solar right envelope” and “solar collection envelope.” Generally, this workflow endeavors 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 handle the point density as it significantly affects the computation time during the simulation.

3.2.3 Design analysis

The third phase is a design analysis that can be performed using the solar envelope model generated from point cloud data. As this phase includes exploratory design studies, a wide variety of possible design scenarios can be defined depending on the intended design case.

Furthermore, a comparative analysis is addressed using two different modelling environments, namely the Triangulation Irregular Network (TIN) model generated from the point cloud and manually-built 3D geometric models based on CAD drawings. This aims not only to investigate further the design configuration produced by the similar urban context but also to identify the discrepancies of simulation results based on three indicators, namely the volumetric shape of solar envelopes, the total radiation value, and the total sunlight hours.

3.3 Case study: The Kruisplein area in Rotterdam, The Netherlands

The selected location is Kruisplein in Rotterdam, The Netherlands (latitude 51.9244° N, and longitude coordinates 4.4777° E). As this area is a densely populated district near Rotterdam Central Station, many people pass by frequently to eat, shop, and rest. This area also varies in functions and scales such as high-rise and wide-span buildings, large open spaces, and vegetation between the buildings. By considering the urban quality of this area, the existence of new buildings should preserve the reciprocal relationship with the surrounding environment. The case study focuses on guaranteeing appropriate solar access between the new design and the surrounding environment.

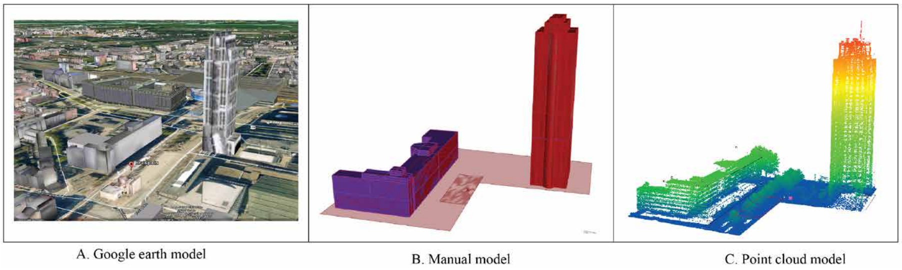


FIG. 3.4 Geometric representation of the selected site in different 3D models

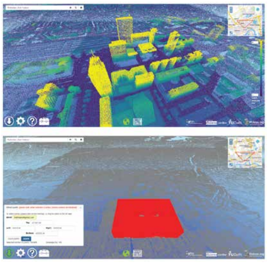
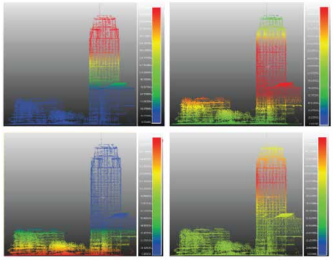
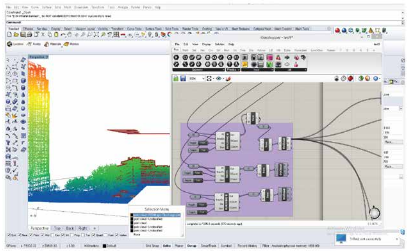
Figure 3.4 illustrates the selected buildings from the case study consisting of a hotel (high-rise building) and a commercial area (wide-span building). Understanding these specific functions enable us to set limits on sun access for the surrounding environment. For example, commercial functions consist of shops, restaurants, and cafes along the ground floor, and offices on the upper floors. In this regard, commercial areas on the ground floor preferably sit within a shaded area rather than direct sunlight. This is because the durability issue of the food will not last long when it gets direct sunlight at certain times, especially those placed at the storefronts. Meanwhile, open spaces are often designed as a mixed-use function for temporal events such as live music, market, and other festivals.

The plot selected in this case study is set as a multi-function building to support activities in the open space. It consists of 16.5 x 42 m with commercial areas on the ground floor while offices are on the upper floor. The proposed building is expected to adapt to the environmental performances of the surrounding site without violating sun access to certain building functions.

3.4 Data collection

In terms of dataset availability, this study uses an open data platform for gathering 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 is a digital altitude map of point cloud according to laser altimetry measurements. During the data collection phase, three steps are performed as illustrated in Table 3.1, namely site selection, data conversion, and computing environment.

TABLE 3.1 Data processing workflow of 3D point cloud data

Step 1	Step 2	Step 3
		
Site selection	Data conversion	Computing environment
AHN map	Cloud compare	Rhinoceros + Grasshopper

3.4.1 Data conversion

Data conversion aims to prepare appropriate datasets to be ready for use in the simulation. To do so, Cloud Compare (CC) is mainly used as supporting tools. The following steps highlight tasks for this phase:

- Activate color fields of the dataset. As the original dataset comes from the AHN map, the initial color remains monochrome. Thus, color fields are essential in order to filter selected areas based on scalar field values. The scalar field value refers to the real number for each coordinate in space such as 3D space $\Phi = \Phi(x, y, z)$ [52], or a structure depicting real (scalar) values [53]. In CC, several 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). Embedded with the scalar field, the gradient color in the Z coordinate represents the elevation of the area. In this regard, the red color indicates the highest position while the blue color shows the lowest position. From this point on, the color scale value can be used to filter and identify specific areas according to its elevation although the filtering features in CC are limited to per area, not per object.

- Export the selected dataset. In order to be legible and interoperable in parametric design environment, the dataset needs to meet the appropriate format. In this regard, we export the original dataset (.laz file) into the .e57 file as it keeps the color field of datasets visible in the 3D modelling environment.

3.4.2 Computing environment

This study considers parametric designs to enable architects to integrate point cloud data into environmental design platforms. Due to unclassified points from imported datasets in CC, site properties such as buildings, trees, and other objects contain the same point entity. Therefore, the following actions are required to run before performing the simulation:

- Classification of existing objects. This task is important to only select relevant existing objects for the simulation. This study, for example, only selects two relevant building facades to be included in the sunlight hour simulations.
- Generation of reference site plans. It is used to set the boundary of selected building areas, especially for the sun right access threshold.
- Generation of the TIN model from the point cloud data.
- To carry out the above mentioned tasks, this study specifically uses Rhinoceros as a 3D modelling platform in parallel with Grasshopper (GH) for a visual programming environment. Besides, several environmental simulation components are used such as Ladybug [54] for constructing the solar right and the solar collection envelope, Volvox [55] for the point cloud processing, and some custom components [56] for generating the TIN model.

3.5 Development of the design framework for solar envelopes

This paper formulates new computational workflow for establishing solar envelopes by considering two design principles, namely the solar right envelope and the solar collection envelope. The integration of these envelopes generates a maximum developable volume of building design according to solar access criteria.

The solar right envelope stands for a maximum height of the envelope surface based on predefined criteria. To achieve the solar right envelope, the sun access level needs to be regulated considering the adjacent buildings during a desirable period. The main rule is to maintain sun access to surrounding buildings without obstruction from the mass of new building design. To do so, the height level of sun right access from the surrounding buildings should be marked first. This height 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 above the 1st floor. This creates a shaded area for surrounding buildings located below a predetermined level.

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 the desirable period. The limit of the solar collection height is determined considering the upper border of surrounding buildings. As a result, areas in the proposed design that are located below the surface of solar collection envelope will not get direct sun access. The mechanism of solar collection envelope can also be used to identify the potential areas of the solar collector in the proposed design. In this case, the solar collector refers to the solar panel instruments to absorb sunlight as a source of building energy.

Furthermore, this study identifies many variations of solar envelope parameters as described in the previous literature. The inclusion of point cloud data allows for the formulation of additional parameters in the existing workflow of solar envelopes. This study particularly considers two main components for the generation of solar envelopes. First, the climate aspect consists of the weather data, longitude and latitude coordinates, azimuth and altitude angle. Climatic properties also include several important information such as the sun path (useful for running the analysis period and radiation analysis by inputting specific location contained in the weather file), sky components (generating a matrix of sky patches based on the Perez's weather model, sky density, and connecting the analysis period for the radiation analysis), and insolation periods. In this case, we set a scenario for 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, site rules and environmental aspects. These aspects consider the plot area, set back, height restriction, vegetation and the TIN model generated from the point cloud data. Last, the simulation results consist of a comparative analysis between performance indicators using different 3D modelling platforms. An overview of the selected parameters is illustrated in Figure 3.5

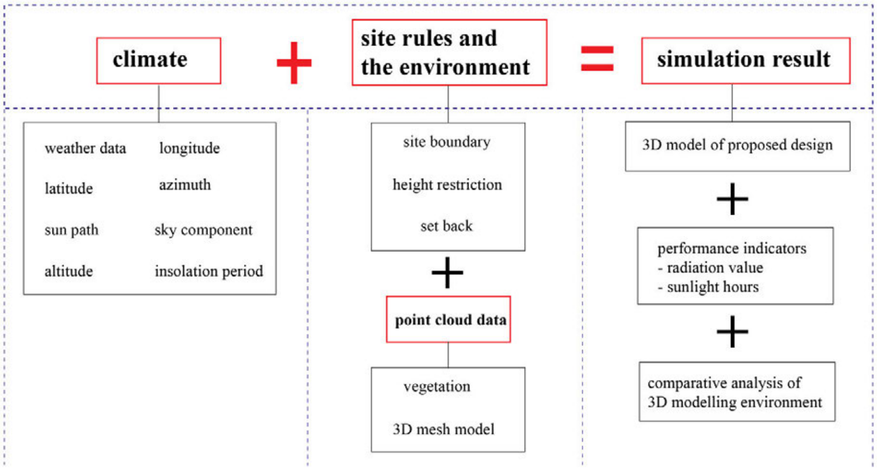


FIG. 3.5 Selected parameters for solar envelope

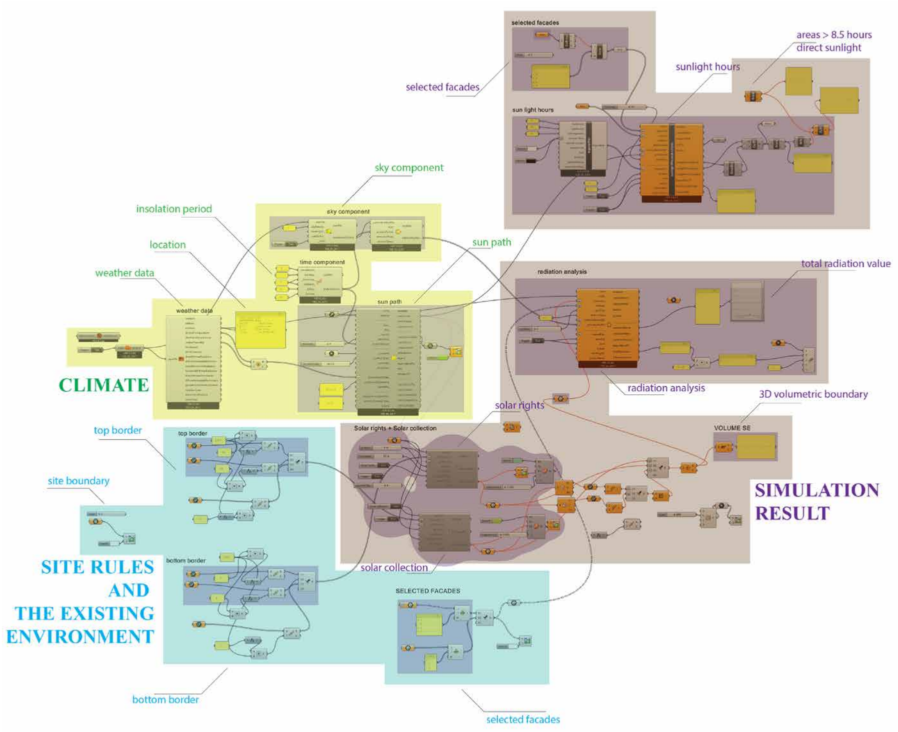


FIG. 3.6 Computational workflow of solar envelope frequency

According to computational workflow of the solar envelope (see Figure 3.6), the use of 3D point cloud data shows the following impacts on the geometric envelope:

- The role of vegetation in the proposed workflow affects the shape and volume of the solar envelope. The proposed scenario sets the sun access protection to the intended design without being blocked by surrounding vegetation. In this case, vegetation acts as part of the site obstruction. Thus, we set the vegetation elevation level within the limits of the solar collection parameter.

- The ability of 3D point cloud to capture complex building geometry can fill gaps in manually built 3D model regarding building surface properties. For example, point cloud data can be used to construct the 3D model of under construction buildings around the plot or areas located in congested environments such as alleys or isolated places. Therefore, modifications that occur to building facades due to renovations can always be modelled as is and included in the simulation of solar radiation analysis.

- The total radiation value and sunlight hours analysis may create significant simulation results when considering only relevant facades rather than entire building surfaces. Accordingly, the simulation in this study only selects facades facing the plot.

- The inclusion of sunlight hour analysis allows the detection of the most accessible areas that receive solar radiation on the building facades and plot areas during a certain time. As a result, we can identify the potential area of solar collectors in the geometric solar envelopes. The simulation results exemplify the different values of sunlight hours produced by two different 3D models.

3.6 Results and discussion

In order to construct an in-depth analysis of the simulation results, this study investigates two comparative aspects that intersect each other as follows (see Figure 3.7):

- The simulation context is divided into two parts, namely the proposed design and the existing context. In the proposed design, two indicators are calculated: the envelope’s volume and the radiation value. 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 radiation values. The simulation mainly covers the areas included in the selected wide-span facades, the high-rise building and the plot.

- In the simulation process, the 3D site model compares two types of modelling techniques: manually-built 3D geometric models and digital geometric models generated from point cloud data that refers to the TIN model.

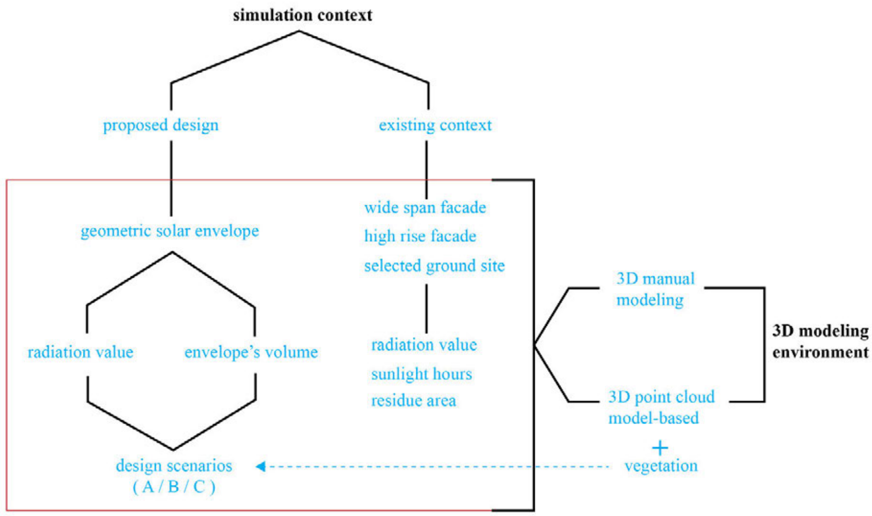


FIG. 3.7 Comparative indicators of the simulation context

3.6.1 Simulation of the existing contexts

As illustrated in Figure 3.7, the simulation assessment based on the existing context consists of three indicators: sunlight hours, radiation values, and residue areas. These indicators are evaluated by comparing two different 3D models, which are manually-built 3D geometric models and the TIN model. In principle, the geometric surface of both 3D models similarly uses the polygon mesh as it contains vertices, edges, and faces [57] and thus, it is easily transformed to any objects. However, the mesh generation techniques are constructed differently for the two models. The manually-built 3D geometric model is generated based on the quadrilateral type of cell shapes. However, this process is applied on the 2D plan extrusion so it makes the surface morphology of the buildings is mostly flat and plain. On the other hand, the TIN model employs the triangle mesh based on the Delaunay triangulation method. Due to a proximal technique, the Delaunay method often results in depth and irregular structures in the surface morphology of the TIN model. This is because the three nodes of a triangle need to be maintained within the boundaries of the imaginary circle [58]. Nevertheless, the automatic generation process of the TIN model takes less time compared to the manually-built 3D geometric model.

TABLE 3.2 Simulation results based on the existing context

The manual model	Total sunlight hours (n hours)	Areas > 8.5 hours of direct sunlight (m^2)	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 (m^2)	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

Table 3.2 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 [59]. Thus, the total hours received by each simulation model is principally the accumulation of direct sunlight retrieved by each mesh face corresponding to each test point. For example, the total test points included in Façade building A are around 124 test points. Then, when the total sunlight hours of Façade building A are divided by 124, the sunlight hours produced for each test point will be approximately 221,58. Furthermore, 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 3.2, the manual 3D model, on average illustrates larger values for all performance indicators in comparison to the TIN model. In the case of total sunlight hours, although the number of test points for the TIN model is greater than that of the manual 3D model, its test point value is quite small. This is caused by two factors. First, the mesh surface of the resulting TIN model is unequal and unstructured from one side of the triangle to another. Afterward, the shape of these triangle faces is constructed by the interpolation factor between control points (referring to the Delaunay Triangulation method). The robustness of triangle meshes and test points shows a trade-off with the point density from the original dataset as they principally affects the grid distribution on the surface of the final mesh. In contrast, by enlarging the mesh surface of both models (see Figure 3.8), it is clear that the manual 3D model illustrates a flat and continuous surface and thus, it affects the equal grid distribution for the test points.

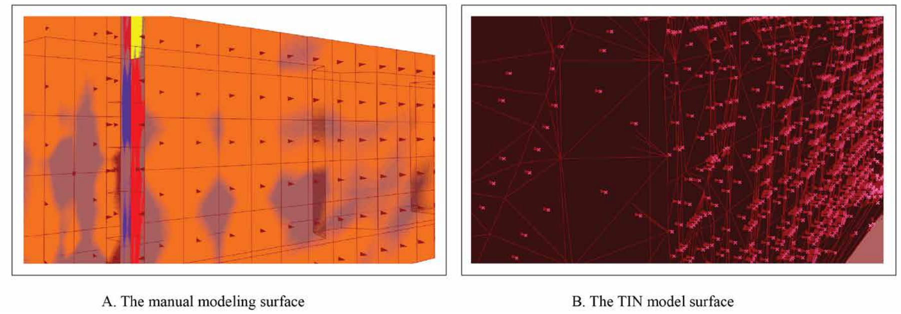


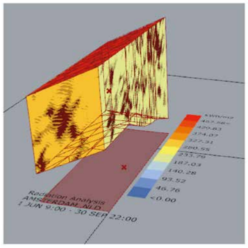
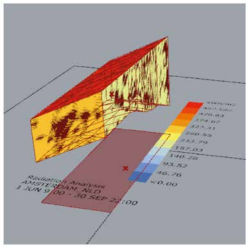
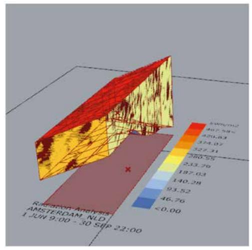
FIG. 3.8 Comparison of the solar point vectors

Second, the direction of the triangle mesh surface in the TIN model demonstrates an irregular position. This means that the test point vector follows the orientation of the triangle mesh due to its normal perpendicular position. Consequently, these point vectors respond differently to incoming sunlight and yield various values in the simulation results. With respect to surface position, the idea of reflection behavior also significantly impacts on the surface properties of both models. The flat surface of the manual 3D model demonstrates an equal angle between reflection and illumination. According to the law of reflection, the incoming lights is directed to the specular path of the reflection process [60] which refers to the regular reflection. This mechanism indicates that the reflected light is either parallel or converged at a point and the accumulated radiation values converge in the same direction. Meanwhile, the scattered light reflection from the TIN model illustrates "the orange-peel effect" because of the reflection pattern from the wavy surface. As this condition is highly reliant on the surface morphological structure, the distribution of solar reflection is spread unequally which then affects the amount of radiation value accumulated during the simulation.

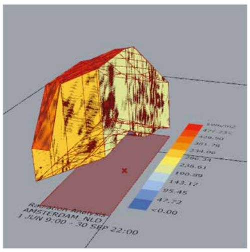
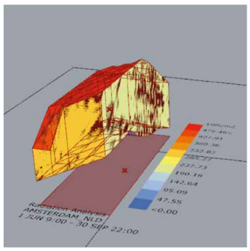
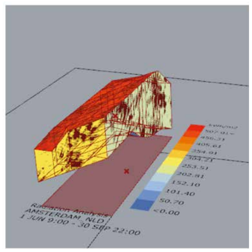
3.6.2 Simulation of the proposed design

The second simulation discusses the results of the proposed design. In this regard, three different scenarios are applied in the simulation of solar envelopes. Each scenario consists of sun access criteria that corresponds to solar rights and solar collection envelopes. The criteria for sun access refer to the upper and lower limits of the context property. As described in Section 3.5, the upper border indicates the height limit of surrounding environment properties corresponding to the solar collection surface. The lower border marks the minimum level of sun right access of the adjacent building which corresponds to the generation of the solar right envelope. The objective of these scenarios is to investigate the geometric configuration of solar envelopes following the sun access settings of the surrounding environment. Furthermore, geometric solar envelopes are then evaluated using two indicators, namely the volumetric envelope and the radiation value (see Table 3.3). The geometric assessment of solar envelopes aims to evaluate the performance of solar envelopes by considering the use of different 3D models of the surrounding environment.

TABLE 3.3 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
Solar envelopes			

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

According to the simulation results shown in Table 3.3, the following items are discussed:The geometric envelope for all the scenarios illustrate a nearly flat surface that inclines on the top envelope. The spatial context arrangement (see Figure 3.4b) shows that only wide-span building are located adjacent to the edge of the plot area. Due to the long and continuous shape of the wide-span, it covers the dimensions of the plot edges. Thus, the edge of the plot facing the wide-span illustrates a flat curve. However, on the other side, there is a high-rise building, but unfortunately, it is almost out of reach from the edge of the plot. This makes the solar envelopes geometry does not fully consider the site obstruction from the high-rise. The higher curve (facing the high-rise) is ultimately affected by the height limit of the upper border parameter. Furthermore, the inclusion of trees as site obstruction in the TIN model shows non-flat surfaces of the top envelope.

- Scenario A demonstrates the largest volume of the solar envelope in comparison with other scenarios in both 3D geometric models. This result indicates that the maximum volume of the solar envelope can be generated by setting a small difference value between the top and the bottom border. The same rule applies to the distance between the high-rise and the wide-span building. The smaller the difference value assigned to the top borders, the greater the volume of the solar envelope can be produced (scenario A for both models).

- Vegetation has successfully influenced the geometric and volumetric size of solar envelopes for all scenarios. Scenario A and C demonstrate the decreasing volume of solar envelopes and radiation values from the manual 3D model to the TIN model. However, different trends are illustrated in Scenario B, with the volume size of solar envelopes and the radiation value increasingly slightly in the TIN model. This is because we set a small difference between the upper and lower border for the vegetation parameter.

- Scenario C illustrates the lowest value for the volumetric size of solar envelopes as compared to others. This result simultaneously indicates the minimum buildable volumes of solar envelopes that can be considered for architects in design exploration.

3.7 Concluding remarks

The simulation results summarized in Table 3.2 and Table 3.3 illustrate that the use of point clouds not only contributes to the generation of solar envelopes but also offers further possibilities in analyzing the existing environment. The proposed method confirms a positive procedure in achieving the main objectives of this study. However, different workflows may appear with the use of data processing tools and levels of detail information.

Furthermore, the comparative analysis between the manual 3D model and the TIN model demonstrates significant discrepancies with respect to the simulated radiation values and sunlight hours. The use of customized components in Grasshopper also provides great assistance in the development of computational workflows, particularly related to the point cloud processing 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 surface accuracy of the TIN model needs to deal with the point density from the original dataset and the unstructured polygon surfaces during the mesh generation process. This study also does not consider further material properties during the simulation process because of the dataset availability from the AHN map. Consequently, the calculation of the radiation value focuses on the surface morphology of the building.

Further study related the aforementioned constraints needs to continue. The concept of “metabolism” by Knowles is of great importance in this study as it can have a broad impact on the quality of the built environment. The following are some potential development areas for future research:

- 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 envelope that can be useful during the conceptual design stage.
- Integration of current solar envelopes workflow into multi-objective optimizations. This aims to explore geometric solutions of the solar envelope according to specific objectives such as maximizing the energy distribution of the solar envelope and the efficient use of space within the solar envelope.
- Adjustment of different climates into the workflow of solar envelopes. For example, places like South East Asian countries will require a different objective of solar envelopes in comparison with European countries. In this regard, shaded areas are more suitable for tropical countries than European countries.

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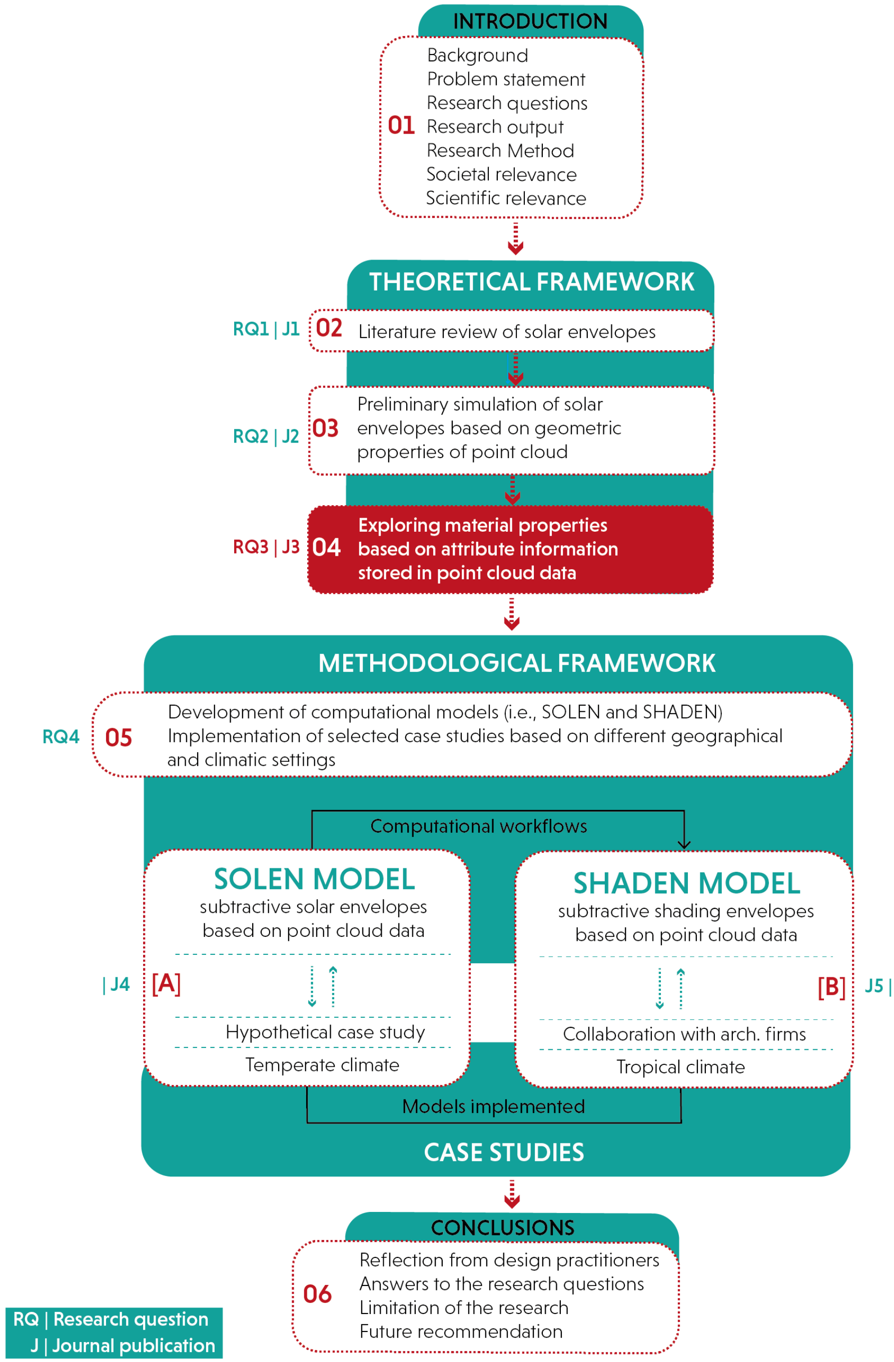
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4 Exploring Potential Applications Of Geometric And Radiometric Information Stored In Point Cloud Data

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The geometric aspects of point cloud contributed to the design context for the solar envelopes simulation in the previous chapter. It has succeeded in including relevant surrounding site properties (e.g., vegetation) to be considered as geographic inputs from the existing context. However, full features of point clouds have yet to be explored optimally due to the limited capacity and features of the ALS dataset regarding accuracy, visual representation, and isolated area coverage. Thus, this chapter investigates further possibilities for attributes information stored in the point cloud such as geometric and radiometric properties based on TLS (Terrestrial Laser Scanning) datasets. This chapter specifically explores surface materials from the existing context by computing optical (e.g., reflectivity, translucency) and thermal (e.g., albedo, emissivity) properties of contextual datasets.

It also simulates solar radiation and develops a material database used to establish an integrated environmental simulation based on the TLS dataset. This study allows architects to further conduct contextual analysis by identifying the potential and impact of the design context during the early stage of the design process. The computational workflow generated in this chapter provides many relevant design features for inclusion in solar envelope simulations, especially those related to material properties and surface characteristics of the surrounding context. Furthermore, these aspects significantly contribute to the development of a methodological framework in Chapter 5, especially for generating the SOLEN model in Chapter 5-Part A and the SHADEN model in chapter 5-Part B.

A computational workflow to analyse material properties and solar radiation of existing contexts from attribute information of point cloud data

ABSTRACT

This paper investigates a prospective application of point cloud data in supporting the contextual analysis of the built environment during the conceptual design process. Often, the complexity of site information causes architects to neglect several relevant properties that may affect environmental performance analysis, especially when dealing with a complex design case. For example, the current approaches of 3D site modelling lack an understanding of the site characteristics of existing environments with respect to either geometrical or material properties. With the advancement of 3D laser scanning technologies, capturing complex information from real contexts offers great possibilities for architects. From geometric and radiometric information stored within point cloud data, this study specifically proposes a novel approach to contextual analysis that considers material aspects and simulates solar radiation in the real environment. In doing so, three computational stages are developed. First, the correction of a raw dataset is designed to not only minimize errors during the scanning process but to also clean the selected dataset. Second, material exploration and the simulation of solar radiation are respectively used to calculate material properties and solar energy in the existing built environment. Third, an integrated environmental simulation aims at identifying materials found in existing areas within a certain level of insolation. As a form of design decision-making support, the present study ultimately generates a computational workflow for analyzing the built environment from which architects may conduct a comprehensive analysis of an existing context before initiating design exploration.

KEYWORDS

site analysis; point cloud data; attribute information; material properties; solar radiation

4.1 Introduction

The conceptual design stage is of the utmost importance to produce the most significant decision of architectural design process [1]. Within this stage, contextual analysis plays a prominent role in identifying relevant information for design input. Architects should be able to measure the environmental impacts of the proposed design to maintain the quality of the existing context. However, due to the complexity of information related to a building site, understanding the characteristics of the existing context comprehensively remains a great challenge when dealing with a complex design case. In most cases, existing approaches to 3D site modelling (e.g., solid modelling [2] [3]) pose several barriers that may result in the following features missing from the contextual analysis.

- The complex geometry of the existing context is not considered, especially when dealing with isolated and dense areas [4]. Consequently, it will often take too much time for modelling construction to consider detailed site properties.

- Building-focused contexts tend to be explored, which consequently neglects surrounding properties such as vegetation or other temporal site elements [5] [6]. This matters when conducting environmental simulations of processes such as the UHI (urban heat island) effect or when addressing microclimatic issues.

- Material characteristics of the existing environment [7] [8] have yet to be considered properly in 3D site modelling. This can greatly affect the calculation of environmental impacts for both proposed and existing buildings. In conventional design processes, material studies are frequently paid less attention to during the form generation process, and most of the material attributes geometrically applies when adapting architectural components (e.g., concrete for walls or ceramic tiles for flooring) [9] [10]. Consequently, it will be challenging to identify different material properties within a single component due to the use of fixed materials. As a matter of the fact, such material properties will be extremely likely to present the same values for different architectural components due to being positioned within the same environmental settings.

On the other hand, the advancement of 3D laser scanning technologies has enabled one to easily capture complex information from real contexts. A potential application of point cloud data may include making information relevant to the aforementioned gaps available. In this case, a point cloud consists of geometric and radiometric information [11] [12] or may refer to visible and invisible properties, respectively.

Visible properties are stored in a colour point cloud, which geometrically represents a real 3D model of the existing environment. Meanwhile, invisible properties include attribute or metadata information associated with each record of measurement [13]. On the basis of point cloud data, this study proposes an approach to environmental performance analysis that involves an integrated workflow of material studies and the solar simulation of an existing context. The present investigation of material aspects aims at mapping surface properties of the existing environment with the support of radiometric information while geometric information may cater to the simulation task of solar radiation. With this integration, the novel method proposed in this work makes several contributions to the current workflow of the architectural design process:

- The attribute information of point cloud data (position-XYZ, color-RGB, and reflection intensity-I) allows one to easily conduct an environmental analysis during the conceptual design phase, especially in regard to the material performance of existing environments. After investigating optical and thermal properties, a surface distribution catalogue can be generated to identify the material characteristics of existing areas. This can be helpful to architects wishing to perform comprehensive site analysis before making a design decision.

- A point cloud-based solar simulation can effectively mitigate geometric concerns related to the 3D modelling context. Relative to the existing approach, the solar simulation method can be performed without necessarily converting a complex dataset of point clouds into a massive 3D mesh model. This process can be used to identify further opportunities to run more environmental simulations directly based on an unstructured point cloud dataset. The inclusion of more site properties during a simulation may also enrich environmental simulation results.

- Integration between a material database and insolation values allows one to measure the specific performance of any surface within an existing dataset. Accordingly, architects are presented with a fully informed site database that can be used to identify vulnerable areas that may affect the performance of the proposed design. In this case, architects not only need to balance the geometrical relationship between surrounding buildings and the proposed design but must also balance surface materials (performance of the building skin) between them.

This work is divided into several sections. Section 4.1 presents an overview of the study, describing information missing from current architectural design approaches and following with a note on the relevance of point cloud data for addressing the highlighted issues emerging during site analysis. Section 4.2 presents a theoretical background that specifically investigates potential applications of point cloud data to material properties, and solar radiation analysis. An in-depth discussion of computational design methods is then given in Section 4.3 Our dataset collection approach and a detailed analysis our findings are given in Sections 4.4 and 4.5, respectively. Finally, Section 6 presents a conclusion and recommendations for future study.

4.2 Theoretical background

As a facet of design decision-making support, we principally attempt to perform a contextual analysis taking into account the real environment. In doing so, point cloud data are used to provide relevant information in support of the two primary subjects of this study: material properties and solar radiation analysis. Raw dataset correction is also briefly discussed as a guide to dataset preparation before processing the next stage. The present section will describe specific features of these subjects through the following discussion.

4.2.1 Point cloud data

Geometric information

As a product of laser technology, point clouds have been widely implemented in many fields such as building construction [14] [15] [16], landscape modelling [17] [18], cultural heritage [19] [20] [21] and environmental engineering [22] [23] [24]. Weinmann [25] describes a point cloud as having two parts: the “point” geometrically speaking represents the particular unit of location in a specific space and the “cloud” refers to the unorganized arrangement within a blurred spatial boundary. Otepka et.al. [26] define a point cloud as a set of points that are attached to three-dimensional Cartesian space. As an extension of these definitions, Randall [27] exemplifies several particular functions of the geometric information of point cloud data as follows:

- To draw the position of an object with 3D coordinates in a global coordinate system.
- To illustrate geometrical features such as the length between two points and the orientation of objects.
- To illustrate visual information such as 2D and 3D digital images and 3D virtual models.
- To support physical features such as textures, cracks and different types of objects of varying density [28].

These functions, furthermore, create an opportunity to not only cater to data visualization but to also drive precise simulation performance [29]. For example, with the support of 3D colour point cloud data, some existing studies of archaeology and heritage [30] [31] have successfully investigated the geometric aspects of building materials. However, these material studies are predominantly performed on the basis of the massive 3D mesh model. This approach, unfortunately, presents several important issues, including the means of reconstructing point cloud data to a 3D mesh model, which consumes large volumes of computational storage, and the scale of the 3D mesh model for archaeology, which primarily deals with smaller objects than those of architectural building or urban scales. Thus, it is critical to develop an efficient method that can handle the dataset processing of architectural contexts without compromising the quality of performance analysis.

Radiometric information

The entity of radiometric information refers to attribute properties of each point within a dataset. Richter [32] notes six values of attribute information that can be further investigated to provide an accurate representation of a point cloud: color [33], object class information consisting of vegetation [34] and terrain [35], surface normal [36], horizontality [37], and global and local height [38]. However, only a few attributes are practically relevant during architectural design practice. The issue is not rooted in mere design objectives; rather, it originates from the prerequisites of particular attributes. Prior knowledge and pre-processing steps are still needed to extract the full functions of information properties. It is necessary, therefore, for architects to identify the feasibility of using attribute information that fits into the domain of a design framework.

To examine the context of environmental performance analysis in greater detail, this study focuses on the exploration of typical attributes of point cloud data, including coordinate positions (XYZ), colour information (RGB), and reflection intensity (I) [39] [40] [41]. Each of these attributes supports different tasks. For example, colour information is used to extract a certain area or object according to its colour values. This possibility can be observed during the identification of road signage by converting RGB colour into HSV values [33]. Similarly, Ochmann et al [42] examine colour and surface normal attributes to identify the inner surfaces of room volumes. Meanwhile, the reflection intensity constitutes the return strength value of the laser pulse of each recorded point, which represents degree of reflectivity measured from scanned objects [43]. In other words, intensity values rely heavily on the surface properties and materials of scanned objects [44]. Practical implementation can involve the detection of damaged concrete in a tunnel, pavement lines or stripping; the mapping of the seafloor, and the mapping of geological layers and damage caused by a natural disaster [12]. Furthermore, position information serves as an index of the coordinate location of each point that automatically aligns to both colour and intensity values of a dataset. For this reason, it is feasible to select certain areas of the dataset according to its attached values.

The attributes mentioned above explicitly facilitate the extension of the particular performance of point cloud data, to not only facilitate impressive 3D visualizations but to also drive environmental analysis during the conceptual design stage. When it comes to the site analysis process, these attributes may be able to enhance the sensitivity of site investigations, especially of those dealing with microclimatic issues affecting a dense area.

4.2.2 Correction of the raw dataset

As end-users of 3D scanning technology, architects are responsible for not only understanding relevant information from a dataset but for also identifying factors that may affect a dataset during scanning such as environmental conditions, meteorological conditions, atmospheric pollution [45] [46], scanner mechanisms, object properties, and scanning geometries [47]. In this case, point cloud data usually present technical issues related to dataset transformation and computational processing. For example, the TLS (terrestrial laser scanner) dataset often consists of a highly dense dataset such that it must be employed using a powerful workstation [48], and the interoperability the dataset results due to the use of different formats, quality levels and units among default scanners [49]. Such aspects must therefore be managed beforehand to allow for dataset processing.

After establishing the selected dataset, the correction of a raw dataset involves intensity correction. This aims at examining nearly “true” values of intensity as a means preventing erroneous measurements from being made during scanning (e.g., sensor noise, hardware sensitivity, laser wavelengths, and the surface geometry of the target) [50] [51]. In addition, Kashani et al [12] specifically describe several parameters that influence intensity values of a raw dataset such as target surface characteristics, acquisition geometries, and instrumental and environmental effects. These factors, however, cannot be fully compensated for due to local constraints such as atmospheric conditions (humidity and temperature pressure levels) and default features from the manufacturer. Consequently, manual adjustment will still be required even though this is challenging for common users such as architects.

This study specifically applies an intensity correction to a raw dataset by focusing on the acquisition geometry from the angle of incident (α). The angle of incident is the angle between the surface normal vector and incident radiation vector [52] [53]. One can be observed from the oblique surface of a building that produces more backscattering cross-sections than a direct surface when struck with a laser beam [12]. As the TLS dataset largely depends on the tools and manufacturers of laser scanners [52], distance effects are not considered further in this case. The distance between the instrument's position and scanned areas also adheres to a tolerated distance between the brightness-reducer and scanner.

4.2.3 Material properties

In the preliminary design stage, a crucial task facing architects is to identify environmental impacts on the existing context that may affect a new building and vice versa. In relation to this, the potential application of point cloud data progressively enables one to investigate materials in the existing environment. Some publications have attempted to address surface material properties by making use of RGB colour and intensity values taken from TLS datasets. Some of these studies perform non-invasive material analysis through the measurement of chemical properties and from the albedo of scanned objects [54], and investigations of reflecting surface properties based on effects on the maximum range and the range delay error [55], and based on different surface conditions (e.g., wetness and darkness) [56] [57] [58]. Material properties can also be found from LiDAR (light detection and ranging) datasets through the BRDF (bidirectional reflectance distribution function) model and intensity data [59], and through the use of lidar return density values in identifying water bodies [60]. The objectives of these works, however, predominantly focus on the geometric accuracy of surface characteristics (roughness and reflectance) of different material samples determined from indoor laboratory experiments while in this study material properties are investigated by taking into account both optical and thermal properties according to a dataset of a real building context. Moreover, we perform intensity corrections on a raw dataset to compensate for factors related to data acquisition geometries, which are mostly absent from the existing material studies of TLS datasets.

Furthermore, Kigle-Boeckler [61] describes four key elements in defining surface properties of objects, including materials (e.g., coating, plastic, or metal), surface topographies (e.g., smooth, rough, or structured), the degree of transparency, and the substrate. Based on these items, the present study examines surface materials of a real building dataset by focusing on two aspects: thermal and optical properties.

First, thermal properties demonstrate the quality or attributes of a material, which shape the response process when dealing with the conductivity of heat or with heat fluctuations over time [62]. For the dataset of a point cloud, the following indicators are measured to facilitate the identification of surface materials.

Albedo

Albedo refers to the fraction of sunlight reflected from a material or surface [63] [64] [65]. Albedo values have a significant impact related on the energy balance of an urban environment, as they constitute absorbance percentages of solar energy. As such, albedo can be used to describe the environmental characteristics of certain areas. Albedo values range between 0 and 1 where a lower value corresponds to a blackbody [66].

Emissivity

According to Ashby et al [67], emissivity refers to heat radiation emitted by the surface of a material. It is also defined as the ratio of radiated light reflected from a material to the volume emitted to a blackbody for the same temperature, wavelength, and emission direction [68]. In contrast to emissivity data, intensity information of point cloud data takes a value of 1.0 for a bright (white) surface or perfect reflector while a perfect emitter (black) is assigned a value of 0. Examples include materials with smooth and shiny surfaces such as plastics, ceramics, water and polished metals, which are generally characterized by high-intensity values but low levels of emissivity [69]. While in principle both emissivity and intensity determine their values contrarily, they consider a similar aspect related to the material of the object's surface. In so doing, the determination of emissivity values can be identified from corrected intensity information.

Second, materials with optical properties are principally determined through their interactions with light or electromagnetic radiation. Regarding optical properties this study focuses on investigating reflectivity and translucent values of materials by taking into account the RGB colour of each point within a dataset. Section 3.1 presents a detailed calculation of these values.

Reflectivity

In general, reflectivity describes the amount of light reflected from a material in relation to the total amount of incident light that reaches the surface of a material [67] [68]. Marsh [70] furthermore distinguishes reflectivity from reflectance. As a boundary property, reflectivity refers to a layer between two particular types of objects while reflectance corresponds to a layer between two specific instances of objects. Nevertheless, in the case of opaque materials, both reflectivity and reflectance are of equal value except in the case of transparent objects, as internal reflections within such materials appear to have a considerable effect. In accordance with a given point cloud dataset, the calculation of reflectivity values in this study predominantly covers opaque materials due to laser scanning capacities. With current applications of laser scanning, a fully transparent record of objects results in a coarse cloud of points within a dataset. This simultaneously confirms the scope of this study on reflectivity properties.

Translucency

An investigation of translucent properties of a material inevitably also involves the calculation of its transmittance values. Transmittance is a material property reflecting a material's capacity to transmit light received through the material itself [70]. In turn, opaque materials should present a zero transmittance value as they cannot be penetrated by light. In regard to a point cloud dataset, one can calculate transmittance values of materials from colour information for each point. Following from this assumption, as long as a dataset contains RGB colour, the translucence of materials can be identified in parallel with a comparison of its reflectance values. Such a calculation is also supported through material mapping with ElumTools [71] when transmittance values are added to opaque material properties, allowing the selected objects to be categorized into a translucent material.

4.2.4 Solar radiation analysis

An insolation analysis involves evaluating how building surfaces absorb thermal energy from the sun [72]. During the conceptual design, evaluating the relationship between a building and the sun is critical to ensuring the behavioral performance of buildings based on optimal sunlight conditions. This process ultimately becomes relevant not only for a proposed building but it can also be extended to existing buildings through contextual analysis. For example, the simulation of solar radiation allows us to map the average solar energy of each panel on a building's façade. In turn, the potential amount of solar radiation reaching a building or site surfaces can be identified and further analysed.

However, as the issue that matters most for current simulation approaches to solar radiation, the 3D digital model of the existing context is primarily constructed by means of basic architectural geometric shapes. In regard to surface characteristics of buildings, the exclusion of textures from the context model and of other relevant site properties can considerably affect the interpretation of simulation results [73]. Things become even more complex when dealing with the 3D model for an isolated context or urban scale forms. Horvat and Dubois [74] reveal that less than 10 % of architects are satisfied with the utilization of various solar simulation tools. It is thus, important to at least consider surface properties of the existing environment during the simulation of solar radiation.

In the meantime, some existing works have conducted solar radiation analysis by making use of point cloud data. For example, in using a LiDAR DEM (digital elevation modelling) dataset, Kassner et al. [23] attempted to identify areas of high solar potential on a building's roof and the suitability of a PV (photovoltaic) system for urban areas by means of pyranometer measurements [75]. Carneiro et al. [24] and Jochem et al. [76] develop solar radiation models in urban areas to deliver an automated solar potential assessment. Similarly, an interactive 3D visualization of the solar urban model [77] has been generated to calculate the solar irradiance distribution based on roof and building facades [78]. Later, Pavlovski et al. [79] from a solar resource campus map and Li et al. [80] in using a pixel-based approach quantify solar energy stored within an existing building's roof and infrastructures. As a major concern related to these approaches, their workflows are inclined towards the domain of environmental engineering, which predominantly uses ALS (Airborne LiDAR) datasets. Meanwhile, studies have yet to focus on the use of TLS datasets rather than ALS datasets due to accuracy concerns [81] [82], high-resolution formats [27] [83], and broader coverage of isolated areas. Moreover, integration with the architectural design process has yet to be addressed and particularly in relation to site analysis based on TLS datasets. The present study ultimately attempts to address these issues by proposing a computational design method in the following section.

4.3 Development of the computational design method

As introduced in the previous section, the ultimate goal of this study is to develop an integrated workflow of environmental performance analysis for material studies and solar simulations by taking into account point cloud data for the existing environment. A series of computational procedures is developed to support this goal (see Figure 4.1); this involves the use of existing frameworks such as point cloud dataset processing and the normalization of intensity values in a first stage and then calculating material properties and sun angles in a second stage. In line with this, several specific frameworks are developed by the authors, including material database formation and the calculation of insolation values of point cloud data in a second stage and the material selection of point clouds based on insolation values in a third stage.

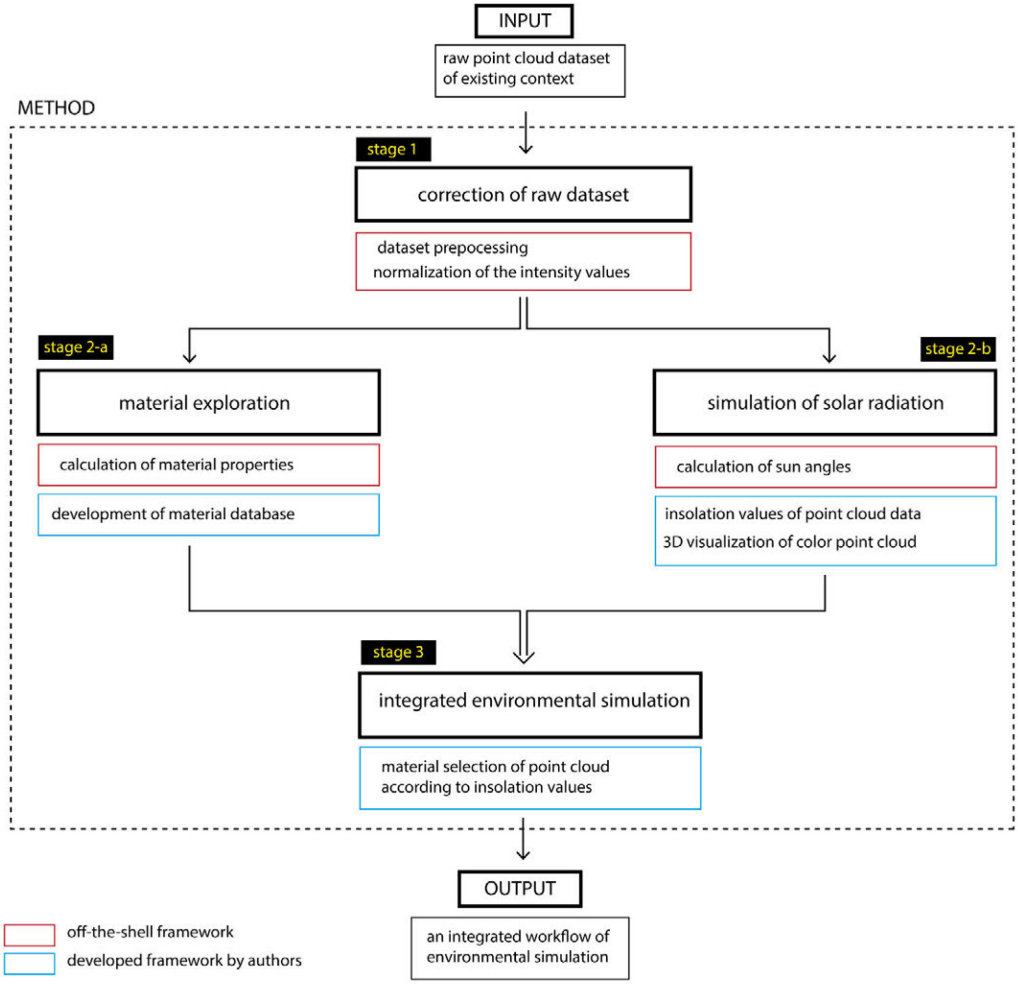

FIG. 4.1 Overview of the computational workflow

To illustrate the proposed workflow, a detailed discussion of inputs, procedures, digital tools, and outputs of each stage are addressed below.

4.3.1 Correction of the raw dataset

As noted in Section 4.2.2, in this study we perform raw dataset corrections. This process mainly involves two tasks: pre-processing and intensity correction. Figure 4.2 presents a detailed account of this stage.

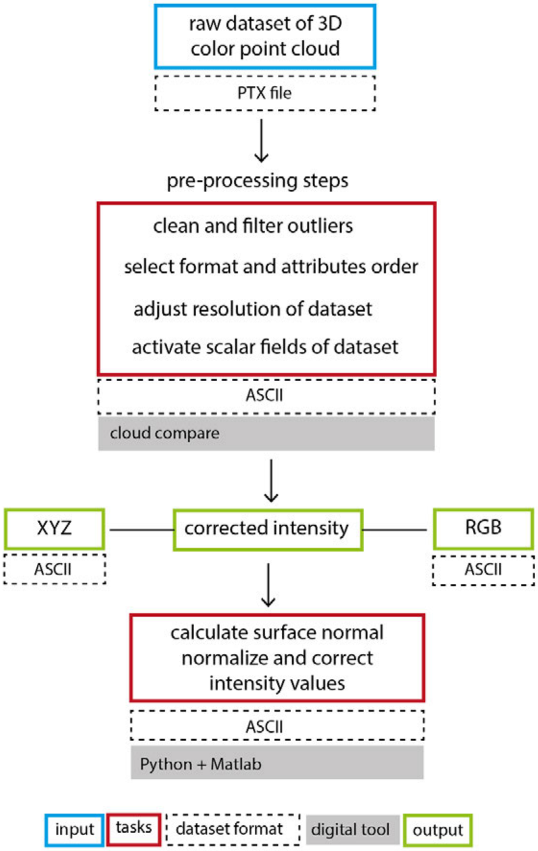

FIG. 4.2 Correction of the raw dataset 3D models

Before the dataset is readily used for architectural design analysis, several preliminary steps are completed to avoid irrelevant properties that may compromise workflow performance. These steps involve noise reduction and outlier (unnecessary clouds of points) removal, the selection of attribute order and dataset formats due to interoperability issues emerging during analysis, and the activation of scalar field functions to identify metadata information for a point cloud.

These preliminary tasks are computationally supported by Cloud Compare (CC) [84]. One task involves reducing the density of points to manage computation time and calculation requirements of the dataset.

For intensity corrections (I_c), we use the following equation [12].

$$I_c = I_{raw} \cdot \frac{1}{\cos \alpha} \tag{1}$$

where I_c = corrected intensity
I_{raw} = original intensity
α = angle of incidence

The angle of incidence is determined with equation [50] below based on the assumption that the initial positioning of the laser scanner is known at (0,0,0).

$$i = \cos^{-1}\left(\frac{\overline{dn} \cdot \overline{dl}}{\left|\overline{dn}\right| \cdot \left|\overline{dl}\right|}\right) \tag{2}$$

where i = incident angle (α)
$\overline{dn}$ = direction of surface normal
$\overline{dl}$ = direction of the laser pulse

Before applying these algorithmic functions for intensity corrections, the raw intensity values must first be normalized. This procedure is designed to calibrate the numerical index of the original dataset during arithmetic operation.

Material exploration

This stage involves two main steps (see Figure 4.3): *first,* material properties (thermal and optical properties) derived from attribute information such as XYZ, RGB, and corrected intensity values are calculated, and *second,* a material database derived from the calculation of material properties is developed. Material selection can then be performed with the material database according to the established criteria.

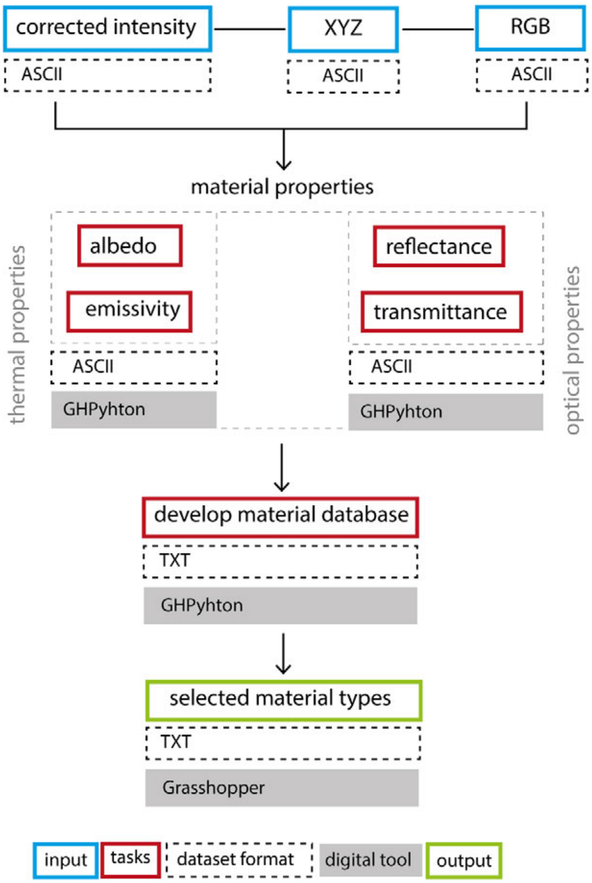

FIG. 4.3 Material exploration of point cloud data

As described in Section 4.2, thermal properties include albedo and emissivity values while optical properties include reflectance and transmittance values. On the basis of colour information of point cloud data, reflectance and transmittance values are calculated by referring to a graphics colour taken from the ElumTools library [71], which is also used as a reference for material and artificial lighting simulations in Revit [85]. Reflectance and transmittance values are respectively determined from the following equation

$$\text{Ref} = \left(0.2125 \cdot \frac{R}{255}\right) + \left(0.7154 \cdot \frac{G}{255}\right) + \left(0.0721 \cdot \frac{B}{255}\right) \tag{3}$$

$$Max.Trans = \left(0.2125 \cdot R_{avail}\right) + \left(0.7154 \cdot G_{avail}\right) + \left(0.0721 \cdot B_{avail}\right) \tag{4}$$

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$$R_{avail} = \frac{R}{255}$$
$$G_{avail} = \frac{G}{255}$$
$$B_{avail} = \frac{B}{255} \quad (5)$$

where Ref = the reflectance value
$Max.Trans$ = maximum transmittance
R_{avail} = the maximum amount of light reflected from the red component
G_{avail} = the maximum amount of light reflected from the green component
B_{avail} = the maximum amount of light reflected from the green component

To obtain maximum transmittance values, the most heavily reflected component should be initially identified based on non-dichroic transmittance. The resulting component is first subtracted by 1 to find the ratio of transmitted value to reflected light. This ratio is useful as a multiplier in calculating the relative amount of light for the other colour components. Accordingly, maximum transmittance values can be calculated by performing the mathematical operation given in equation (4). Emissivity values are determined from the corrected intensity attributes as both emissivity and intensity based on similar material aspects related to surface reflectance. In this case, however, their values principally work in reverse.

Furthermore, albedo values are computed from both colour information and corrected intensity. As is exemplified in equation (6), the calculation aims at not only measuring light reflected from the average of RGB colours but also capturing incident solar energy through the multiplication of corrected intensity values.

$$Alb = \left(\frac{\sqrt{\left(\frac{R^2 + G^2 + B^2}{3} \right)}}{255} \right) \cdot I_c \quad (6)$$

where Alb = the albedo value
R = the red value
G = the green value
B = the blue value
I_c = the corrected intensity value

After establishing formulas for all material properties, each point of a dataset can readily be inputted into the material database. This material database will then evaluate each point in a conditional loop according to the threshold value taken from optical and thermal properties. Due to a lack of compatibility between existing material libraries (e.g., Honeybee-Grasshopper includes Radiance, Open Studio 1.12.0, Energy Plus V8-5-0, THERM 7.6 [86] and CES Edu Pack 2017 [67]) and the proposed method, we propose a sample of relevant materials that matches the conditions of the selected dataset (see Table 4.1).

TABLE 4.1 Material database for the outdoor building context (collected from various sources)

Index	Material types	Material properties			
		Emissivity	Albedo	Reflectance	Transparency
0	Brick	0.93	0.4	0.2	Opaque
1	Asphalt	0.9	0.12	0.07	Opaque
2	Stone (granite)	0.44	0.30	0.25	Opaque
3	Stone (white marble)	0.75	0.6	0.45	Opaque
4	Wood	0.8	0.35	0.5	Opaque
5	Plaster	0.9	0.4	0.65	Opaque
6	Cement	0.54	0.8	0.4	Opaque
7	Ceramic tile	0.5	0.35	0.72	Opaque
8	Glass with a zenith-angle of 40-80 degrees	0.95	0.52	Transmittance – 0.75	Translucent

Discrepancies between existing material libraries can be observed from computational workflows and materials formats. For example, in Radiance, material setup involves using a specific type of material at the beginning of the workflow, which is then followed by material properties. By contrast, the method proposed in this work involves identifying materials at the end of the workflow as the output according to the selection process used for the point cloud dataset. Considerable efforts have been made to compensate for this issue by inputting material properties in CES Edu Pack beforehand. This approach generates several types of materials that correspond with input properties. However, a further consideration not only concerns the availability of material properties but also the complex range of material types that are to some extent seemingly irrelevant to the proposed context. For example, material selection in CES Edu Pack concludes with formation of many unexpected variations of specific engineering materials. Such a result would produce biased outputs from this study, which is intended to deal with architectural materials used for outdoor building surfaces.

Simulation of solar radiation

Due to the requirement of similar inputs from point cloud data (see Figure 4.1), the proposed process (stage 2b) is based on a similar level as that of stage 2a focused on material properties. As such, a portion of the employed dataset also takes selected points from the corrected intensity values. The workflow of our simulation of solar radiation is illustrated in Figure 4.4.

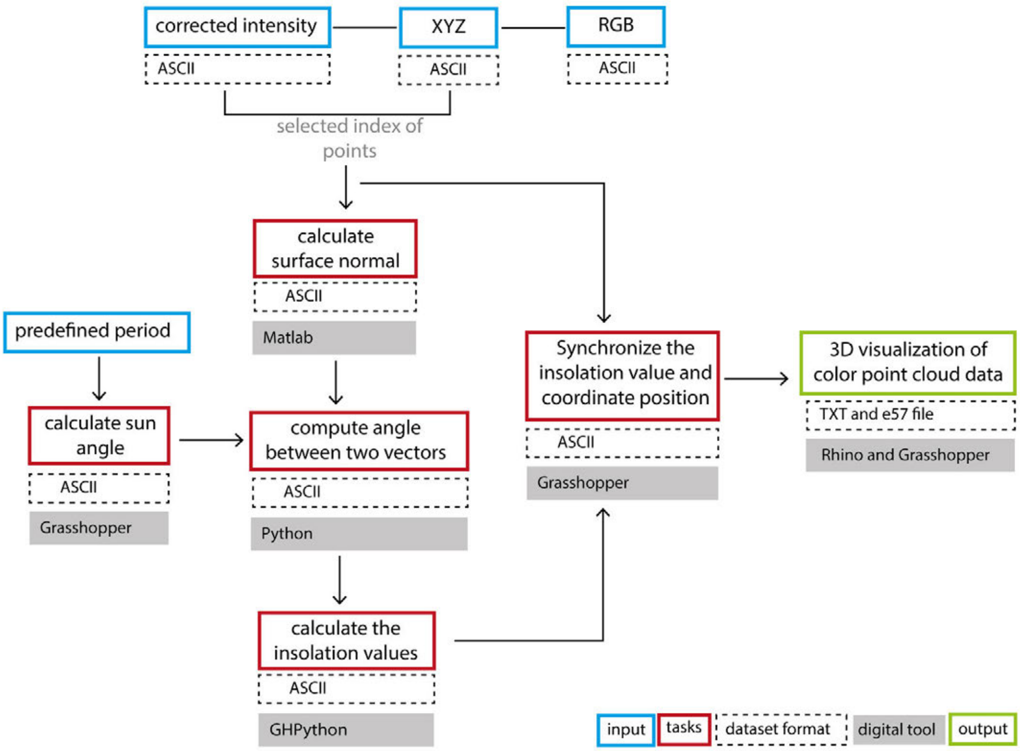

FIG. 4.4 Solar radiation simulation workflow

In general, the simulation of solar radiation involves the use of two main inputs: the sun's direction vector from the environmental variable and normal vectors of the site surfaces. The calculation of the sun vector involves the use of climate and geographic inputs such as latitude, longitude, and the specific point of time of given a year. Specifically, for this study this process is performed by using components available through Grasshopper, some of which include Ladybug and DIVA, but of course this can be done with other tools. Meanwhile, normal vectors of site surfaces are computed in CC due to the large number of points to be calculated.

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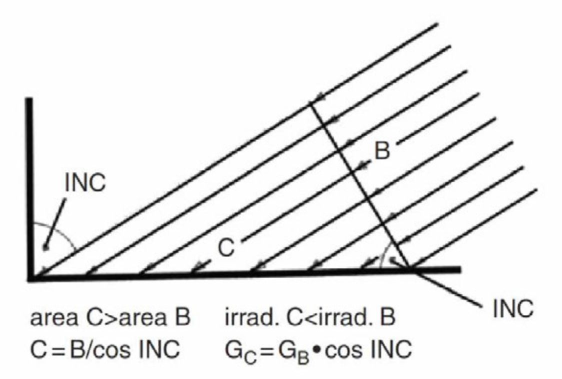

FIG. 4.5 Calculation of solar irradiance (INC: angle of incidence, G: global irradiance) [87]

With a trigonometric principle (see Figure 4.5) the insolation values of each point of a dataset can be calculated from the normal irradiance (the angle between sun vectors and normal vectors of the site surfaces) multiplied by the cosine of the angle of incidence (INC). In principle, solar energy is fully absorbed by the surface when the sun vector and the normal vectors are aligned. To reflect this, the cosine value of the angle will be 1 when the angle formed is zero such that as the angle increases, the cosine value will decline.

Furthermore, the following process requires the use of a synchronization value between the simulation result of the insolation analysis and the index of the coordinate position from the initial dataset. This allows for the identification of a surface's degree of direct sun exposure for the point cloud dataset. With a colour 3D point cloud, the lowest and the highest degrees of direct sun exposure can then be visualized to each point of the dataset. For outputs the proposed workflow produces a 3D point cloud model aligned with an ASCII file that presents a simulation analysis of the dataset.

Integrated environmental simulation

This stage involves investigating an integrated workflow between a material database and a simulation of solar radiation. It aims to not only identify materials in areas exposed to a certain level of direct sunlight but to also generate a highly informed site database through a fully integrated simulation analysis conducted in the preliminary design stage. The following figure describes the process of the integrated workflow (see Figure 4.6).

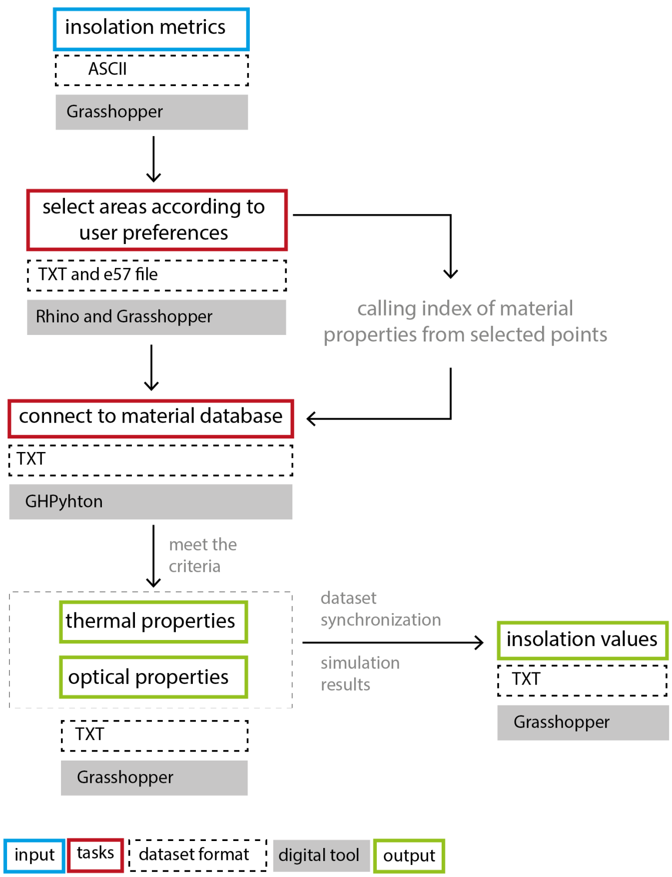

FIG. 4.6 Integrated simulation workflow

The main procedure of the workflow focuses on material selection according to material properties of the point cloud dataset. In this workflow, insolation values are integrated with material types such that surfaces subjected to high or low levels of solar exposure can be identified and extracted along with their materials. In this case, a numerical index of each point within the dataset plays a crucial role in synchronizing metadata between material properties and solar simulation results.

Ultimately, a list of insolation values corresponding with material types is the final output of the proposed integrated workflow. An evaluation of the whole dataset will generate the number of points that meet and do not meet the criteria of the material database. Accordingly, a comprehensive analysis of the environmental performance of the existing context can be conducted. To implement the proposed computational workflow, a sample 3D colour point cloud dataset is used in the following section.

4.4 Dataset collection

The proposed approach is implemented on a selected small sample of 3D point cloud data (see Figure 4.7). Several criteria are used during dataset collection, some of which include the following: *First,* the dataset consists of a 3D colour-point cloud. Colors can help architects not only visualize the representation of real objects in the digital environment but also analyse the appearance of materials and textures during simulation. *Second*, the dataset includes information on at least three typical attributes as mentioned above: XYZ, RGB, and reflection intensity (I). *Third*, the dataset includes multiple site properties for the sake of material property investigation. After setting these criteria, dataset collection can be applied to any architectural context.

FIG. 4.7 The selected 3D colour point cloud dataset

The collected dataset is for a Middelstum Church located in Groningen, the Netherlands. Its geometric properties include a building facade, trees and a surrounding landscape with a total number of points spread across 31,5 million points. Via cloud sub-sampling in CC, the minimum distance between two points can be adjusted to limit the density of points. In this case, the dataset is ultimately set at 5 cm, producing roughly 449.267 points from the total collection of points. Dataset collection is supported with a Faro Focus 3D laser scanner set to a wavelength of 950 nm. We also use a Nikon D5300 DSLR camera for the processing of the 3D colour-point cloud.

4.5 Study findings and discussion

Having established the selected dataset, this section discusses the implementation of the proposed workflow. The analysis results are presented under four categories: intensity correction, the surface distribution of material properties of the dataset, simulation results of the insolation analysis, and material selection for each selected point cloud dataset. These are presented in the chronological order of the proposed workflow described above.

4.5.1 Intensity correction

During dataset preparation it is important to first calculate the incident angle before determining the corrected intensity (I_c). For an unstructured cloud of points, the surface normal of the points is calculated by using a Hough Normals plugin [88] in CC. This condition requires that such a task identifies optimal normal values in the dataset. Several tolerance angles are then simulated into raw intensity values of 10° to 90° (see Figure 4.8).

Figure 4.8 shows the dispersion of points among cosine values from the range of angles. It shows that points can be scattered at a certain angle. However, the majority of dense points seemingly make up a small portion of each plot of cosine values. It can be said that some points on a certain surface might correspond very well to a laser beam projected at a certain angle during scanning. Roughness and material characteristics of the surface also play an important role in this condition. Furthermore, an evaluation of the scattered points is run by reducing them while maintaining the densest one. In doing so, a standard deviation of each cosine value is plotted to identify the density distribution of points within the dataset (see Figure 4.9).

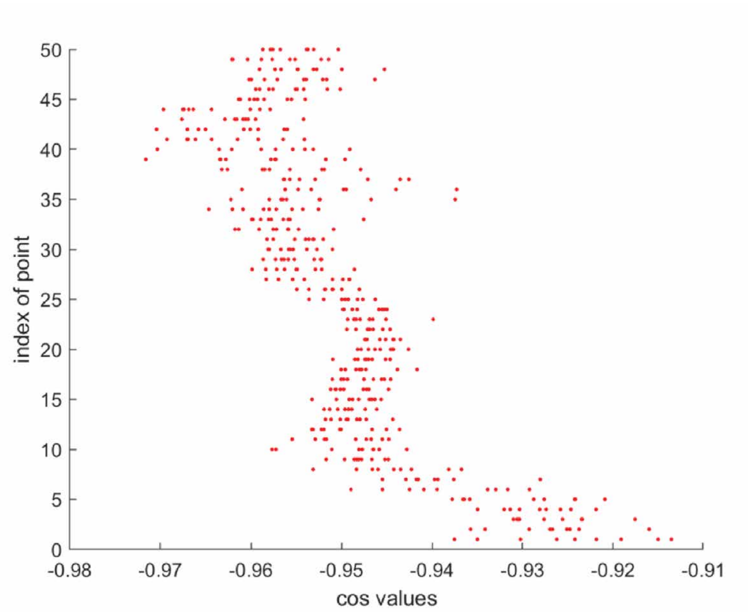

FIG. 4.8 Distribution of points according to the angle of incidents

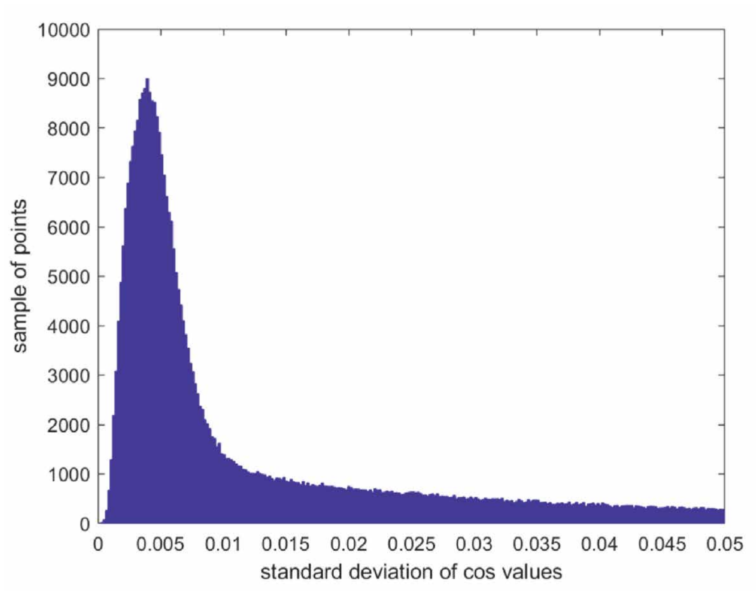

FIG. 4.9 Distribution of points according to the standard deviations of different cos values

According to the distribution of points shown in Figure 4.9, the proximate truncation of the dataset is set to range from 0 – 0.015. What results are roughly 266.864 points or 59.3 % of all points. As such, intensity corrections can be calculated using equation (1). Figure 4.10 below presents a comparison between the raw dataset and the corrected intensity values

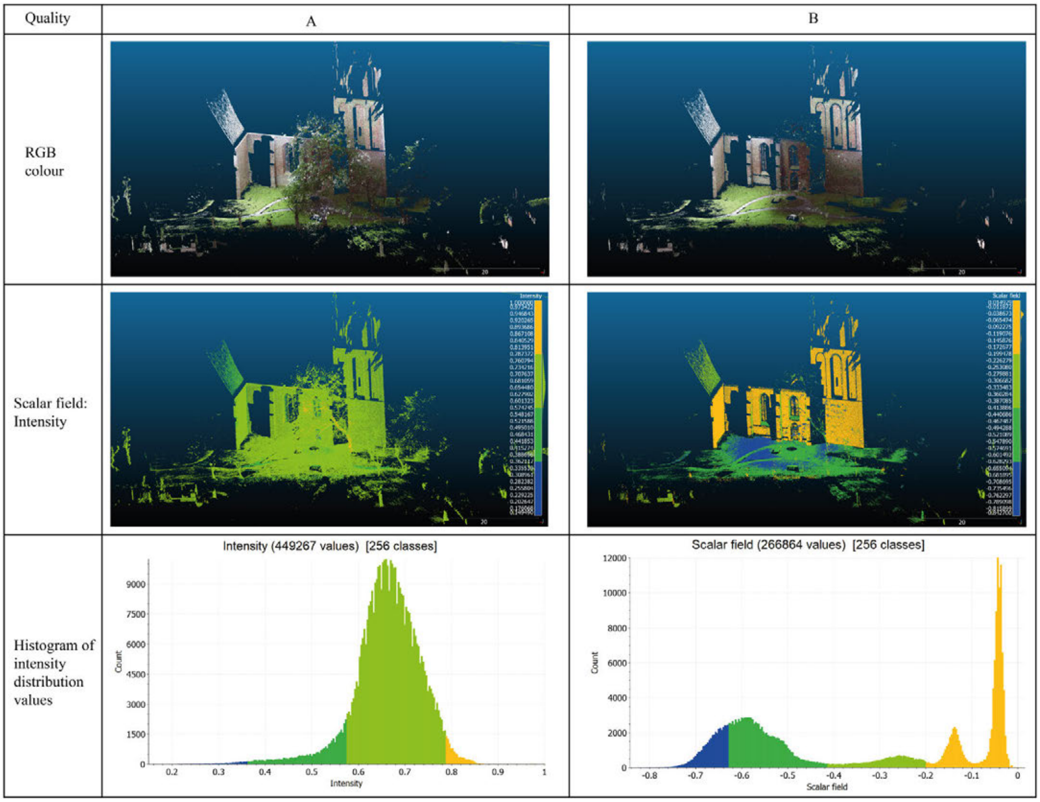

FIG. 4.10 Comparison of the (A) Original dataset and (B) Corrected intensity

The following aspects describe major changes in the dataset's performance resulting from the initial intensity level:

- As is illustrated by certain RGB colour features, several geometric properties of the original dataset (specifically trees and edges along the building) disappeared. In this case, intensity correction mostly affected not only the scattered points but also the uneven surfaces. This result simultaneously provides us with enough insight to temporarily exclude vegetation properties during the intensity correction phase, as vegetation will considerably affect all dataset values during the calculation of material properties and during the simulation of solar radiation.

- The colour value of intensity also undergoes significant transformation. Four colour steps are set to facilitate the legibility of the intensity range. As a bright colour, the color yellow represents a high-intensity value that concurrently refers to the most reflective surface while the color blue denotes the opposite. In Fig. 10-A (see part of the scalar field) the most reflective surfaces are predominantly distributed across the wall of the building. This intensity distribution reveals a major discrepancy from Fig. 10-B based on tree trunks located on reflective surfaces. In general, this serves as a crucial aspect of surface material properties to consider when determining intensity values particularly dealing with real building contexts.

- According to the histogram results, the distribution of intensity values observed within the original dataset concentrates at a green color representing approximately 89 % of the total density of the points. This means that green values are scattered across the entire surface of the dataset. On the other hand, from the calibration of the incident angle of the scanner and the normal vector of the datasets, the corrected intensity values ultimately present an obvious boundary between areas of high (yellow), moderate (green) and low (blue) intensity values.

4.5.2 Surface distribution of material properties

This step involves mapping material properties of the surface of the dataset in parallel with the calculation of point densities of each identified surface. With information on surface materials architects can measure the specific performance of certain areas within an existing dataset. Figure 4.11 presents the surface distribution of the selected material properties within a range of 0.0 – 1.0.

In general, the point density of surface materials follows a similar pattern as property ranges of the largest and smallest values. The three material properties of reflectance, emissivity, and albedo are measured within an equivalent range for the largest values, at 0.0 – 0.3. These constitute 21.4 %, 28.6 %, and 21.2 % of the total density of points, respectively. The only exceptions found for this largest range are transmittance values, with 19.097 % ranging from 0.4 – 0.5. Meanwhile, for the lowest percentages of values, reflectance, emissivity, and transmissivity occupy a similar range of 0.9 – 1.0. Only the albedo values are valued within a range of 0.0 – 0.1. Moreover, translucent properties are evaluated by comparing values of average reflectance and transmittance for each point. This evaluation is performed with a Boolean operation. When the reflectance is larger than transmittance values, the translucent material will be *False* and vice versa. The results show that translucent materials constitute 48.7 % of the points while the remaining 51.3 % have opaque properties. A comparison of these values statistically reveals that surface materials covered within the dataset primarily constitute non-reflective surfaces. This simultaneously shows that other surface characteristics of the existing context mostly include rough textures and high surface temperatures observed during the daytime [89].

A surface material catalogue allows architects to select particular areas to analyse further under an environmental design framework while providing supplementary information on which design treatments to apply to specific areas based on material parameters.

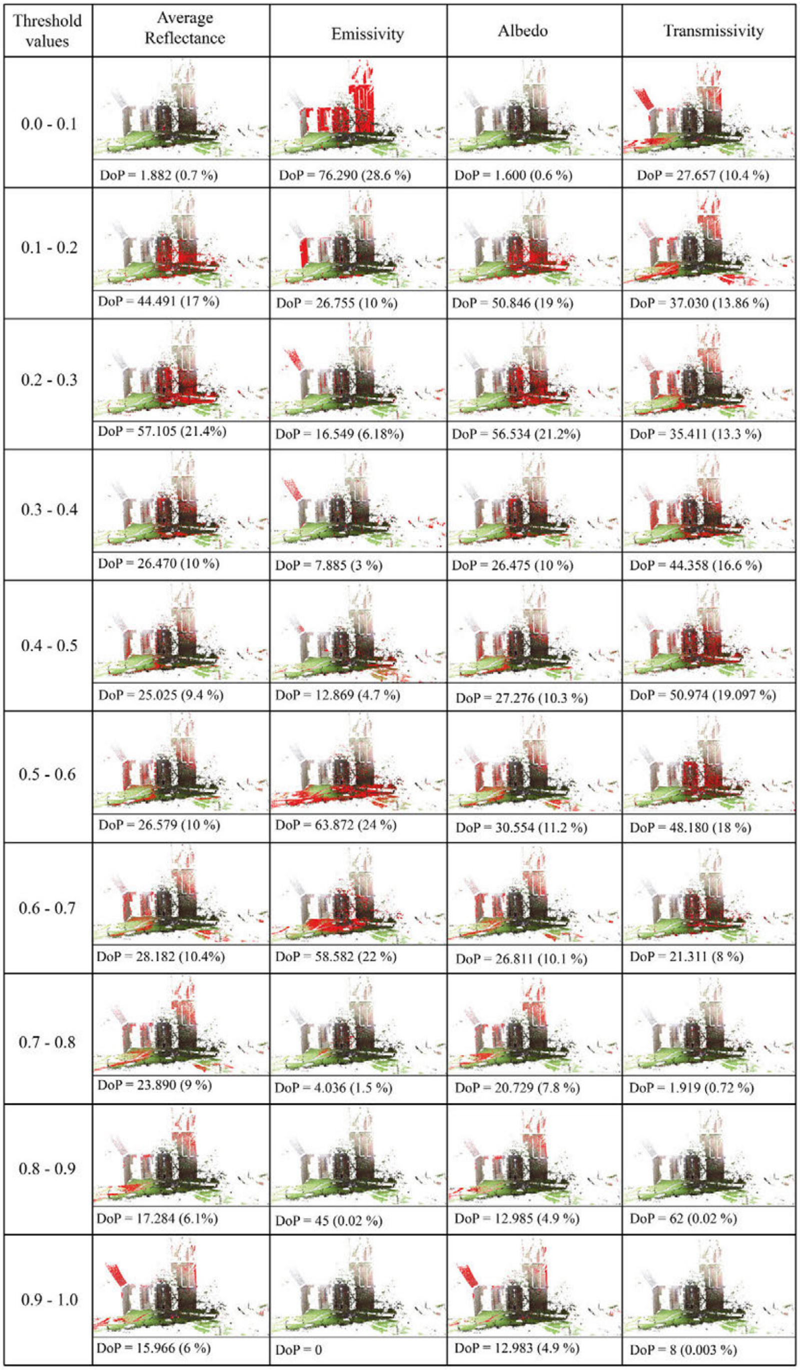

FIG. 4.11 Surface distribution catalogue of material properties

4.5.3 Simulation of solar radiation

As noted in Section 4.2.3, this step involves quantifying the solar energy of the existing context according to solar radiation simulation results for a point cloud dataset. In this case, the simulation focuses on the period of June – September 2017 (9 am to 8 pm Central European Time) with a coordinate position of 52.1326° N, 5.2913° E. From this setting, 36 values of sun vectors are produced from the sun angle calculation. These vectors are then computed to each surface normal of the point cloud dataset. Accordingly, each point of the dataset is evaluated from 36 sun vectors. The evaluation yields approximately 9.6 million radiation values. The aggregation of the time range will result in robust output values with the effect of consuming time during the simulation process.

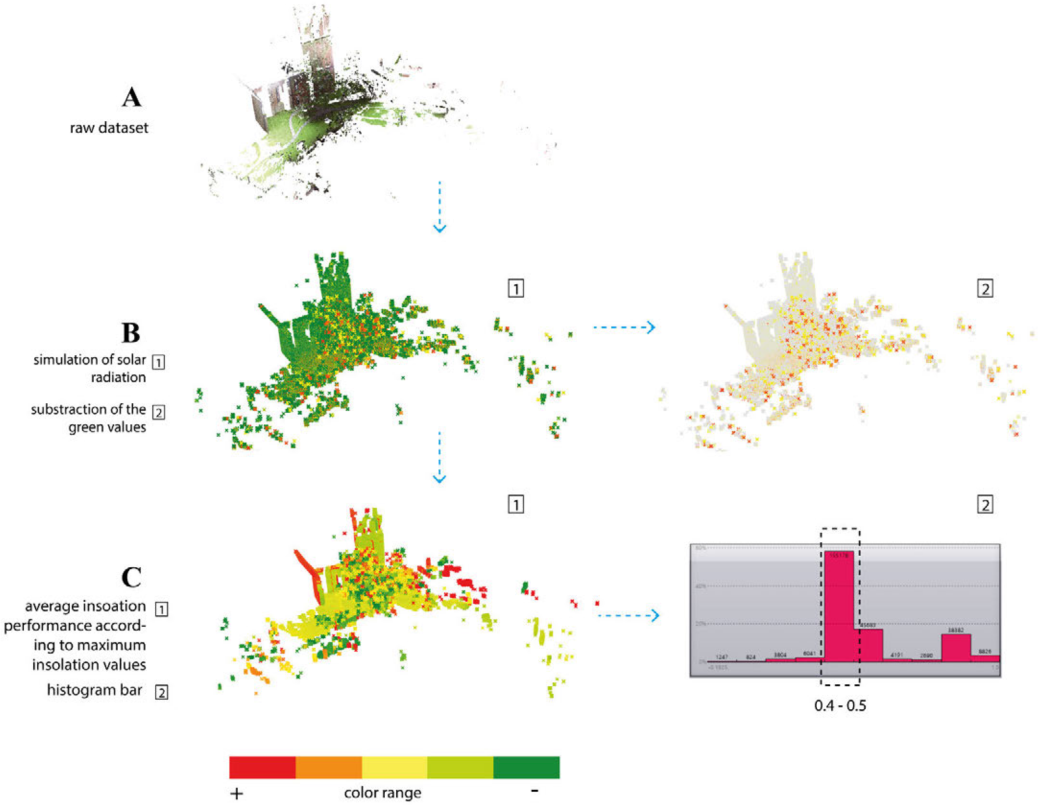

FIG. 4.12 Simulation of solar radiation

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Figure 4.12 presents simulation results for incoming solar radiation for the point cloud dataset. The simulation results are visualized based on five colour properties ranging from red to green, which respectively denote high to low radiation values. As is illustrated in Figure 4.12-B, less than 10 % of all radiation values meet the criteria required to absorb solar energy. The domination of green colours across the surface of the dataset indicates a lack of solar energy absorption. Meanwhile, yellow and red points reflect the dataset remaining from green subtraction (see Figure 4.12-B2) and originate from values of 0.8 – 1.0 according to their histogram bar values

Figure 4.12-C furthermore presents average insolation values received by each point of the dataset. During the simulation, only maximum insolation values from each point are counted. The histogram bar (Figure 4.12-C2) shows that yellow colours constitute the largest proportion of insolation values at 0.4 – 0.5 (58 % of all points). On the other hand, red colours as the highest values can only be found in certain areas with low proportion. For example, red points are unevenly distributed along the edges of the building's walls and along tree branches, which are unfortunately less conducive to solar collection technology application.

4.5.4 Material selection with integrated insolation values

This section discusses the workflow of integration for the material database and for insolation values derived from the simulation of solar radiation. With a developed material database, the proposed algorithm evaluates the material properties of the dataset according to a threshold value of optical or thermal properties. This approach allows for the identification of material types in parallel with the total number of points exhibiting optical or thermal properties. The database is furthermore employed to identify materials presenting certain ranges of insolation values.

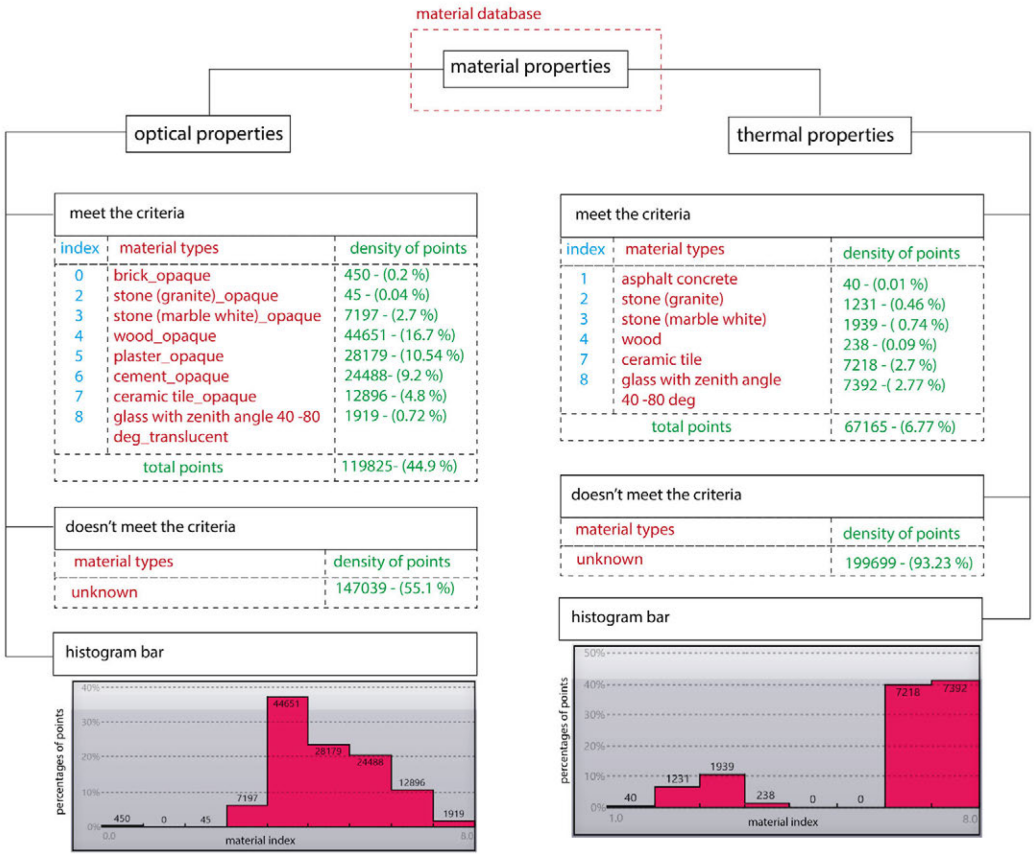

FIG. 4.13 Material selection according to optical and thermal properties

According to the material selection results (see Figure 4.13), the dataset most likely fulfils the criteria for material properties for the database (see Table 4.1). Unknown materials are found those points that do not fulfil the criteria. Eight of the 9 materials successfully meet threshold values for optical properties while for thermal properties only 6 materials meet the selection criteria. Regarding the density of points, the resulting optical properties of the materials are predominantly registered throughout the whole dataset, which includes over 44.9 % optical properties. Thermal properties represent only 6.7 % of the points.

Further results on this material selection are as follows:

- We find that transmittance criteria heavily affect dataset selection regardless of the number of points of transmittance values. This can be observed, for example, from optical properties, as wood materials quantitatively represent the largest proportion of registered materials, while stone (granite) makes up the lowest proportion. These results can be examined from the material database (see Table 4.1) and by then referring back to a comparison of surface distribution catalogues (see Figure 4.11). In this case, wood and stone (granite) consist of opaque materials with reflectance values of 0.5 and 0.25, respectively. For the range of 0.5, surface distribution values (see Table 4.1) show that a threshold of 0.5 (0.4 to 0.6) accounts for over 19 % of the density in points in terms of average reflectance. Meanwhile, stone materials (granite) (thresholds of 0.2 to 0,3) account for more points at approximately 21.4 %.

- The resulting materials successfully identify a number of points from opaque and translucent materials in terms of both optical and thermal properties.

- The point properties of the dataset confirm similarities among the material types. Accordingly, various objects with different surface characteristics (e.g., roughness and glossiness) can actually be composed of the same materials. This case can be observed from a group of points that fall within several material thresholds. As an example, a point with index 42633 in terms of optical property criteria refers to three types of materials: stone, wood, and cement. Fleming [90] implicitly confirmed this point in that material estimations computationally support a higher fidelity of representation than mere material categorizations.

The final step of the proposed workflow produces a list of materials found within the dataset according to insolation values generated from the simulation (see Figure 4.14). As an input, insolation values of a different colour range (as illustrated in Section 4.5.3) cover various point densities. From our evaluation of the material database the results show that each colour range on both optical and thermal properties covers a large variety of material types. Eight out of 9 materials were successfully identified for both properties. The properties also follow similar trends in point density for each identified material within the insolation colour range. This result indicates that the developed material database positively responds to calculations of material properties acquired from point clouds of the existing context, highlighting further opportunities to modify the environmental performance of certain areas according to a material analysis.

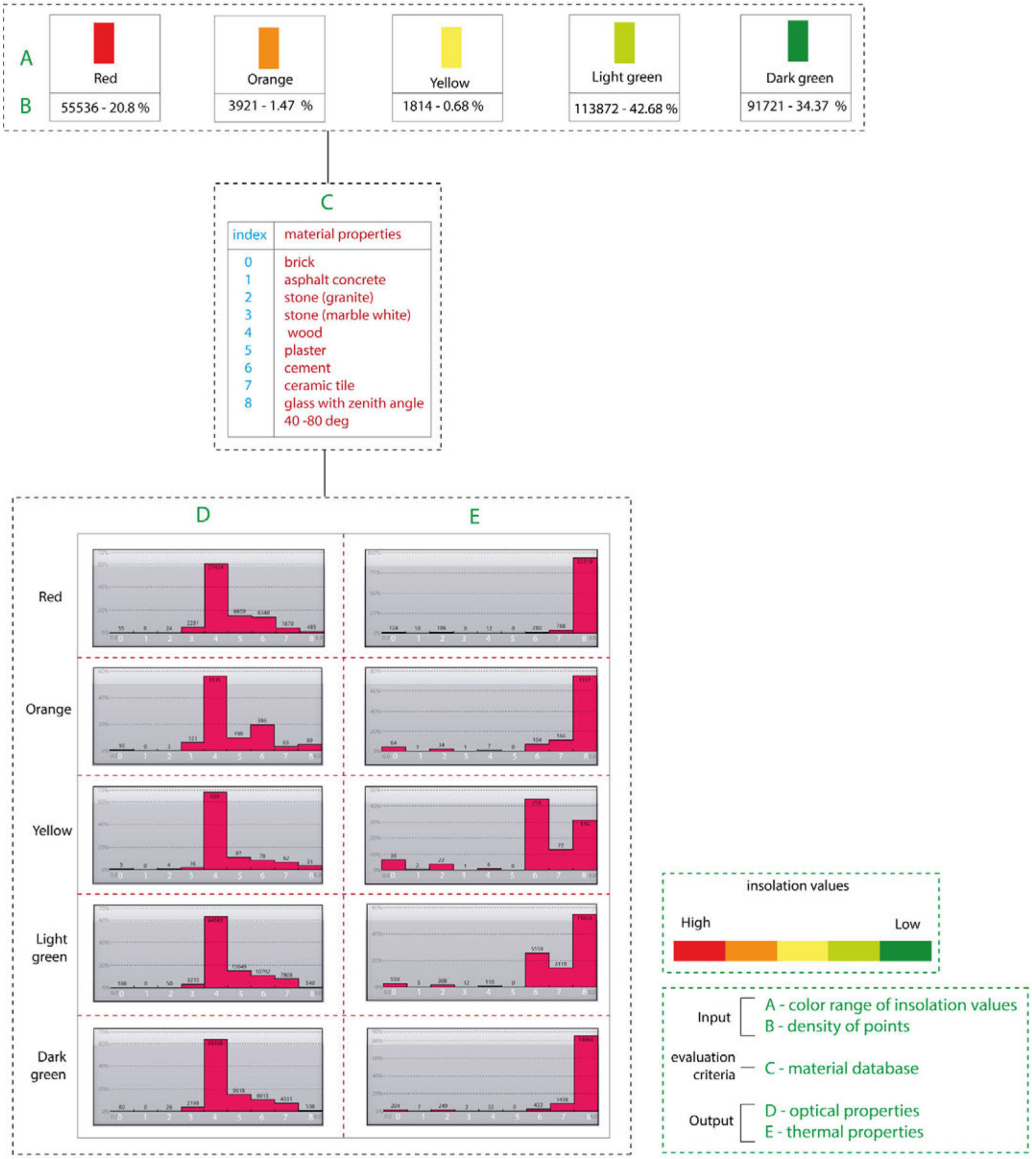

FIG. 4.14 Material selection according to insolation value simulation results

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Figure 4.14 shows that the highest material distributions in terms of optical and thermal properties are respectively found for wood (index 4) and glass (index 8), though yellow colours also denote the presence of cement (index 6) in terms of thermal properties. The least common values are found for stone-granite (index 2) in terms of optical properties and for asphalt (index 1) and white stone-marble (index 3) in terms of thermal properties. From the material performance within these properties, environmental characteristics of the context examined in this study can be hypothetically addressed. For example, a massive discrepancy in insolation values between the largest (denoted by light and dark green areas with a point density of over 70 %) and smallest portions (denoted by red and orange areas with a point density of only 21 %) may affect how the environmental context generates ambient temperature. As Ramirez and Munoz [89] point out, areas absorbing less energy denote high albedo values. It can then be useful to moderate the urban heat island effect. This means that materials within 70 % lower insolation values can be substituted with materials with high albedo values. This strategy may be used to measure the thermal impacts of microclimate issues on the built environment.

4.6 Concluding remarks and future perspectives

In this study, we perform an environmental performance analysis of an existing context by making use of potential applications of point cloud data. Through material studies and simulations of solar radiation, the proposed computational workflow allows architects to fortify contextual analysis during the initial design stage. Several concluding remarks regarding this process are made as follows:

- The exploration of material properties (optical and thermal) from attribute information on point clouds extends particular functions of 3D scanning technologies related to performance simulation and environmental analysis during the architectural design process. The proposed workflow reveals an additional opportunity to map impacts of the built environment before applying a new building to the selected context.

- Post-processing datasets necessarily help architects not only select relevant information to be employed during analysis but also minimize the environmental effects of dataset measurement during scanning.

- The integrated workflow between the material database and solar simulation may reveal specific characteristics of the existing environment. For example, the identification of highly reflective surfaces or high insolation values of a certain area can help architects to decide whether to maintain or alter the design process.

While the workflow presented in this work presents partially positive results, it requires further consideration in certain respects. For example, dataset corrections may require one to consider more radiometric parameters, especially related to intensity properties such as surface roughness, range, and target reflectance. These parameters are expected to reduce erroneousness of dataset measurements. Storing more relevant materials in a database also allows for a broad range of selection criteria used for the datasets. The material database employed in this work focuses demonstrates the feasibility of applying the proposed workflow for architectural design practices.

With further developments from this study may extend several potential features, some of which may include the use of temperature parameters in defining thermal properties to enrich albedo information on existing contexts or expanding the scale of case studies so that aspects of urban morphology and building functions can be addressed. Finally, using a reflectometer in combination with a thermal camera during scanning might prove useful for verifying and calibrating dataset reflectance values.

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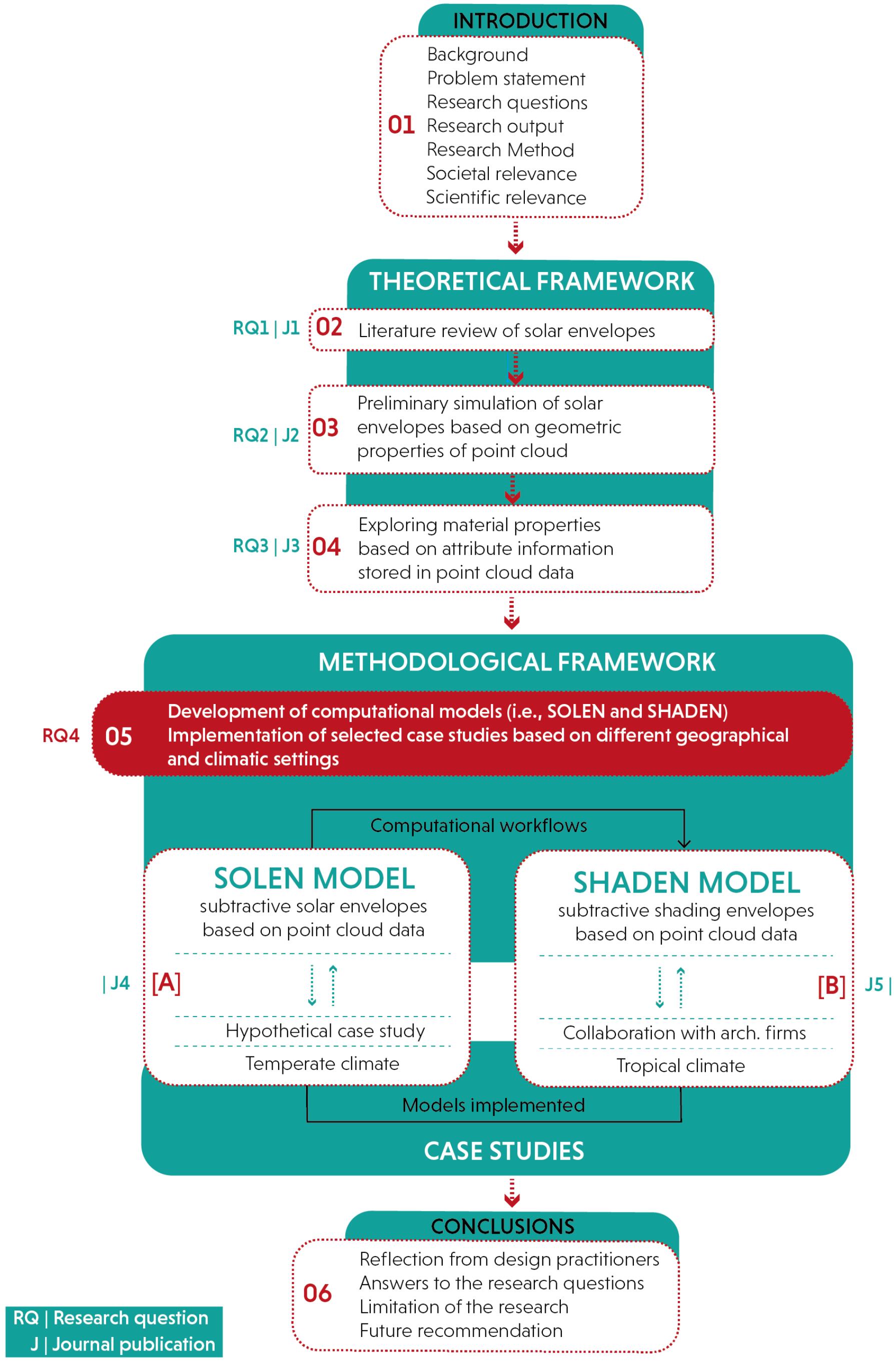
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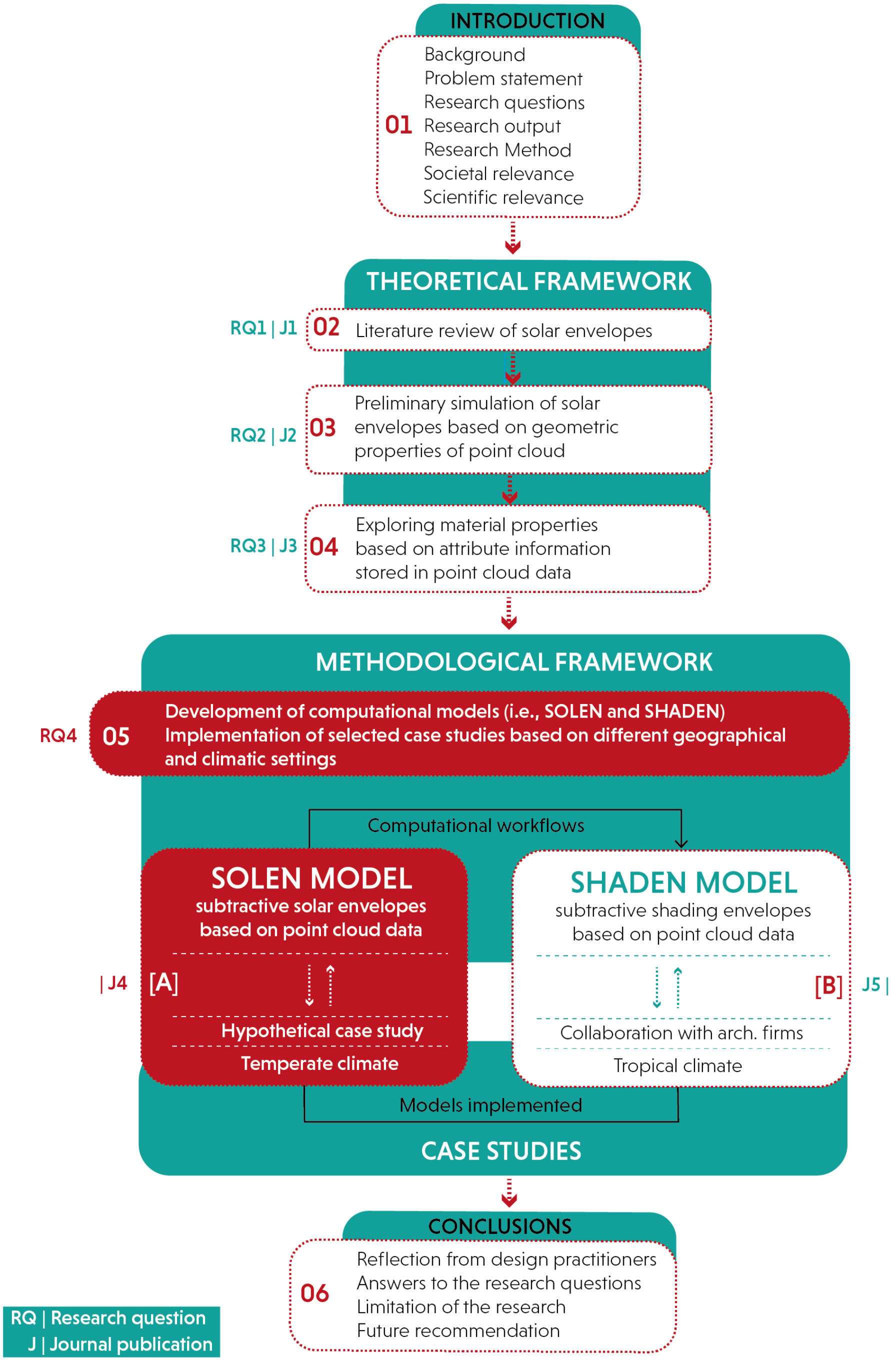
5 Computational Models For Constructing Solar Geometry Based On Attribute Point Cloud Information

This first part of this chapter (Part A) has been published as: Alkadri, M. F., De Luca, F., Turrin, M. and Sariyildiz, S., 2020. An integrated approach to subtractive solar envelopes based on attribute information from point cloud data. *Renewable and Sustainable Energy Reviews*, 123, pp. 109742. Meanwhile, the second part of this chapter (Part B) has been published as: Alkadri, M. F., De Luca, F., Turrin, M. and Sariyildiz, S., 2020. A computational workflow for generating a voxel-based design approach based on subtractive shading envelopes and attribute information of point cloud data. *Remote sensing*, 12(16), pp. 2561. The layout has been adjusted to fit the template of this thesis.

As part of methodological framework of the thesis, this chapter presents the development of the computational models (i.e., SOLEN, SHADEN) for solar geometry based on the subtractive design principle of solar envelopes and attribute point cloud information. In chapter 4, attributes information stored in point cloud data (i.e., XYZ, RGB, I) was confirmed to be feasible to analyze the performance of the existing context through several functions such as computing material properties, developing material database, and conducting solar simulations. These functions simultaneously make a relevant contribution in dealing with missing features (i.e., materials, surface morphology) in the preliminary simulation of solar envelopes in chapter 3. Furthermore, this chapter utilizes environmental simulation features generated from point cloud data to develop subtractive solar envelopes and subtractive shading envelopes referring to SOLEN model in chapter 5-Part A and SHADEN model in chapter 5-Part B, respectively.

Each model contains a series of computational workflows that are developed based on their design objectives, contextual settings, and climatic parameters. In this regard, the SOLEN model aims to generate solar envelopes based on a specific amount of direct sunlight obtained from ray tracing analysis between the new building's 3D polyhedra and the existing site's point cloud dataset. Radiometric point cloud information is used to conduct insolation analysis and to detect material behavior of the existing environment as part of the environmental performance assessment of the solar envelope's final geometry. The SOLEN model is particularly applied to temperate climates with a selected case study in Delft, the Netherlands. Meanwhile, the SHADEN model is developed to generate an appropriate building mass based on the shading performance criteria. In this part, radiometric point cloud information is used to investigate material properties and sun visibility of the given context as part of form generation process to establish the final geometry of shading envelopes. As a solar radiation-reduction model, the concept of self-shading envelopes is also integrated into the workflow of SHADEN model based on the solar protection plane. It aims to create a self-building protection from overheating during critical periods. Thus, the new building can receive solar protection both from the surrounding context and the building itself. This model is specifically applied to tropical climates with a case study in Bandung, Indonesia. In design practice, these models may help architects in making comprehensive design decisions during the early stage of the design process based on actual contextual datasets.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PART A
An integrated approach to subtractive solar envelopes based on attribute information from point cloud data

ABSTRACT

As a passive design strategy, solar envelopes play a significant role in determining building mass based on desirable sun access during a predefined period. Nowadays, advancements in the area of computational tools permit designers to develop new methods for establishing solar envelopes. However, current approaches lack an understanding of the existing environment's site characteristics, especially when dealing with geometrical information about the surrounding context. Consequently, this aspect affects the contextual analysis process during the generation of solar envelopes because of insufficient information for the relevant input of simulation modelling. With the support of geometric and radiometric properties stored in point cloud data, such as position (XYZ), color (RGB), and reflection intensity (I), this study has proposed novel subtractive solar envelopes that specifically consider the surface properties of the existing environment. Through a subtractive mechanism, the proposed method caters to several computational frameworks such as dataset pre-processing that aims to correct erroneous measurement during scanning. In alignment with that, the proposed building's visible sun vectors, optimal normal values, and 3D polyhedra are generated for the hit-or-miss analysis of subtractive solar envelopes. Furthermore, environmental assessments consisting of insolation and glare analysis are performed on the solar envelopes' final geometry. These performance assessments aim to investigate the potential and impact of the generated solar envelopes as it pertains to the existing buildings. Ultimately, this study supports architects not only in producing a new generation of subtractive solar envelopes based on real contextual settings but also in comprehensively understanding the microclimate condition of design context.

KEYWORDS

solar envelopes; point cloud data; solar access: passive design strategy; material properties; computational design method

5.1 Introduction

Interrelations between new buildings and existing context play a significant role in achieving appropriate solar access in the built environment [1]. It is necessary to understand these relations during the early design phase in order to maximize proper daylight within the design process and address microclimatic conditions for a sustainable approach. The significance of this approach has been mentioned explicitly in The United Nations Framework Convention on Climate Change, specifically in Article 4, which addresses the improvement of environmental quality as a response to climate change [2]. In the built environment, it is crucial to avert any potential unforeseeable failures once a new building has been built. These failures may very well consist of unexpected microclimatic impacts created by a building and imposed on the local context (and vice versa). For example, the building at 20 Fenchurch Street in London, EC3M 8AQ, United Kingdom (2014) has reflected an extreme amount of sun glare into its surroundings because of its glazed, curved south façade. Multiple reports of severe effects have confirmed this issue; such reports include incidents such as a melted car, a heatwave around the building that exceeded 70 degrees Celsius, and the high cost of finally fixing the design flaw of the façade [3]. On the other hand, a new UCL student housing building, which is located at 465 Caledonian Road, North London, N7 9GU, United Kingdom, perfectly exemplifies a poor relationship between a new building and the existing context. As a result of the student housing building's poor suitability to its environment, over 175 rooms receive an insufficient amount of direct sun access because the building's windows are obstructed by a historic 19th century façade. These cases clearly show a lack of design integration between new buildings and existing contexts. Given that architects have a responsibility to ensure a reciprocal relationship, it is necessary to start at an appropriate point during the preliminary design process, especially when dealing with solar access performance.

The concept of solar envelopes presents a contextual design approach that has great relevance for addressing the aforementioned issues. Designers can use solar envelopes to define solar access between a proposed building and its surrounding context. Initially introduced by Knowles [4] [5], this concept consists of an imaginary mass that allows adjacent buildings the required amount of direct sun access. Since then, several variations of solar envelopes have been proposed [6] [7]. However, the existing method has several gaps in contextual analysis: for example, cut-off times that merely focus on a fixed period, resulting in surrounding facades hardly receiving the same quality of direct sun access due to different site orientations and obstructions. In addition, solar envelopes' geometric properties rely heavily on the

Z-axis of neighboring facades' shadow fences, resulting in the limiting of the design configuration of solar envelopes during the simulation process. Subtractive solar envelopes were developed in response to these issues [8]; these are constructed on the basis of specific quantities of direct sunlight hours as obtained from the surrounding windows of existing building's facades. The subtractive approach also allows for the generation of a larger volumetric size of solar envelopes, which is useful for high-rise buildings in fragmented urban environments [9].

Nevertheless, the integration of subtractive mechanisms into design practices needs to comply with several critical aspects such as sun visibility and ray tracing analysis. *First*, the selection of visible sun data aims to identify the number of sunlight hours that are being blocked (or not) by adjacent buildings. The issue that matters most is that the resulting areas that are identified as having blocked sun are only dependent on the building-oriented context. Consequently, these areas are assumed to be located on a clear plot, which is due to an absence of characteristics and relevant site properties (e.g. vegetation) [10] [11]. *Second*, the use of centroid points on surrounding windows during ray tracing analysis primarily counts on a sample of surrounding windows, which is limited to representing the area of neighboring facades. Indeed, these issues may affect environmental performance calculations during solar envelope simulation, especially in relation to solar radiation analysis between planned and existing buildings.

In order to compensate for missing features within the current workflow of subtractive solar envelopes, this study has employed the technological advancement of 3D laser scanning that includes point cloud data. Its potential application may support several contributions, which are as follows:

- The geometric information offered by point clouds may fill the gaps in sun visibility analysis since it can significantly cover buildings and their surrounding objects. This section specifically provides information about the surfaces that are the most and the least exposed to the sun, and the existing facades. Accordingly, the resulting areas with blocked sun (indicated as the surfaces that are the least exposed to the sun) can be eliminated because those areas are shaded by the surroundings (e.g. buildings and vegetation).

- Ray tracing simulation can be performed on each point that is found in the point cloud dataset, which can be used as an alternative to a limited sample of the surrounding windows. This allows for the identification of any obstructed areas within the 3D polyhedra (a proposed building). Voxels that consist of 0 obstructions can be transformed into solar envelopes while voxels with values above 0 need to be disregarded due to an obstruction of surrounding buildings' direct sun access.

- Radiometric point cloud information (RGB color and reflection intensity) can be utilized to detect material behaviors in existing environments. This is specifically done by investigating both optical (reflectivity and translucency) and thermal properties (albedo and emissivity) calculated from a point cloud of the contextual dataset. Thus, material performance analysis between a planned and an existing building can be performed. This is achieved by projecting the ray tracing of the surrounding buildings to the final geometry of solar envelopes.

This study has primarily focused on the development of the computational workflow of subtractive solar envelopes based on attribute information from point cloud data. Two aspects of the workflow have been presented in previous papers. *First*, a previous paper presented the basic mechanism of subtractive solar envelopes [9]. This work focused on generating and subtracting a proposed buildings' 3D matrix based on a sunlight hours analysis that came from surrounding buildings' windows. This idea has stimulated the further exploration of methods for establishing computational solar envelopes based on point cloud data. *Second*, another previous paper has presented on the correction of the preliminary dataset and the calculation of material properties based on attribute information stored in a point cloud [12]. The dataset correction contributes to the extraction of the dataset's optimal normal values while material properties become an input parameter for performing glare analysis on the final geometry of solar envelopes. This paper will present a comprehensive approach for establishing new solar envelopes by making use of geometric and radiometric information contained in point cloud data with an integrated environmental performance analysis based on glare and solar radiation.

The present study has a six-part structure. Section 5.1 will give a general overview of the study. Section 5.2 will present the theoretical background, which consists of the basic principle of solar envelopes, the potential application of point clouds, and an existing method for creating subtractive solar envelopes. Section 5.3 will describe the computational workflow of new subtractive solar envelopes. This will be followed by the description of a case study's implementation in Section 5.4; this description will range from dataset collection to the details of the simulation process. Section 5.5 will present the simulation results and an environmental analysis that investigated the performance of glare and solar radiation. Finally, Section 5.6 will offer concluding remarks and suggestions for future research.

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5.2 Theoretical background

This study has proposed a new generation of solar envelopes by making use of the subtractive mechanism with specific consideration to the existing environment's surface properties. In order to elucidate this, three major subjects will be comprehensively discussed: the basic concept behind state-of-the-art solar envelope methods, the potential implementation of point cloud data with geometric and radiometric properties, and the design procedures of the existing subtractive mechanism.

5.2.1 Basic principle of solar envelopes

In the distant past, there was some form of awareness of the performance of solar access as part of urban fabrics development. This approach can be recognized as part of the ancient world's concept, and it was represented within several cultures such as the Hanging Gardens of Babylon, which were constructed during the Babylonian period (605-562 BCE) [13] [14], the El-Lahun village of Egypt (1857-1700 BC) with its checkerboard urban layout that rigidly implemented narrow north-south streets [15]; and finally, the classical Greek cities of the 4th century BC, which developed solar-oriented homes [16]. Examples such as these not only laid the foundation for the principle of solar access but also contributed to the generation of the solar envelopes that were introduced by Knowles [4]. In a further development, Knowles [5] translated the concept of solar envelopes with considerations of space-time constraints before putting any design parameters in place. According to this principle, solar envelope's parameters can be categorized as both geographic and climatic [6]. Geographic parameters refer to aspects that relate to the spatial relationship between a land parcel and its surrounding context. These can be physically defined by terms such as longitude, latitude, orientation, courtyard, surrounding facades, sidewalks, building height, floor area ratio (FAR), setback, shadow fences, and streets. In comparison, climatic parameters constitute of non-physical characteristics that are related to the time construction of geometric models; these can be identified by terms such as solar angle, cut-off times, dry bulb temperature, sun path, solar azimuth, solar altitude, and sun access hours. In principle, geographic and climatic parameters correspond inversely to the solar envelopes' volumetric size; that is, the greater the time interval in solar envelope construction, the less solar envelope space is produced.

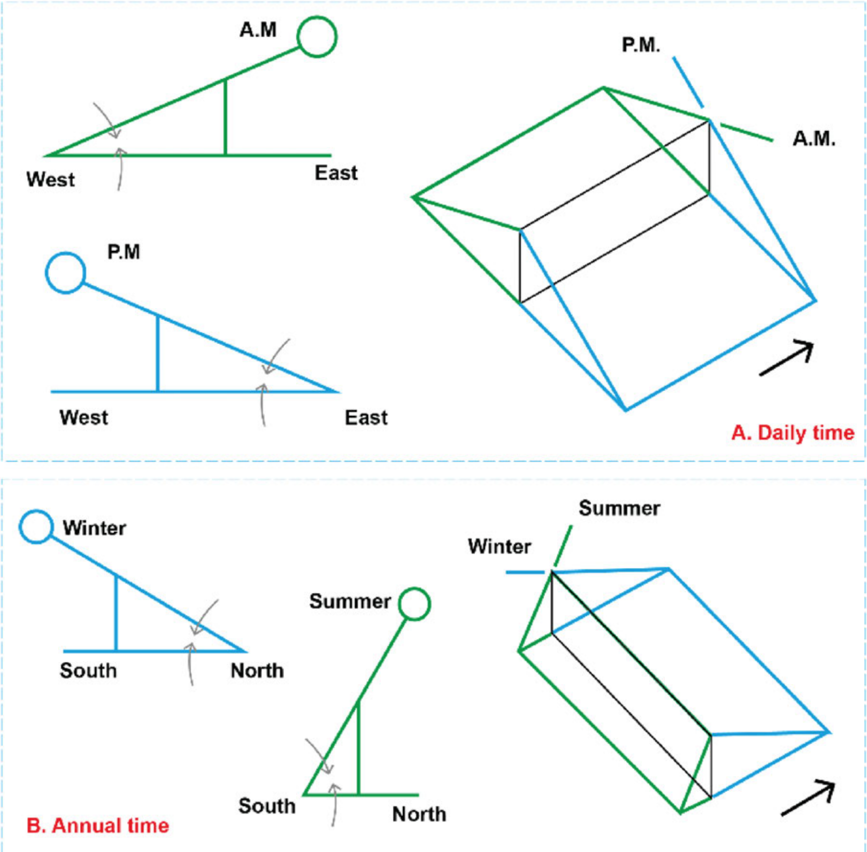

FIG. 5.1 A design mechanism for establishing solar envelopes, generated from A. Daily time limits and B. Annual time limits. These diagrams are elaborated from a book of Sun, Rhythm, and Form, authored by Knowles [5]. It specifically demonstrates the time setting before 9 am, and after 3 pm at 34° north (Los Angeles, USA).

As illustrated in Figure 5.1, daily and annual time settings demonstrate different solar envelope geometries. In a full day setting (Figure 1-A), the morning sun governs the envelope boundary at the western limits while the afternoon sun establishes the envelope shape at the eastern limit. This setting yields a relatively symmetrical shape that is divided between east and west. This is because of the similarity of their solar altitude angles between 9 a.m. and 3 p.m. On the other hand, the generated envelope for the annual time limit shows moderated steepness toward the north-facing surfaces. This is because the sun's altitude angle is larger in summer when striking the north-facing surfaces.

Furthermore, advancements in the area of computational tools inevitably affect both the workflow of and the method for constructing solar envelopes. Methods of establishing solar envelopes can be sub-divided into four categories that are based on both design parameters and computational platforms [6], and are as follows:

- Descriptive geometry—this method involves an intersection between the geometric lines of solar altitudes and the boundaries of the plot according to a predefined period (cut-off-times). The cross-section between these two lines generates a final envelope that fulfils the determined criteria of solar access [17] [18] [19] [20] [21] [22] [23] [24] [25] [26] [27] [28].

- Solar obstruction angle—the obstruction mechanism is derived from reference lines within a set of profile angles [29]. It transforms the angle of solar altitude to the solar azimuth that is perpendicularly related to the building façade being analyzed during a specific time of the day. As such, the reference lines also include the horizontal property line in the north and the vertical axis of the building within Cartesian space [30] [31] [32] [33] [34] [35] [36] [37] [38] [39] [40] [41] [42].

- Constructive solid geometry—this method primarily consists of site extrusion on the basis of solar vector settings. This setting contains rules that will help generate the initial shapes that were extruded from the plot while also taking into account the solar access constraints of the building and its surroundings. Furthermore, the intersection result of these initial shapes generates the final geometry of solar envelopes [43] [44] [7] [45] [46] [47] [48] [9].

- Digital elevation modelling (DEM) —on the basis of image processing techniques, this method quantifies a solar exposure map in order to generate solar volumes [49] [50]. This approach simultaneously introduces the concepts of iso-solar rights and iso-solar collections, both of which can be used to implement energy-oriented shapes on urban surfaces.

These approaches have successfully showcased a progressive trend of implementing solar envelopes as primary components within the architectural design process. During the generation of solar envelopes, these approaches can be categorized into two parts according to the contextual settings. In this case, 'contextual setting' refers to several parameters such as land parcel and surrounding site properties (e.g. vegetation, surrounding buildings, and open space) that might be relevant for generating solar envelopes. Some references properly consider parameters within the local context so that the interdependent relationship between the planned building and surrounding environments can be negotiated [17] [18] [19] [20] [21] [22] [23] [24] [30] [33] [34] [35] [38] [48] [9] [49] [50]. Meanwhile, others only consider the given plot so that the implementation of solar envelopes primarily focuses on new development areas [25] [26] [27] [28] [31] [32] [36] [37] [39] [40] [41][43] [43] [44] [7] [45] [46] [47]. However, the contextual setting of each method needs to be taken into account in terms of design concept and the complexity of the projects due to design parameter variation. Interestingly, the concept of solar envelopes has also been used in the recent projects of the Dutch architectural and urban design firm MVRDV: for example, the P15 Ravel Plot, which is located in the Zuidas district, 1082 LC, Amsterdam [51]. This project addresses the idea of solar-oriented design with the integration of a three-dimensional landscape of terraces and greenery. By studying the optimal line of sight and environmental performance, proposed buildings can have open southern exposures with plentiful sunlight.

Furthermore, the rapid development of 3D laser scanning technology has spanned multiple disciplines, especially in the domain of design and engineering. Point cloud data has also become more accessible than ever before, especially for collecting and processing complex information within an existing contextual environment. While this technology continually improves, a feature of reality-based datasets may provide useful support for the proposed subtractive method of solar envelopes.

5.2.2 Point cloud data

As a product of laser scanning technology, a point cloud consists of a three-dimensional location with supplementary metadata that corresponds to each measurement record [52]. Similarly, Otepka et al. [53] described each point ($\mathrm{P_i}$) by defining the three coordinates $(\mathrm{x_i, y_i, z_i})^{\mathrm{T}} £ \mathrm{R}^3$ and complementing these with auxiliary attributes ($a_{j,i}$) where $j = 1, \ldots m_i$ and i = the number of point attributes. If Pi is a vector $(\mathrm{x_i, y_i, z_i}, a_{1i}, \ldots, a_{m,i})^{\mathrm{T}}$, then the first three components constitute a fixed meaning, like point coordinates, and the other components correspond to a different value for different point entities in the cloud. Another definition was offered by Weinmann [54] who illustrated the entity of a point within Euclidean space (R^D) where D = 2 represents two-dimensional properties such as an image location or a 2D key point while D = 3 indicates a three-dimensional element such as a 3D scanned object. As such, the value of a point can principally be assumed to have no real dimension, such as length, area, or volume because its dimension equates to a container of points.

According to the above definitions, the data structure characteristics that result in a point cloud can be described further using permanent information. This can be done through the implementation of spatial XYZ coordinates [55] that are followed with supplementary attributes such as colour information (RGB) [56] and reflection intensity (I) ([57] [58]). To identify a specific function for each attribute, its metadata structure needs to be categorised into geometric and radiometric properties [59] [60] in the following ways:

- Geometric properties—this characteristic not only facilitates the configuration of the geometrical [61] and visual features of 2D and 3D models [55] but also allows simulation performance to be executed reliably [62]. An interesting example of this can be observed during the development of 3D reconstruction models within the fields of archaeology and heritage [63] [64]. In cases such as these, existing buildings have successfully been recreated within 3D models with colour details and representative material characteristics. However, this approach is limited to archaeological projects' contextual scale, which predominantly works with smaller objects, especially when compared to architectural scales. In addition, the modelling procedure from point cloud data to a mesh model inevitably poses a high cost in terms of computational issues. This is a critical matter, especially when dealing with the simulation analysis of complex projects in architectural design practice. For example, a previous study implemented an approach that simulated a descriptive solar envelope method [6]. This method was based on a 3D mesh model created with airborne laser scanning (ALS) datasets. Although this approach has successfully captured more detailed information regarding the site properties of an existing context, it has, unfortunately, presented a major concern for contextual modelling due to the solid modelling process [65] [66].

- Radiometric properties—this characteristic refers to the attribute information that is attached to each point within a dataset (e.g. RGB colour and reflection intensity). In addition to typical attributes, this type of point cloud also contains high order attributes or the so-called point feature. In this regard, some authors have defined these features into several categories. For example, Richter [67] developed six identification categories: colour, vegetation, terrain, surface normal, horizontality, and global/local height. In addition to these, Mallet [68] described 27 types of features that are separated into three groups: geometrical features [69], echo-based features, and full-waveform features [70] [71] [72]. Unfortunately, these features are only partially applicable to architectural design practices. This is because the amount of effort that needs to be invested in dataset processing makes the process unfeasible. In most cases, its practical application should deal with prior knowledge of technical dataset processing because it only caters to very particular tasks.

Understanding the main characteristics of a point cloud allows for the exploration of more relevant properties in architectural design. This can be observed through several implementations such as building construction [73] [74] [75], landscape modelling [76] [77], cultural heritage [78] [79] [80] and environmental engineering [81] [82] [83]. For example, colour information (RGB) can specifically be used not only to identify the inner surfaces of room volumes [84] but also to detect road signage by calculating of hue (H) and saturation (S) values within a dataset [56]. On the other hand, observed reflection intensity primarily deals with the surface and material properties of scanned objects [85] since it contains a return signal strength from laser pulse energy [86]. Thus, this method can be used to identify and map challenging characteristics such as damaged concrete inside tunnels, pavement lines, seafloor stripping, reflective detections signs, and geologic layers [60]. Furthermore, position information (XYZ) plays an essential role in synchronizing the coordinate locations of a dataset with various selected values made up of color and intensity information. This is done so that complex indicated areas can be extracted.

Due to the usefulness of attribute information datasets in point clouds, architects are able to generate environmental performance analyses for proposed architectural designs.

5.2.3 Subtractive solar envelopes

As a part of the solar form-finding concept that De Luca [9] proposed, subtractive solar envelopes consist of a volumetric three-dimensional matrix, namely 3D polyhedra; this is subtracted based on building facades' required sunlight from surrounding windows (Figure 5.2). 3D polyhedra are extruded from a selected land parcel based on a proposed building's criteria, which can encompass width, height, functional utilities, and even the number of floors. In principle, this mechanism has been proven as an effective strategy for dealing with daylight optimization, direct sunlight, and solar radiation since it capitalizes on voxel performance's space tessellation and form generation [87]. In alignment with this approach, Leide and Schlüter [88] developed an analytical and visual methodology through volumetric insolation analysis (VIA) and volumetric visibility analysis (VVA). Their method aimed to embrace the diversities that exist in the urban context combined with various performances such as radiation analysis, airflow, and visibility. Such approaches are also addressed in several references [89], [90], [91], [92], [93]. However, these references merely address the generative architectural form while neglecting the concept of solar envelopes.

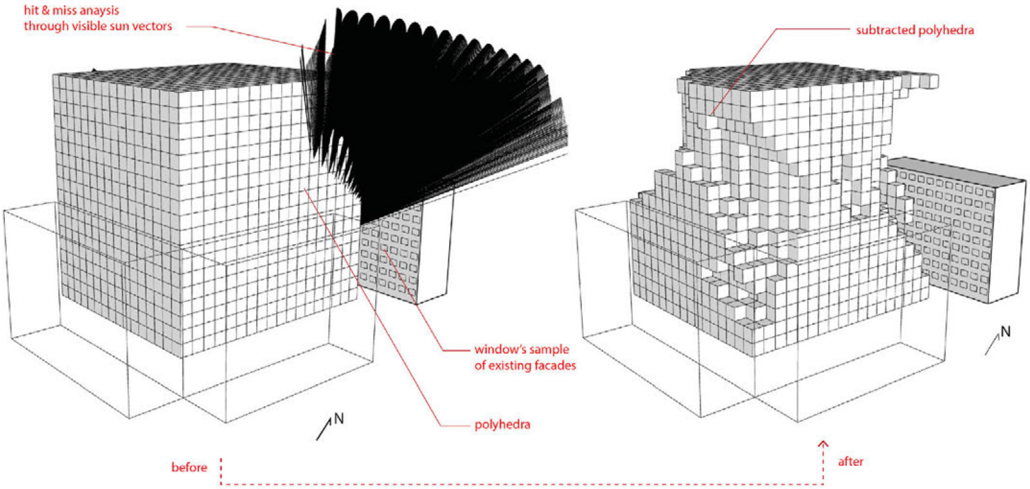

FIG. 5.2 The design mechanism of existing subtractive solar envelopes. These diagrams are elaborated from the paper of solar form finding, authored by De Luca [9]

The subtractive simulation process primarily consists of three main stages. *First*, there is window selection per surrounding facades. At this stage, existing facades are selected and subdivided into window configurations according to predefined criteria, such as dimension and surface grid, which correspond to a particular amount of direct sun access. The selected windows are then represented by centroid points for establishing the sun vectors that are generated from the sunlight hours analysis. *Second*, there are evaluations of the sun vectors that come from the selected windows, affecting the surrounding facades, and the 3D plot, which uses a hit-or-miss procedure. This step involves Boolean intersection with a true or false statement. The statement will be true when sun vectors pass through the polyhedra and false when sun vectors do not hit the polyhedra. This procedure indicates that a true statement will subtract the voxels within the 3D polyhedra while a false statement will contribute to the generation of solar envelopes. *Third*, there is the obstruction index of the remaining polyhedra. The process of ray tracing sun vectors to polyhedra principally generates an obstruction range that is represented by colour-coded voxels. It indicates surrounding buildings' direct sun access obstruction level.

The study will now present a new method for generating solar envelopes by making use of the subtractive mechanism and point cloud attributes.

5.3 A proposed method for new subtractive solar envelopes

Based on the subtractive method, this study has developed a new generation method for solar envelopes that considers the potential use of point cloud attributes. A series of computational frameworks were formulated to reach this goal (Figure 5.3). In general, the proposed method consists of three phases: input, tasks, and output. *First*, **input** constitutes several parameters that construct solar envelopes' geometric shapes and affect performance. It is then divided into climatic and geographic properties. Climatic properties contain a specific location in addition to the indicated periods that are used to calculate solar vectors. Meanwhile, geographic properties include surrounding context parameters that have been obtained from both TLS datasets and the 3D plot of a proposed building (polyhedra generation). These are in addition to the predefined criteria of building height and number of floors. *Second*, **tasks** cater to a set of operations that are performed by calculating and analyzing a varied range of inputs from a raw dataset. These operations involve several off-the-shelf frameworks that have been adapted from existing studies and include factors such as dataset correction, calculation of material properties [12], and the computational procedures of a hit-or-miss analysis for 3D polyhedra [9]. *Third*, **output** consists of the geometric shapes of solar envelopes with an integrated performative analysis based on insolation (solar irradiance) and glare analysis. In this regard, glare refers to the discomfort of visual performance caused by the concentrated reflection of the sun from the surrounding building context to the proposed new building. These analyses aim to evaluate and integrate the environmental performance aspect into the final geometry of solar envelopes. Accordingly, a comprehensive contextual analysis can be performed as decision support for architects during the early design phases. In this case, a simulation of solar radiation would be run to reveal solar energy potential on solar envelopes' geometrical surfaces. This would help architects estimate and identify a new building's solar collector. A glare analysis could be conducted between existing buildings and proposed solar envelopes based on material properties with the goal of avoiding uncomfortable glare as a result of reflective materials on building façades [94].

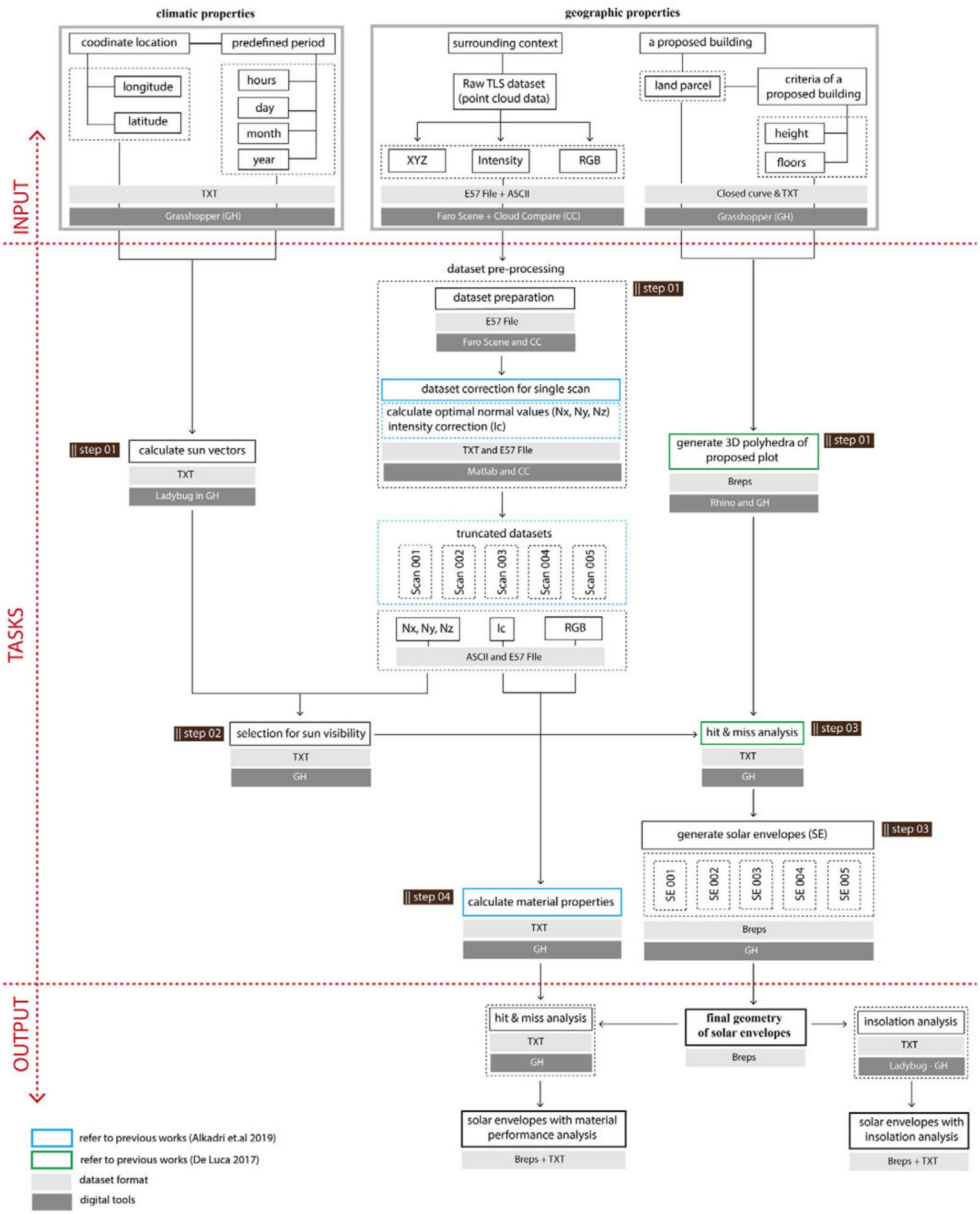

FIG. 5.3 The computational workflow used in the proposed method of generating new subtractive solar envelopes

The proposed workflow employs several supporting tools that cater to the specific tasks in each step. For example, Faro Scene and Cloud Compare (CC) [95] are digital instruments that are used to prepare the raw dataset, which is necessary to create simulation input. Specifically, Faro Scene facilitates scanner-workstation data transfer. This also includes the registration process, color coding, and clipping box procedures. In comparison, CC is primarily used for dataset preparation. It involves outlier (unnecessary points within a cloud) removal, attribute order selection, point subsampling, dataset formatting, and the scalar field feature, which enables the identification and calculation of point cloud metadata information (e.g. the surface normal of unstructured point clouds and the reflection intensity). Matlab is used to support dataset correction, especially when calculating point clouds' optimal normal values. As a 3D modelling tool, Rhino coupled with Grasshopper is used to simulate solar envelopes. Ladybug (an environmental Grasshopper plugin) [96] is specifically used to calculate direct sunlight hours and perform ray tracing analyses. In general, the proposed workflow uses various dataset formats depending on the tasks and steps that need to be performed. For example, the E57 file is exploited to transfer the 3D point cloud from Faro Scene and CC so that the selected datasets can be interoperable in 3D modelling tools. In alignment with that, the ASCII file is also used to load the 3D point cloud with embedded attribute information. Breps (boundary representation) and TXT files are primarily employed in Rhino and Grasshopper to extract or input geometric properties and textual information, respectively.

The proposed workflow was tested by using a hypothetical case study. Each specific task was performed in correspondence with real datasets that were collected using a Faro laser scanner. Section 5.4 will provide procedural details of the computational workflow.

5.4 The implementation of the case study

5.4.1 Dataset collection

The method that this study has proposed was applied to a building context using on-site scanning datasets. At this particular site, the dataset collection needed to comply with several predetermined criteria. *First*, the acquired 3D point cloud originated from terrestrial laser scanning (TLS) datasets. This method aimed to supply accurate geometric properties [97] [98] in combination with an attractive, representative 3D model. This can be observed through the inclusion of both the texture and material visualization of real building contexts which enables view point switching between an intensity format and RGB color so that attribute value changes can be quickly and easily detected during the dataset preparation in a point cloud environment. In comparison between ALS and TLS datasets, it is crucial to note that TLS can cover a wide range of surrounding elements from isolated areas. These contextual elements include vegetation, temporal site objects, and other properties that are potentially relevant for solar envelope simulation. *Second*, attribute information should at least include the properties of position information (XYZ), color information (RGB), and reflection intensity (I). These attributes play a great role in dataset correction and calculating material properties for the environmental analysis of solar envelopes. This study specifically collected a sample of 3D point cloud data located in the Faculty of Architecture, TU Delft, Delft 2628 BL, the Netherlands. Geometrically, the selected dataset consisted of building facades, ground areas (pavements), vegetation, and surrounding buildings and objects. This dataset was harvested using a Faro Laser Scanner Focus S350. As a long-range scanning application, this tool not only supports extended distances and precise angular accuracy but also facilitates on-site data quality optimization. The tool's main technical specifications are as follows (see Table 5.1): [51].

TABLE 5.1 Technical specifications of the tools [99]

No	Parameters	Performance specification unit
1.	**Ranging unit**	
	Range	0.6 – 350 m
	Ranging noise	@ 10 m – 0.3 mm (90 % reflectivity)
	Range error	± 1 mm
	Angular accuracy	19 arcsec for vertical/horizontal angles
	3D position accuracy	@ 10 m – 2 mm
2.	**Colour unit**	
	Resolution	165 megapixels
	High dynamic range (HDR)	Exposure bracketing 2x, 3x, 5x
3.	**Laser**	
	Laser class	Laser class 1
	Wavelength	1550nm
	Beam divergence	0.3mrad(1/e)
	Beam diameter at exit	2.12mm (1/e)
4.	**Extended operating temperature**	-20° - 55° C
5.	**Humidity**	Non-condensing

The harvested dataset consisted of five single scans in order to capture the facades of the architecture faculty building and its surroundings (Figure 5.4). Each scan was taken within less than 6 minutes. The approximate scan size was 10240 x 4267 Pt with a point distance around 6.1 mm/10 m. This setting yielded a point density of around 22 million points for each scan.

FIG. 5.4 Dataset collection and the different views captured in relation to the scanning position

5.4.2 The computational design process

As illustrated in Figure 3, the proposed method is divided into four sequential design process, each of which consists of different tasks depending on the type and level of information received from the input section. An in-depth discussion of each step is given below.

5.4.2.1 Step 01

This step contains several parts that can be simultaneously performed. This is due in part to different preliminary inputs. *First*, the calculation of sun vectors requires a specific coordinate location and a selected period. In this case, the position of Delft is located at latitude 52.0116° N and longitude 4.3571° E. The time setting takes a sample of the required period on the 21st of each month, ranges from January to July, and starts between 9 a.m. and 6 p.m. This setting yields a total of 16 sun vectors that comprise the selection of the visible sun. S*econd*, the pre-processing step caters to the two aspects of dataset preparation and scan correction for each scan. Essentially, this step enables architects to not only filter important information from the raw dataset but also identify parameters that considerably influence the values of metadata properties during scanning. These parameters can originate from environmental and meteorological factors, atmospheric pollution [100] [101], and scanning geometries [102]. To minimize the effects of these conditions, tasks are performed to prepare the selected dataset. For example, removing outliers removal and clipping boxes both determine and clean dataset boundaries (Figure 5.5). These outliers usually arise when scanning objects using a 3D laser scanner. This is due to the varying point densities and measurement errors that are experienced during scanning. In addition, sub-sampling procedures are applied to each scan in order to manage dataset point density by setting the distance between points to 5 cm. On average, this step produces 200.000 total points for each data scan.

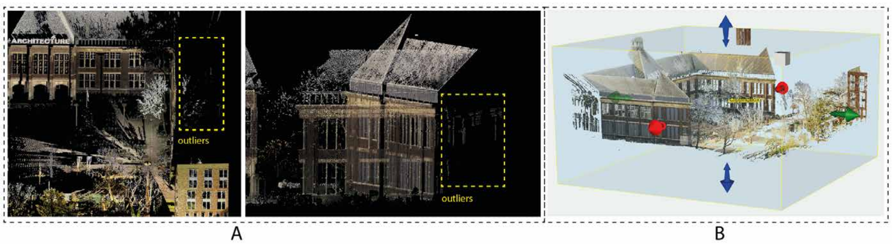

FIG. 5.5 Dataset preparation A. Outlier removal B. Clipping box

After the selected dataset is prepared, the correction procedure is applied to each data scan. This specifically aims to correct the erroneous measurements within dataset attributes that have been generated due to noise interference in sensors, equipment sensitivity, laser wavelengths, and by targeting the surface geometry [103]. In this specific case, dataset correction involves the calculation of optimal normal values (Nx, Ny, Nz) and intensity correction (I_c). These normal values are calculated to find the average distribution of points that constitute a good projection as created by the laser beam during scanning. This is because the scattering condition of points corresponds differently at certain angles. This requires that the surface normal of datasets be identified first. Accomplishing this means applying the Hough Normal plugin [104] to each scan because of the unstructured cloud of points. In alignment with the previously stated requirements, the distribution of points is plotted by simulating different cosine values that have been extracted from various angles of incidence, which range from 10° to 90° (Figure 5.6-A). This step is performed using the following equation [103] and taking into account the original location of the laser scanner at (0,0,0):

$$i = \cos^{-1}\left(\frac{\overline{dn}\cdot\overline{dl}}{\left|\overline{dn}\right|\cdot\left|\overline{dl}\right|}\right) \tag{1}$$

where i = incident angle (α)
$\overline{dn}$ = direction of surface normal
$\overline{dl}$ = direction of the laser pulse

Afterwards, the distribution of point density is evaluated by calculating a standard deviation of cosine values within the dataset (Figure 5.6-B). Thus, the discovered scattered points are removed and the densest is truncated. As a result, each data scan shows a different number of truncated points depending on the density level of datasets within the plot of cosine values. These truncated datasets consist of optimal normal values that can be used for intensity correction and the calculation of sun visibility, which will be explained in the second step.

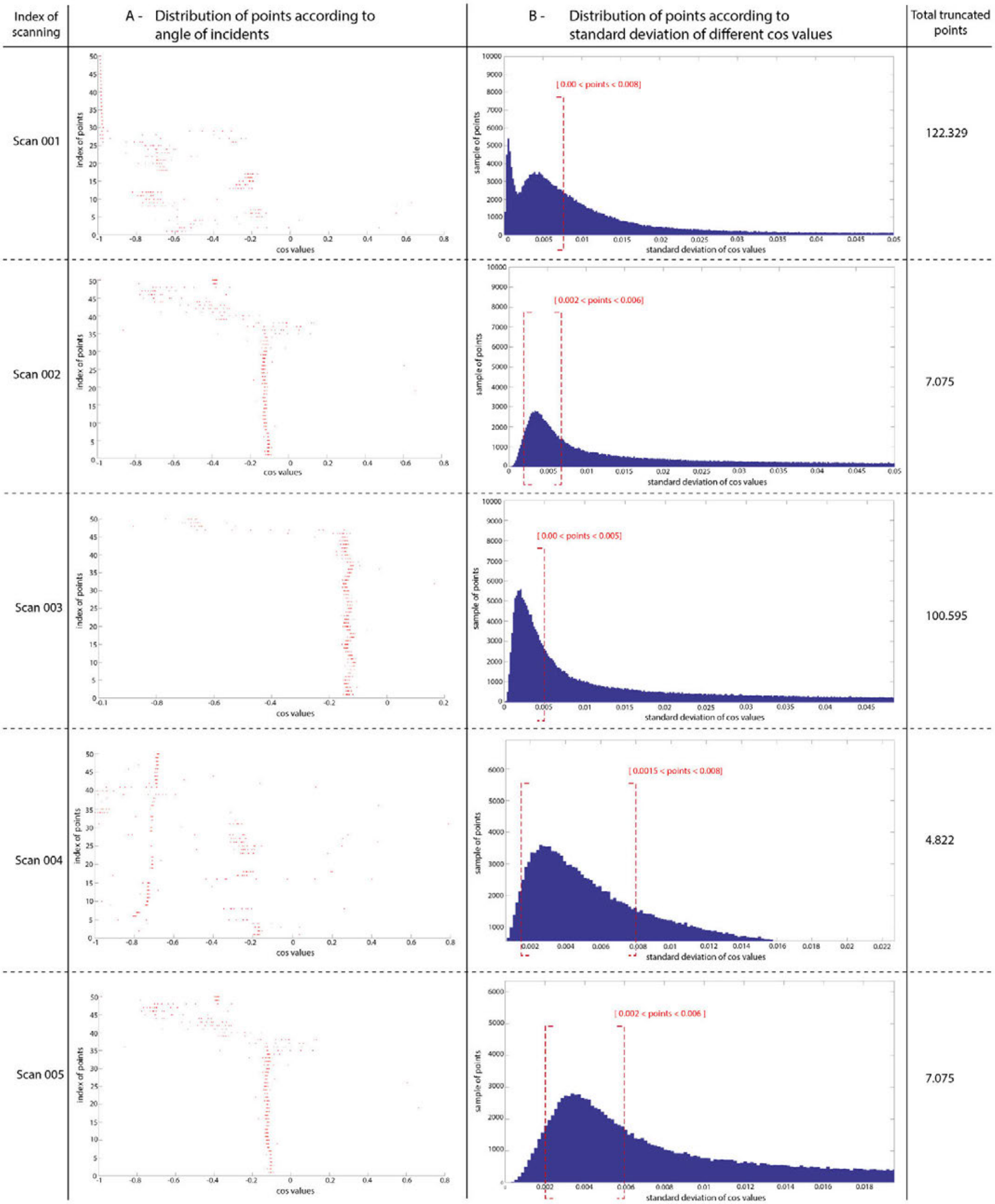

FIG. 5.6 The distribution of points on each data scan according to A. Angles of incidence and B. The standard deviation of different cos values

In principle, intensity correction is performed to calculate nearly ‘true’ values of intensity from the raw dataset (Figure 5.7). According to Kashani et al. [60], intensity information is influenced by several parameters such as the behavior of the target surface, acquisition geometries, equipment and environmental factors. However, some local constraints, such as climatic condition (moisture and temperature pressures) and tools’ default settings during scanning, make the full correction of these parameters impossible to perform. Accordingly, this study performed intensity correction by only taking the relevant and significant parameter, such as the angle of incidence (α) to the TLS dataset. The following equation [60] was used for intensity correction:

$$I_c = I_{raw} \cdot \frac{1}{\cos\alpha} \tag{2}$$

where I_c = corrected intensity

I_{raw} = original intensity

α = angle of incidence

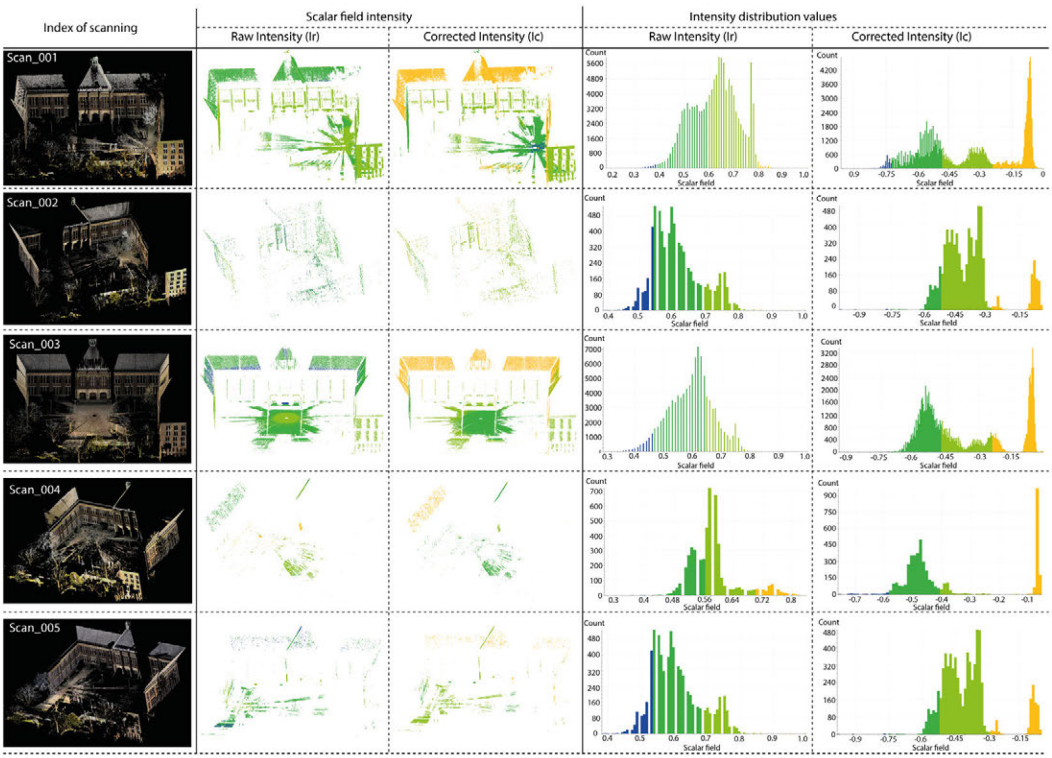

FIG. 5.7 Intensity correction on each data scan

As illustrated in Figure 5.7, the dataset transformation that resulted from intensity correction employed four color steps. The colors ranged from blue, which represents the lowest intensity value, to yellow, which represents the highest intensity value and refers to the most reflective surface. Dark and light green are intensity colors that straddle the threshold. The following results describe the distribution of the intensity datasets:

- In general, a major discrepancy between initial and corrected intensity can be observed primarily in roof areas and in some minor parts in building walls (see part of the scalar field intensity). The predominant intensity colour changes from dark green (in the column of raw intensity) to yellow (in the column of corrected intensity). This transformation is principally affected by spectral reflectance and oblique surfaces. In this case, the material on the building's roof consists of smoother surfaces (copper roof) than the material on the building's wall (old brick). Spectral reflectance on a smooth surface returns the same incident energy to the scanner due to the mechanism of specular reflection [105]. The same rule also applies to the oblique position of the building's roof in relation to the scanner's location. The backscattering intensity of a laser beam is greater on oblique surfaces than on direct surfaces [60].

- According to the intensity distribution values (from the raw intensity to the corrected one), all scans show a similar statistic regarding the increasing values of yellow (high reflective surfaces) while other color intensities are distributed dynamically depending on the data scan. For example, dark green and blue show a similar pattern regarding the increasing (Scan_001 and Scan_004) and decreasing values (Scan_002, Scan_003, and Scan_005). Meanwhile, light green has more scans with decreasing values (Scan_001, Scan_003, and Scan_004) than increasing values (Scan_002 and Scan_005). Identifying color intensity on these scans enables us to not only create a clear boundary between a different range of values but also more deeply understand the characteristics of surface material properties in the existing building.

Third, the polyhedra act as a proposed building's 3D envelope (Figure 5.8). The envelope is built according to the new building's relevant criteria such as width and height, functional utilities, and number of floors. Principally, each polyhedron represents a typical room in the real building. In this scenario, it consists of 3 x 3 x 3 m with the total number of polyhedra being equivalent to 180 rooms. The polyhedra are then placed in the courtyard of the faculty building so that the spatial relationship with the surrounding buildings can be examined. A proposed building's function should support academic environments, thus including, for example, space for meeting rooms, a library, and staff offices.

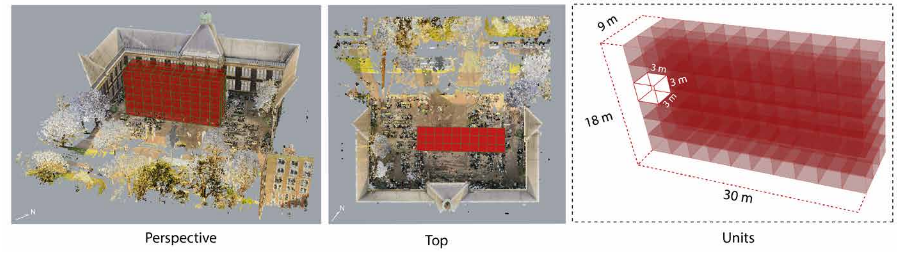

FIG. 5.8 3D polyhedra of a proposed building

5.4.2.2 Step 02

In principle, the calculation of sun visibility aims to identify visible sun vectors that are not violated by existing buildings and surrounding properties. This requires that the sun vectors from the indicated period be multiplied by optimal normal values that have originated from truncated points in each data scan. In order to identify points that meet sun visibility criteria, the calculated vectors are filtered by considering only those values that are smaller than 90º. This is because sun vectors with angle values that are equal to and larger than 90º are not visible to the scanned point. Ultimately, the procedure results in a group of points within each data scan that meet the criteria of the visible sun vectors.

5.4.2.3 Step 03

This step calls for the performance of a hit-or-miss analysis that requires input from selected points in the second step and the 3D polyhedra in the first step (Figure 5.9). In this case, 16 sun vectors continuously evaluate the 3D polyhedra over 1,008 hours. This procedure is subsequently run on each data scan, resulting in a different number of ray intersections. With a Boolean operation, each polyhedron is automatically transformed into a voxel and assigned the true or false criteria. Voxels with 'false' values are indicated as obstruction indexes that need to be eliminated. These obstruction indexes can be viewed as green dots attached to the polyhedra (see Figure 5.9, specifically part of the obstructive points). Meanwhile, 'true' values are used to generate solar envelopes. This is predominantly illustrated in yellow boxes (see part of selected voxels for solar envelopes) with a different number of voxels for each data scan.

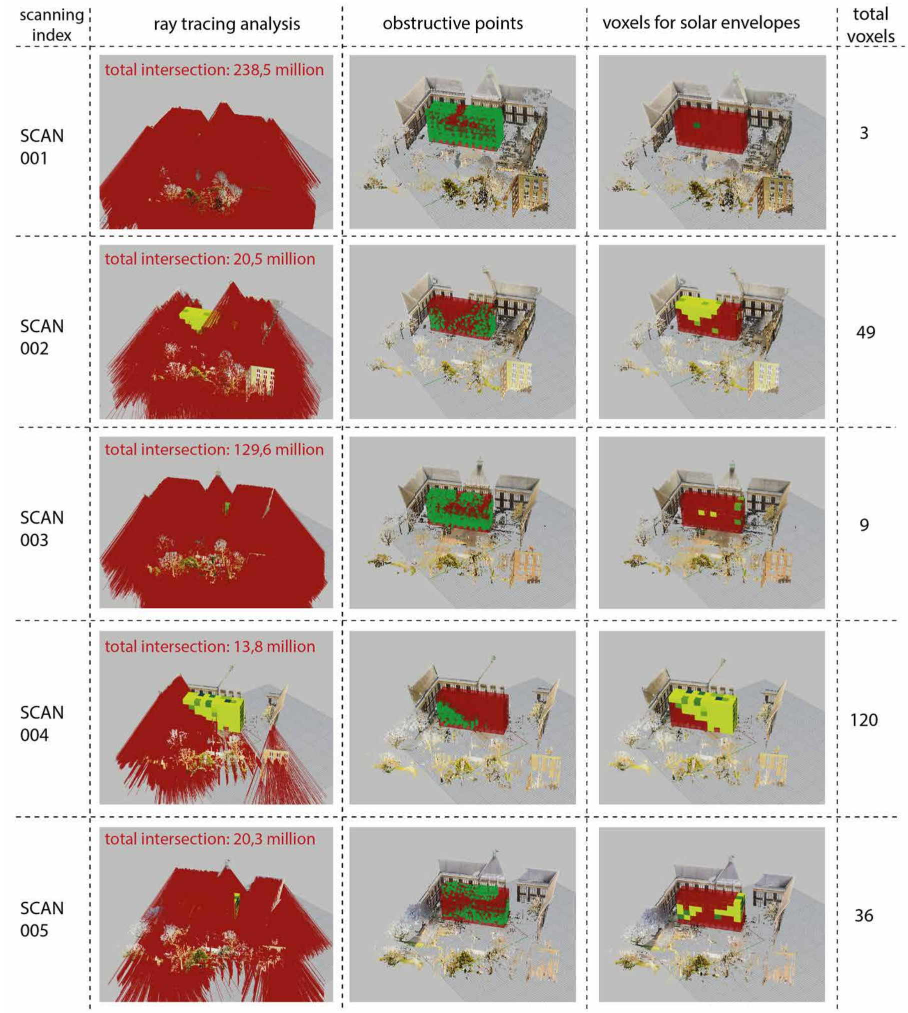

FIG. 5.9 Hit-or-miss analysis for each data scan

Based on Figure 5.9, some analysis elements can be further discussed as follows:

- Scan_004 illustrates the highest number of voxels that ultimately meet the criteria of solar envelopes while Scan_001 and Scan_003 show the least. This trend demonstrates that the densest points are involved in ray tracing analysis, and the smallest number of voxels are produced. This can be observed on the intersection lines of Scan_001 and Scan_003; they nearly cover the polyhedra, especially when compared to the other scans. These intersection lines are principally affected by the density of existing site properties and the number of truncated datasets that generated correction. On the other hand, it can be argued that increasing site properties (e.g. tress, adjacent buildings, and other elements) during simulation can significantly reduce the total voxels for solar envelopes. However, in this case, dataset correction plays an important part in filtering optimal normal values from the dataset, which means that not all points are available for use. Moreover, the step of sun visibility guarantees that only relevant points that meet the criteria of visible sun vectors may proceed to ray tracing analysis.

- The generated voxels for solar envelopes consist of color-coded values. Sequentially, these go from yellow to green, indicating the level of obstruction from low to high. As illustrated in Figure 9, most of the data scans show yellow and light green voxels, meaning that, for the indicated period, only some are dark green in Scan_004. It follows that the remaining voxels can be further synchronized with a proposed building's functional program.

- With regard to the geometrical configuration of generated voxels, each data scan shows a different voxel composition depending on the distance between the polyhedra and the surrounding facades. In this case, obstructive points that were generated from ray tracing affected most polyhedra facades that faced the scanner's position.

5.4.2.4 Step 04

As a part of environmental performance simulation, this step calculate the material properties of existing buildings as extracted from the point cloud data. A glare analysis between the final geometry of the solar envelopes and the existing buildings is also performed to identify voxels that might be affected by certain material properties. Given that radiometric information (RGB color and corrected intensity) is collected from the point cloud data, the material properties are calculated according to the thermal (albedo and emissivity) and optical parameters (reflectivity and translucency). As Figure 5.3 showed, the detailed procedure for the calculation of material properties has been extensively addressed in previous research [12]. Accordingly, the present study mainly focused on integrating materials workflow into the computational framework of solar envelopes.

Furthermore, the calculation of material properties was performed on the sample of data scans. In this case, Scan_003 was selected to illustrate the result of material distributions because its scanner position was located in the center of the selected site. This was done so that dataset coverage could be evenly captured on all sides of the building (Figure 5.10). Setting the threshold value of material properties in a range of 0.0-1.0 allows for the density of points in each material property to be calculated. In addition, the resulting areas can be visually illustrated within the dataset.

Figure 5.10 shows that all material properties illustrate a similar trend regarding the point density of the smallest and largest values. For example, the smallest values with a point density of less than 1 % can be identified in several ranges within one material property, such as albedo and reflectance, with three property ranges, and emissivity and transmissivity with 4 and 2 property ranges, respectively. Within these ranges, only the threshold values of 0.8–0.9 and 0.9–1.0 illustrate an equivalent range in all material properties. In this case, the range of 0.9 – 1.0 shows that albedo and average reflectance have similar 0 values. This is also in alignment with the trend exhibited by the largest value point density. With a value of more than 20 %, albedo, reflectance, and emissivity constitute the same range at 0.5–0.6, consisting of 20.9 %, 21.83 %, and 36.36 %, respectively. With regard to the surface distribution of these properties, the range of 0.5–0.6 predominantly covers ground areas around the scanner position with additional areas on the building roof for the albedo and reflectance property, and the building wall the emissivity. Meanwhile, for transmissivity, the largest value of the property range is found within the ranges of 0.2–0.3 and 0.3–0.4. Identified areas are primarily scattered around the building roof and the ground. In general, this surface material catalogue enables architects to identify particular areas within the dataset based on certain property thresholds so that the surface characteristics of the existing context, especially the ones that are related to the material performance of specific areas, can be better understood.

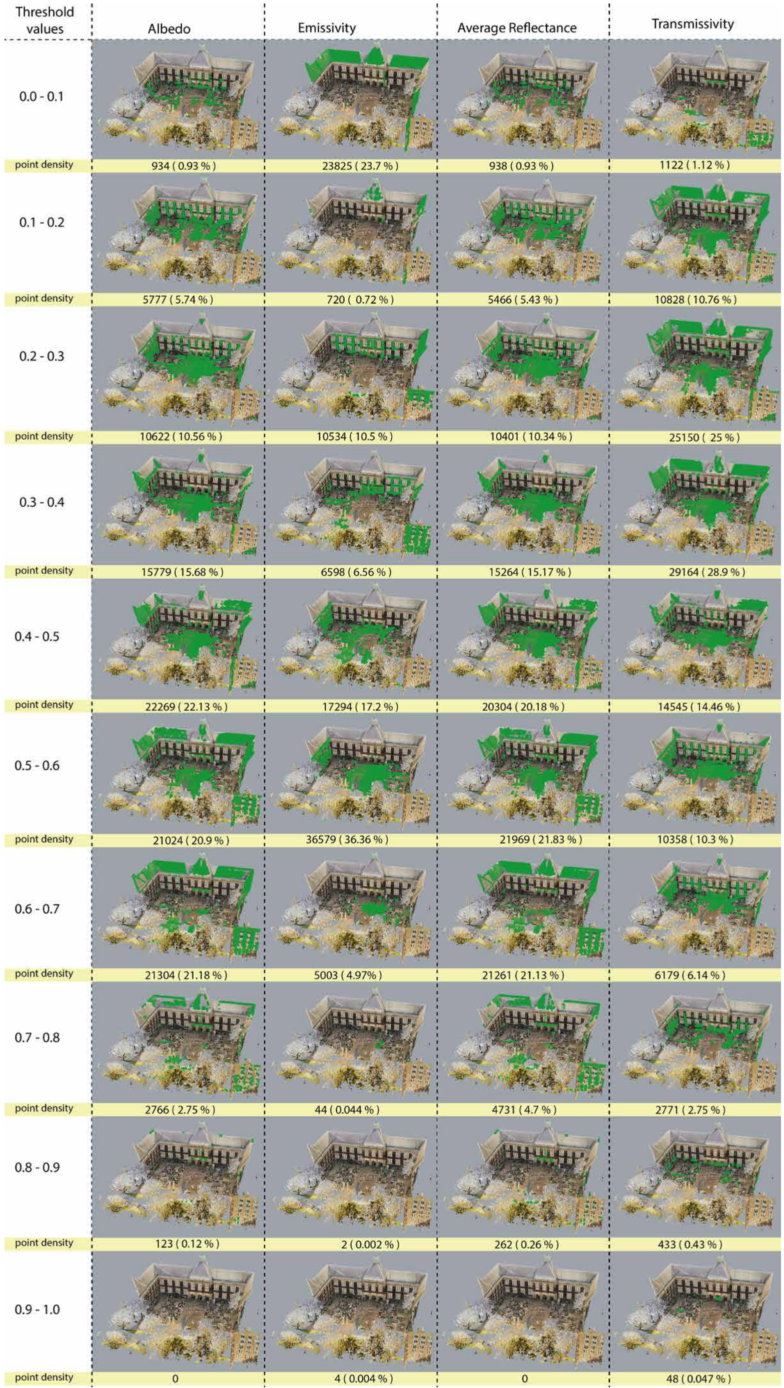

FIG. 5.10 The surface distribution of material properties in Scan_003

5.5 Results and Discussion

The present work has articulated the research in three main parts. The first part described the geometric configuration of solar envelopes as a final output of the simulation result. This solar envelope was subsequently followed by an environmental performance assessment that the other two parts addressed. These parts aimed to investigate the potential and impact of the geometric solar envelopes as it pertains to both the building and its surroundings. This involved an insolation analysis on the final solar envelopes and a glare simulation based on material properties. A sequential in-depth discussion of these parts is presented below.

5.5.1 The final geometry of solar envelopes

Having created solar envelopes for each data scan, the resulting geometries can ultimately be combined into single envelopes within the completed datasets of the surrounding context (Figure 5.11). In total, it consists of 217 voxels due to overlapping envelopes from all data scans. However, after overlapping envelopes are removed, the number of final envelopes is reduced to 133 voxels. Based on Figure 5.11, some analytical conclusions can be drawn as follows:

- The final geometry of solar envelopes principally acts as a geometrical core that fulfils the criteria of solar envelopes. Accordingly, additional voxels that are generated beyond the volumetric size of initial envelopes can still be a part of solar envelopes as long as the indicated voxels fit the required number and plot of the 3D polyhedra (the proposed design). Therefore, architects can simultaneously consider the functional program and related activities that correspond to the intended voxels.

- In order to identify the distribution of overlapping voxels from all data scans, the combined solar envelopes were plotted with color-coded attributes. The final voxels were divided into three color ranges: dark, medium, and light red. *First*, voxels with a dark red color illustrate the highest level, consisting of at least more than two overlapping envelopes. This indicates that those voxels have successfully fulfilled the solar access criteria of several data scans. Accordingly, the selected voxels can be prioritized in order to fulfil the main activities of the building that require fulltime sun access during the determined period such as those buildings that contain meeting rooms. *Second,* the voxels with a medium red color consist of two overlapping envelopes. These voxels can be fulfilled with any functional programs that do not require a full day of sun access criteria, such as staff or work rooms. *Third,* light red voxels might be relevant to the building's tertiary or supporting activities, such as open space, corridors, and service areas.

— In general, voxel distributions in each color range are not only varied in terms of the quantity, but are also diverse in terms of geometric configuration. In this case, the light red category constitutes the largest volume of envelopes with 66 voxels followed by the medium and dark red categories with 52 and 15 voxels, respectively. This indicates that the geometric characteristics of each data scan may considerably affect the number of identified voxels within the combined solar envelopes. Moreover, an interesting pattern can be observed in the vertical geometry of stacked voxels that can be assumed as equal to building floor levels. The light red voxels nearly fulfil space on the first, second, and third floors while the voxel distribution of the medium one mainly concentrates on the fifth and sixth floors.

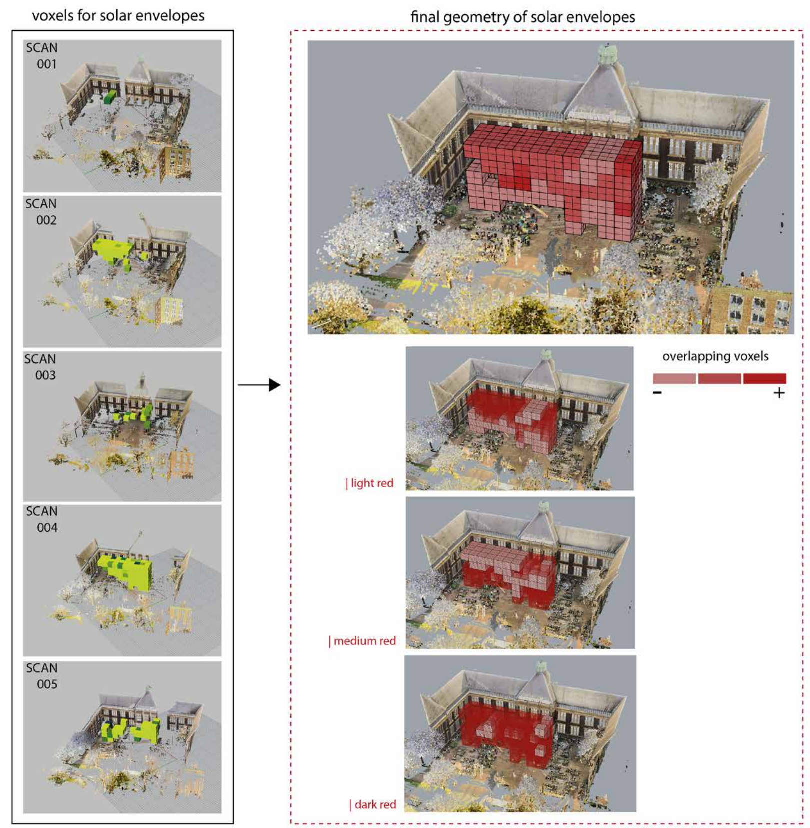

FIG. 5.11 The final geometry of solar envelopes

5.5.2 Insolation analysis for solar envelopes

In principle, insolation analysis performs an integrated environmental assessment on the final geometry of solar envelopes that focus on solar radiation. The objective is not only to identify and calculate the potential of solar energy that can be permeated by a geometric surface of solar envelopes but also to illustrate for architects how integrated environmental analysis can be achieved through this approach. Accordingly, architects can draw a sustainable impact for future scenarios regarding buildings and their surroundings.

Furthermore, the simulation of solar radiation employs a trigonometric principle by calculating cosine values between the surface normal of each voxel and solar vectors that are originated from climatic properties (Step 1 in Figure 5.3) [106]. In this case, only positive cosine values are considered because of the inability of surfaces to absorb negative amounts of energy when dealing with incident angles over 90°.

As shown in Figure 5.12, all scans illustrate a similar trend regarding the surfaces that have the most potential for collecting solar energy, which are north-facing facades. This is because the location of existing buildings creates a massive obstruction to direct sun access for the south-facing facades of solar envelopes. In addition, the site is characterized by a low solar elevation angle due to its location's high latitude. This condition makes the surfaces of solar envelopes inaccessible in terms of receiving direct sun access, especially when there is close proximity to surrounding buildings. Thus, north and west-facing façades are identified as potential surfaces for the placement of solar collectors or the implementation of passive heating strategies.

Ultimately, the resulting values of insolation analysis show that the entire surface of solar envelopes reaches around 844 kWh during a predefined period. For comparison, this amount of energy can be used to supply an average Netherlands household with electricity for around 2.89 months [107]. For a standard practice, considering the system efficiency about 15 to 20 %, the useable energy can be sufficient for 3 weeks. Therefore, this result should spur architects to internalize a good recommendation, enhance environmental awareness, and make better design decisions in future planning. Nevertheless, the proposed insolation analysis would benefit from further consideration with regard to the parameters that are involved in the calculation, such as diffuse and reflected radiation [108], air mass, temperature, and other environmental factors.

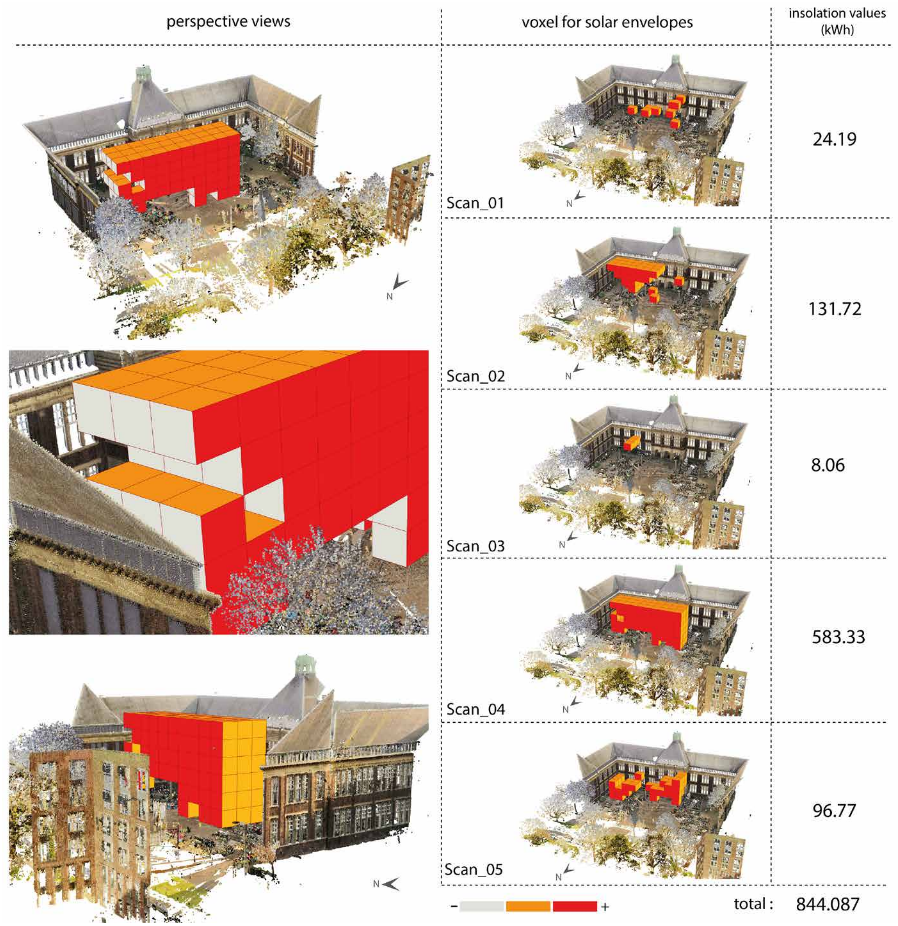

FIG. 5.12 The insolation analysis of the final solar envelopes

5.5.3 Glare analysis simulation

Before performing a glare analysis between the final geometry of solar envelopes and the identified material properties of the existing context, two selection criteria must be set, namely selected points based on sun visibility and normal vectors based on specular reflection. *First*, this criterion employs a similar mechanism as in the second step in Sub-section 5.4.2 (part of computational design process). In this regard, the threshold values of material properties only consider selected points for extraction from the sun visibility selection. As a result, the number of points registered in all material properties decreased significantly due to incompatibility with the visible sun criteria (Figure 5.13). The largest discrepancy (before and after the sun visibility selection) illustrated a similar trend among the material properties, especially for albedo, emissivity, and average reflectance. These properties constituted the same value range of 0.5–0.6, similarly consisting of more than 17 thousand points, while transmissivity was identified at value ranges of 0.2–0.3 and 0.3–0.4. Regarding the surface distribution of the dataset, most of the identified values after the sun visibility selection were located on the building's roof with a significant decrease in the ground areas. This suggested that the sun vector of points located on the ground level predominantly consisted of zero and negative values, meaning that those points were automatically filtered by the criteria of visible sun.

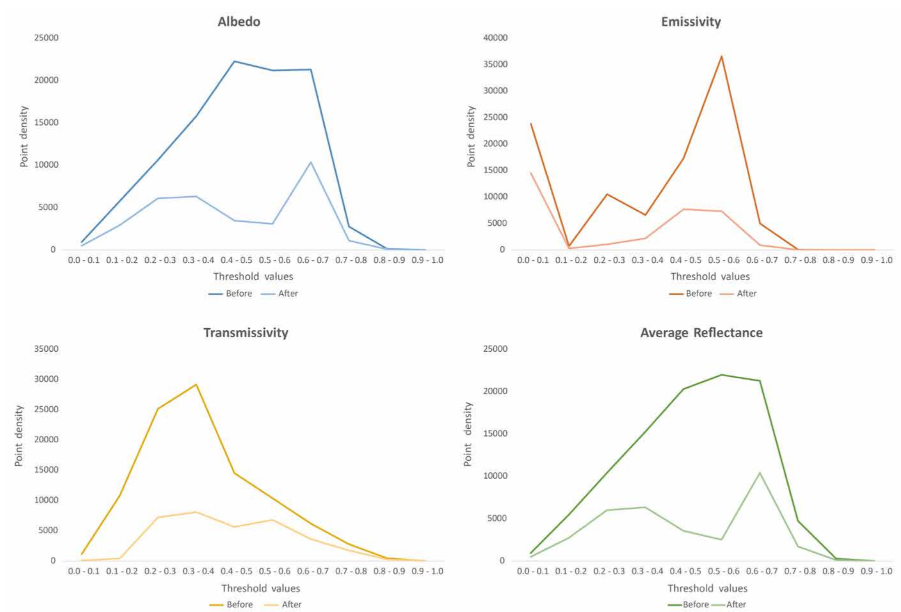

FIG. 5.13 A comparison of material properties before and after the sun visibility selection

Second, sun vectors that were acquired from the selected points and threshold values of material properties were simulated by considering specular reflection. This was done by assuming that the angle between the normal vector and the incoming light was equal to the one between the normal vector and the reflected light. This requires that sun vectors around the point normal be rotated to 180°. Furthermore, the selected vectors and points were carried forward to the hit-or-miss analysis step with the final geometry of solar envelopes.

5.5.4 The geometric configuration of solar envelopes based on glare simulation

This section discusses the result of glare simulation between the proposed solar envelopes and the existing buildings on the basis of material properties. Since this simulation adopted a similar mechanism as the sun visibility criteria, its procedure was therefore limited with regard to the geometric intersection between the solar envelopes and the sun vectors reflected from the surroundings. The simulation result primarily identified affected geometries within the solar envelopes without considering the luminance level of reflected lights. Architects can use this approach to avert proposed building's microclimate issues by considering material performance during the conceptual design stage.

As shown in Figure 5.14, the geometric configuration of the identified voxels have a similar pattern for specific ranges of thresholds. For example, a zero voxel is predominantly identified at the range of 0.8–1.0 except for the transmissivity property, which refers to the range of 0.0–0.2. This value means that the reflected light from the surroundings fails to intersect with the geometry of the solar envelopes due to a different incident angle and point density (refers to Figure 5.13) within the performed threshold. In addition, the emissivity had a different pattern when compared to the others. This is because emissivity refers to the intensity values within an inverse range. Consequently, it affects the calculation of other properties. The indicated patterns are listed as follows:

- Emissivity consists of three zero voxels (in a range of 0.7–1.0) while others only consist of two zero voxels (albedo and average reflectance, similarly in a range of 0.8–1.0, with transmissivity in a range of 0.0–0.2).
- With regard to the distribution of the voxels, all properties contain four threshold ranges for registered voxels, amounting to less than ten, except for emissivity which consists of six ranges.
- Emissivity results show significant contrast in terms of the quantity of identified voxels in comparison with others. This can be observed in ranges of 0.0–0.1, 0.2–0.3 and 0.6–0.7.

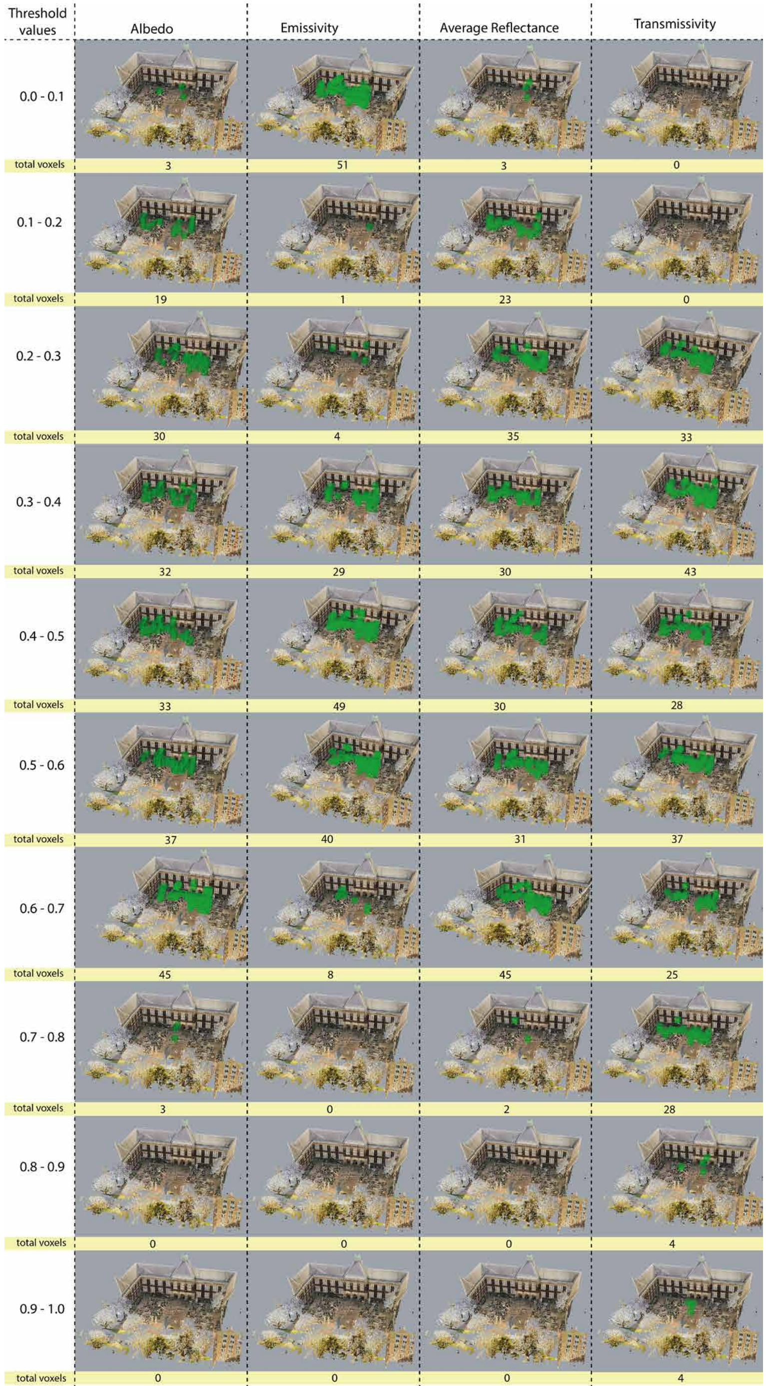

FIG. 5.14 The geometric configuration of solar envelopes according to glare simulation analysis

5.6 Conclusion and Future Recommendations

This study has built on a novel method of generating subtractive solar envelopes that are based on the attribute information found in 3D point cloud data. The present workflow has confirmed the feasibility of integrating both geometric and radiometric properties of a point cloud, especially when supporting the contextual analysis of a proposed building. In particular, point cloud data acts as a basis for making an informed design context, therefore allowing environmental performance to be embedded in the workflow that is associated with the development of new solar envelopes. This approach ultimately allows architects to not only compensate for missing information during site analysis but also identify the context's microclimate conditions during the preliminary design stage. In general, this work warrants several remarks, which are listed as follows:

- With the overarching goal of developing new subtractive solar envelopes, attribute information in a point cloud enables the expansion of the functional properties that are available with 3D scanning technology. This is important in the architectural design stage, especially when dealing with environmental performance analysis, since it provides an alternative to focusing exclusively on 3D reconstruction and data visualization.

- Dataset correction is necessary not only to obtain a point cloud's corrected optimal normal values but also to minimize erroneousness in datasets during scanning. This will also help architects select relevant information to comprise the input that is needed to develop solar envelope simulations.

- Integrating aspects of material properties into the new workflow of subtractive solar envelopes will help contribute to the expansion of performance analysis in the relationship between new buildings and their local contexts. This also supports architects in more appropriately configuring any activities that are suitable, especially with regard to the solar and material performance of certain voxels and activities that need direct solar access within a certain period.

Acknowledging the limitations of this study, there are some elements that would benefit from further consideration. For example, the computational issues that were experienced during simulation were created by highly dense datasets, and this remains a major concern. Some of the study's aspects merely require very particular

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adjustments, such as the number of sun vectors or the point density of datasets. Moreover, synchronization between more existing urban properties and different functional utilities may affect solar envelopes' final geometry.

In further research, some potential aspects can be explored by investigating the relationship between the floor plan and an optimized layout design for both solar envelopes and energy efficiency. This will allow architects to define the layout configuration for each voxel within solar envelopes given that solar envelopes are based on the direct solar access that is available in a specific timeframe (per hour and per day). Moreover, the proposed method can be explored using different climatic contexts, such as tropical climates, as doing so can potentially expand possibilities for implementing designed solar envelopes within different urban settings.

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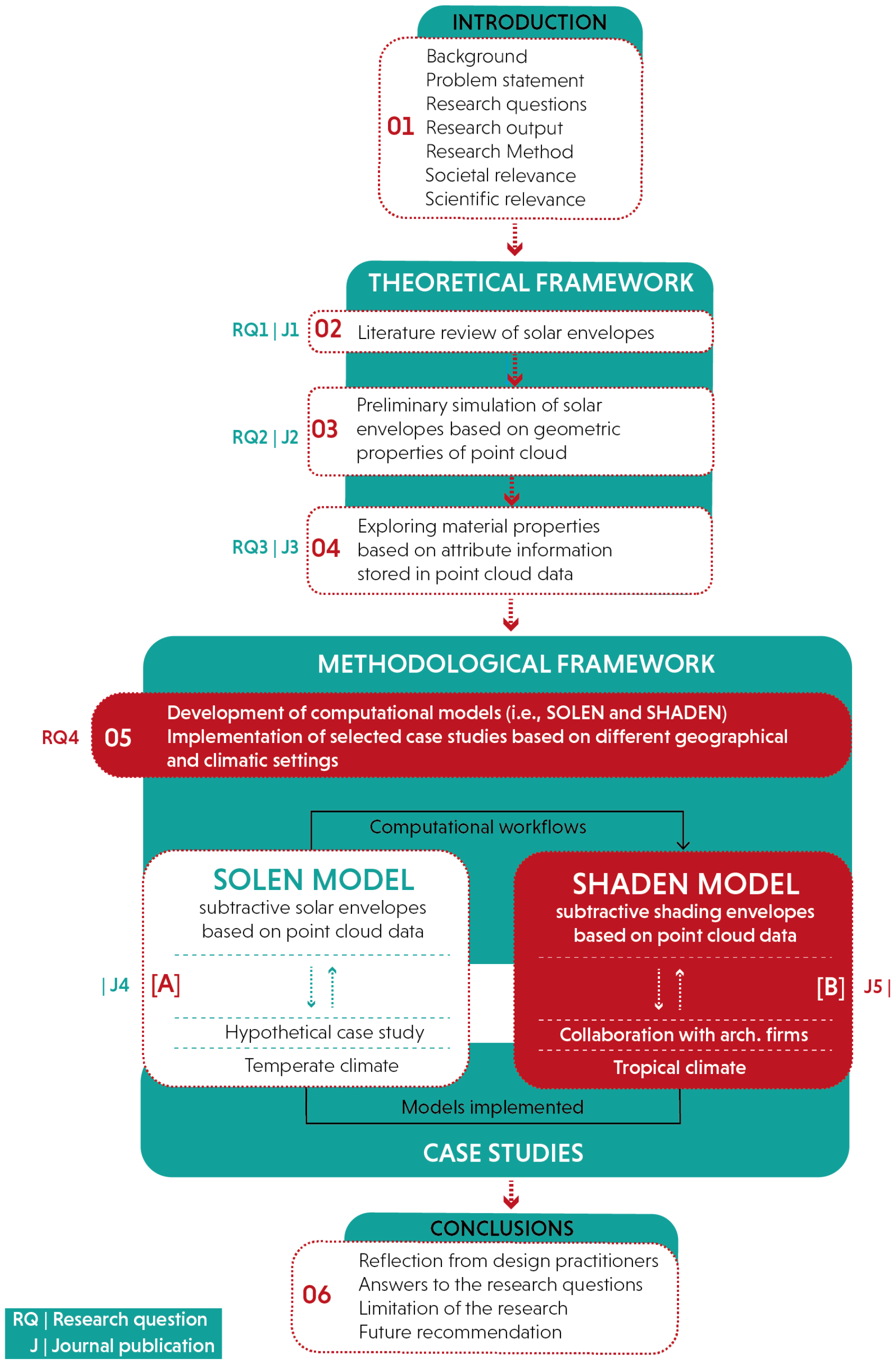
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PART B

A computational workflow for generating a voxel-based design approach based on subtractive shading envelopes and attribute information of point cloud data

ABSTRACT

This study proposes a voxel-based design approach based on the subtractive mechanism of shading envelopes and attributes information of point cloud data in tropical climates. In particular, the proposed method evaluates a volumetric sample of new buildings based on predefined shading performance criteria. With the support of geometric and radiometric information stored in point cloud, such as position (XYZ), color (RGB), and reflection intensity (I), an integrated computational workflow between passive design strategy and 3D scanning technology is developed. It aims not only to compensate for some pertinent aspects of the current 3D site modeling, such as vegetation and surrounding buildings, but also to investigate surface characteristics of existing contexts, such as visible sun vectors and material properties. These aspects are relevant for conducting a comprehensively environmental simulation, while averting negative microclimatic impacts when locating the new building into the existing context. Ultimately, this study may support architects for taking decision-making in conceptual design stage based on the real contextual conditions.

KEYWORDS

voxel-design approach; shading envelopes; point cloud data; computational design method; passive design strategy

5.7 Introduction

5.7.1 General background

The rapid development of 3D laser scanning technology has reached across multiple-disciplines within design and engineering. However, the practical implementation of this technology is often applied in major fields, such as photogrammetry [1] [2], cultural heritage [3] [4] [5] [6], and environmental engineering [7] [8]. Digital reconstruction as one of the main subjects in these scopes has been used predominantly for building performance assessments [9] [10], where the contextual modeling of existing studies is frequently based on a 3D solid modeling context [11] [12]. As a consequence, high computational costs and time are required to cover the entire set of complex building forms. On the other hand, the use of point clouds during the early stage of architectural design has not yet been fully explored, especially related to the performance simulation task and design decision support.

As an entity of 3D data scanning, Otepka et al. [13] illustrates the point cloud as a universal denominator for laser scanning and photogrammetric data. Its data structure is principally characterized by position information (XYZ) as a permanent element coupled with auxiliary information attached to it, such as color attributes (RGB), reflection intensity (I), and any abstract information [14]. The prospective applications of these attributes not only represent metadata information of the real environment, but also enable designers and researchers to perform numerous tasks, such as data processing, visualization, and analysis. Moreover, this can help architects further to address environmental design issues, such as solar and shading performance.

The technological advancement of point cloud reveals the relevance of integrating it into the passive design strategy, especially when dealing with generative architecture designs that currently lack several relevant aspects. For example, first, understanding the site characteristics of an existing environment. While 3D site modeling primarily deals with a building-oriented context, surrounding properties, such as vegetation and adjacent buildings, are often neglected [15]. This may not only affect the performance simulation of a proposed design, but also potentially create microclimatic issues when it comes to the real context. Second, the absence of surface properties, such as roughness and material characteristics on a manually-built 3D model, may cause a crucial discrepancy when dealing with environmental simulation between planned

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and existing buildings [16]. With geometric and radiometric information extracted from point cloud data, this study, therefore, proposes an integrated passive design approach based on shading performances of new and existing contexts.

As a contextual design approach, this study specifically investigates the idea of subtractive shading envelopes that are principally extracted from the concept of solar envelopes initially introduced by Knowles [17]. In this regards, solar envelopes permit architects to design appropriate massing of a new building into the existing environment by guaranteeing desirable sun access for surrounding buildings during the critical period [18], while subtractive shading approach aims to extract potential performances of the existing contexts and integrate it with a 3D volumetric massing of a proposed building based on predefined shading performance criteria.

Since then, various computational methods of solar envelopes, such as descriptive geometry, solar obstruction angle, and constructive solid geometry have been defined [19]. These approaches have successfully demonstrated the concept of solar envelopes into various urban settings (e.g., single building, open space, and urban scale) and multiple functional utilities (e.g., housing, offices, and commercial buildings). It is worth noting that the contextual settings of the existing methods primarily focus on temperate zones of southern and northern hemisphere countries, which have distinct climatic conditions during the four-seasons. This means that design objectives and climatic parameters of most existing methods for solar envelopes become less applicable when it comes to tropical countries, especially for those located on the Equator, such as Indonesia. Since tropical countries present wet and dry seasons all year round, the objective of solar envelopes significantly shifts and aims to minimize the penetration of direct sun access to the buildings, due to high temperatures. For example, housing in Indonesia is typically designed in a way that prohibits direct sunlight from penetrating the dwelling, especially into primary living spaces, so that temperatures are kept low during the day. Consequently, the air conditioner (AC) frequently becomes a short-term solution to mitigate the building's temperature, which unfortunately contributes to the annual increase in energy consumption [20]. Accordingly, shading conditions become considerably relevant for urban forms generation in tropical contexts. This study specifically proposes an environmental design strategy that integrates shading performance aspects and attributes information from point cloud data through a computational workflow of a voxel-based design approach.

Furthermore, the following section will present a theoretical background of the existing studies, starting from solar envelopes, shading envelopes, subtractive solar envelopes, and subtractive solar envelopes based on point cloud data so-called SOLEN approach. This will be followed with a description of a proposed method in

Section 2, while case studies in Section 3. Section 4 will comprehensively discuss the findings of the simulation results. Lastly, Section 5 will describe the conclusions, limitations, and future recommendations of the study.

5.7.2 Related works

5.7.2.1 Solar envelopes

In the remote past, the concept of vernacular architecture has successfully contributed to preserving sustainable building envelopes [21] [22]. This can be observed through the development of the Indus Valley, Mohenjo-Daro in India, 2500 BC [23], El-Lahun village in Egypt (1857–1700 BC) [24], and many classical Greek cities, such as Olynthus in North Hill—a city designed to benefit from passive solar energy for the heating of buildings [25]. This strategy was known as solar-oriented homes or so-called “solar architecture”. Since then, solar architecture has become an essential guide for designers to develop sustainable urban planning. For example, Andrea Palladio has discussed the proper norms of city planning by considering wide streets for cold climate countries and narrow streets for tropical countries [26]. Additionally, Ildefons Cerdà integrated green areas into the public and private space of Barcelona in his masterplan of the city so as to enhance the comfort of inhabitants [27]. During the industrial revolution, the idea of urban solar policy or refers to the post-war housing was also implemented in France (in 1912), Germany (in 1920), and New York (in 1916). These examples have shown a positive contribution to architectural buildings, not only to reduce the energy consumption of the built environment [28], but more importantly, to support a healthy living environment [29]. Furthermore, the idea of solar accessibility has been elaborated further through the concept of solar envelopes.

By definition, solar envelopes stand for imaginary boundaries that are constructed based on the sun’s movement. It is regulated based on specific space-time constraints [18]. According to this principle, solar envelopes can be transformed into geographic and climatic properties within the size of on-site buildings [19]. Geographic properties deal with a group of parameters that define the spatial relationship between the design plot and existing context related to orientation typology, surrounding facades, sidewalks, building height, longitude, latitude, floor area ratio (FAR), setback, shadow fences, and street sizes. On the other hand, climatic properties consist of parameters that determine the geometric transformation of the proposed building based on the time construction, such as cut-off-times, solar angle, sun path, dry bulb temperature, sun access hours, solar altitude, and solar azimuth. These parameters are used not only to generate solar envelopes, but also to identify the character and qualities of the built environment. For example, orientation plays a great role in examining the geometrical shape of solar envelopes, especially when dealing with the street layout in relation to various angular values, colonnades with a variety of direct solar radiations, and solar urban layouts [30]. A seasonal leaf cover from the surrounding vegetation can also affect the geometrical configuration of solar envelopes as it may be considered as a part of geographic elements for violating excessive direct sun access during summer [16]. Besides, the solar angle as a climatic property is used to determine geometric solar envelopes based on the construction planes [31]. It is mostly employed for simple shape plots, with borders aligned with the main cardinal directions in east-west (EW) and north-south (NS) and for the main hours and days, such as the noontime during summer and winter solstice, and spring/autumn equinoxes.

5.7.2.2 Shading envelopes

As opposed to solar envelopes, the concept of shading envelopes primarily deals with the solar radiation-reduction to achieve appropriate daylight for urban equatorial climates. This permits architects not only to establish a geometrical configuration of solar shading envelopes, but also to control the direct sun exposure of the building’s own façades and surroundings during a critical time. Two different types of shading approaches are identified as follows:

Building forms

In this part, the concept of shading envelopes aims to promote a passive design strategy through the form generation within the conceptual design stage. This means that the volumetric shape of proposed buildings is developed based on the consideration of solar shading criteria. An interesting example can be observed through the concept of “shadow umbrella” introduced by Emmanuel [32]. This concept proposed a design approach of shading strategies incorporated with natural elements, such as vegetation and water bodies, aiming to create shading for adjacent buildings and to mitigate the urban heat island for tropical neighborhood areas. Accordingly, a new configuration of urban block shapes with a thermally comfortable can be generated. DeKay [33] addressed a similar strategy with the concept of climatic envelopes. The climatic envelope primarily aims to generate a building mass that guarantees access for diffused daylight and solar energy resources for the surrounding buildings. This concept specifically contains a geometrical intersection between daylight and solar envelopes based on the sky exposure plane and solar protection plane, respectively. In this case, sky exposure plane refers to imaginary sloping planes that allow penetration of natural light and air on the building facades in higher density districts [35]; meanwhile, solar protection plane refers to an inclined plane that is generated from the profile angle, the so-called vertical shadow angle (VSA) [34]. In a similar vein, Capeluto [35] proposed the concept of self-shading envelopes by extending the functional properties of the sky exposure plane through the solar collection envelopes (SCE) model. The geometrical configuration of self-shading envelopes results in cone shapes, due to the required façade inclination and shading orientation. Therefore, the envelope's roof areas should be larger than the bottom part of the envelope geometries. This approach aims to avoid overheating and at the same time, to maximize the self-building protection for a certain period during summer.

Building components

In addition to building forms, shading approaches are also applied to specific building components, such as windows, cantilevers, and openings on the building façade, based on the determined building shapes. Although this study limits the scope of investigation on a form-finding design solution, some studies on shading mechanisms drive potential efforts to handle more complex projects. For example, Yezioro and Shaviv [36] proposed SHADING as a design and evaluation tool for analyzing mutual shading between buildings and other surrounding properties, such as vegetation. It specifically calculates the insolated fraction on the building surfaces quantitatively and performs a ray-tracing algorithm to identify the shadows visually at a particular time. Similarly, Marsh [37] also used a ray-tracing analysis to identify the external obstruction of solar intensity on the optimized shape of shading geometries. In this case, optimized shading designs have effectively accommodated passive solar control through the building apertures [38] [39]. Other approaches deal with a graphic solution of shading design tools [42], form-finding of static exterior shading devices called SHADERADE [40], and a cellular method to define optimal shading patterns [41].

Although these approaches may address the aspect of tropical design contexts, they lack some critical aspects during the simulation of shading envelopes. First, the quality of solar radiation (i.e., the quantity of direct sunlight hours) received by surrounding buildings is not taken into account by most methods and tools, due to a fixed period when determining direct sun access. Consequently, all geometrical

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shapes of existing buildings are treated similarly when receiving the irradiation qualities without considering the obstruction of properties and building orientation of the plot. Second, shadow fences of surrounding buildings' facades are primarily regulated by a Z-axis. This makes the design configuration of the resulting envelopes rely only on the horizontal shading lines. In fact, shading areas of surrounding façades are more complex, especially when dealing with dense areas and multiple urban forms. In order to compensate for these issues, the existing studies present some relevant aspects, such as subtractive mechanism and point cloud data that may be useful for further development. This will be discussed in the following section.

5.7.2.3 Subtractive solar envelopes

As previously mentioned in the general background, this approach specifically subtracts a volumetric matrix of the 3D plot according to solar accessibility criteria. This is done by projecting solar vectors acquired from the number of direct sunlight hours on surrounding building facades. In principle, this mechanism has been addressed by Leide and Schlüter [42] [43] via volumetric site analysis (VSA). Their approaches aim to explore urban site information by simulating multiple environmental performances, such as solar radiation, airflow, visibility, thermal comfort, and wind velocity through volumetric insolation analysis (VIA), volumetric visibility analysis (VVA), and computational fluid dynamics (CFD). Such this approach and other related developments [44] [45] [46], however, merely focus on the architectural form-finding without any further consideration on the concept and design principles of solar or shading envelopes.

On the other hand, De Luca [47] [48] [49] and Darmon [50] have proposed a similar subtractive mechanism based on the performance criteria of solar envelopes or so-called subtractive solar envelopes. This approach specifically involves sun visibility that aims to evaluate sun vectors from a predefined shadow grid of surrounding building windows without any obstruction from other existing buildings. In parallel, ray-tracing analysis is performed from surrounding windows to the voxels within the 3D plot using a Boolean expression (true or false statement). In this operation, the true statement will be executed when sun vectors hit or intersect the 3D polyhedra, and accordingly, the voxels subtraction procedure to the 3D polyhedra can be performed. Meanwhile, the false statement indicates an unsuccessful intersection. This condition means that voxels that are not intersected may contribute to the generation of geometric solar envelopes.

The subtractive solar envelopes ultimately permit architects not only to deal with various geometric configurations based on solar performance analysis, but also to highlight the potential use of voxel-based generative designs for urban environments. However, despite such potential improvements, aspects (such as sun visibility and ray-tracing analysis) pose several critical considerations, especially when addressing the contextual design strategy. For example, the identification of visible sun vectors merely considers the surrounding building contexts while neglecting relevant geometric properties, such as vegetation and other site characteristics (e.g., material properties). This consequently can affect irradiation analysis during the environmental performance simulation between a proposed building and the existing contexts. Besides, the window's grid configuration lacks in representing the insolation values of building facades during the ray-tracing analysis, due to its limited consideration of geometric centroids of each surrounding window.

In order to address these gaps, the existing workflow of subtractive solar envelopes has been improved by incorporating it with the prospective application of 3D laser scanning (point cloud data). By exploiting the practical usability of the point cloud in different fields, the scope of information properties in the real contexts can be improved, and to some extent, it becomes relevant to the specific aforementioned issues. Regarding sun visibility, the 3D point cloud not only captures the most and the least sun-exposed areas through buildings and vegetation, but also investigating material performances of contextual datasets through optical (reflectivity and translucency) and thermal properties (albedo and emissivity). Besides, the ray-tracing analysis between a proposed building and surrounding contexts is performed based on 3D point cloud datasets of the existing context. In other words, it substitutes the surrounding window's grid on the building facades proposed by the existing approach.

5.7.2.4 Subtractive solar envelopes based on point cloud data (SOLEN)

With the support of geometric and radiometric properties [51] [52] stored in a 3D point cloud, the integrated computational workflow between subtractive solar envelopes and attribute information of point cloud data has been established [53] [54]. It specifically integrates functional properties of position information (XYZ), color information (RGB), and reflection intensity (I). Each of these attributes caters to different potential tasks. For example, color information (RGB) can be used not only to extract and segment certain areas within the dataset based on its values [55] [56], but also to translate them into new information properties [57] [58].

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This can include converting data attribution of RGB into HSV values to perform the measurement analysis and road maintenance [59] and extracting the semantic information of the indoor environment with automatic room labeling [60] [61]. Meanwhile, reflection intensity (I) predominantly deals with surface and spectral properties of the scanned objects [62] as it constitutes the return strength values of laser pulse or backscattered echo for each recorded point [52]. Accordingly, the intensity values can be used not only to map geological layers and pavement lines [55], but also to detect natural phenomena, such as frozen and wet surfaces on roads [65], and the measurement of seasonal snow cover [67]. On the other hand, position information (XYZ) constitutes of geographic coordinate that marks each recorded point's specific location. This attribute plays a great role in synchronizing index between color and intensity values as it can attach to both attributes. Thus, complex areas of the dataset can be precisely extracted based on selected values. In general, these attributes contribute not only to extend particular performances of 3D point cloud data, such as identification of existing material properties [68], but also to extend the applicability of environmental analysis during the conceptual design stage.

Before performing the subtractive solar envelopes, the dataset correction is required to minimize erroneous levels during scanning. In this case, some aspects, such as environmental and meteorological conditions, atmospheric pollution [69] [70], unit specification of the scanner, surface properties of the scanned objects, and scanning geometries [71] can principally affect metadata information of the datasets during scanning. While correcting all these variables seems impractical, due to some local constraints (i.e., manufacturers), this study specifically focuses on correcting the acquisition geometry based on the angle of incidence, which is relevant to the proposed subtractive mechanism. Having established the corrected datasets, it can be further used not only to perform the ray-tracing analysis between the 3D polyhedra and selected solar vectors, but also to calculate the material properties of existing contexts that are useful to evaluate the environmental performance of a proposed building. In parallel, insolation analysis is performed to identify the potential solar energy of the resulting solar envelopes.

5.8 Proposed methods for subtractive shading envelopes

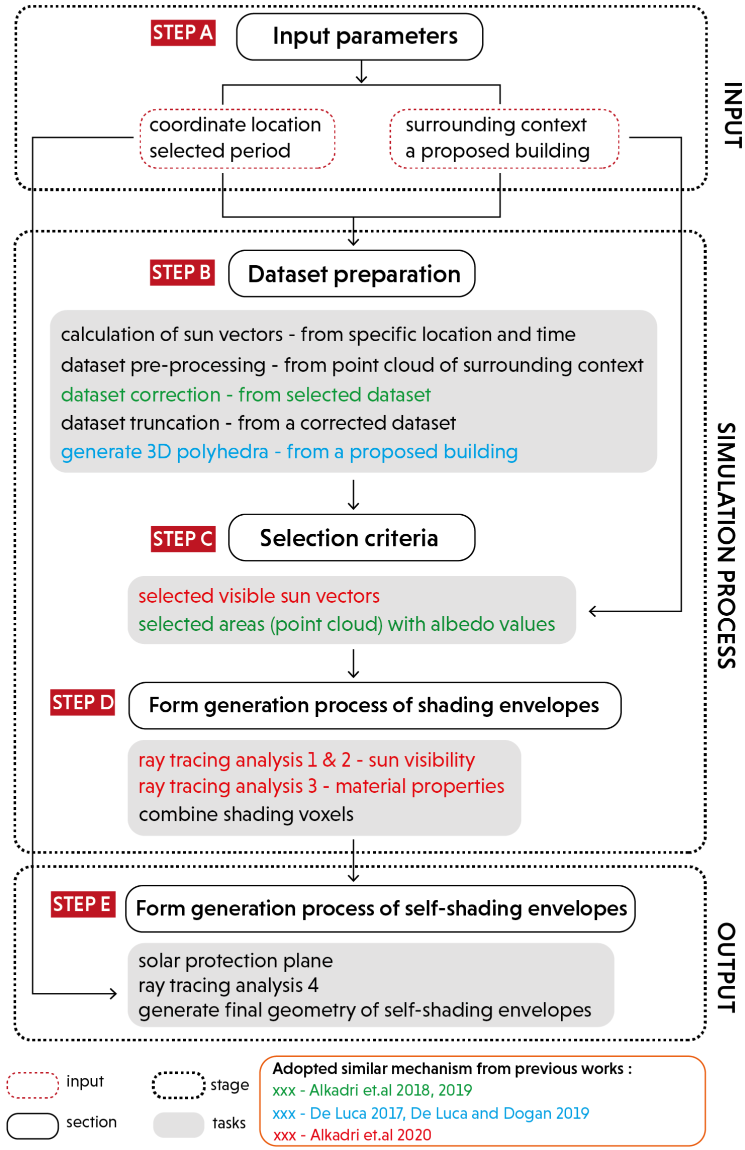

FIG. 5.15 An overview of the proposed computational workflow.

This study proposes a computational framework that consists of three phases: input, simulation process, and output (see Figure 5.15). Within a simulation process, five sequential procedures are developed, ranging from A (input parameters) to E (form generation process of self-shading envelopes).

To perform specific tasks in each predefined step, the proposed workflow was supported by several digital tools. For example, Topcon GLS 2000 [71] was employed to collect high-resolution point cloud datasets. It was complemented with Maptek I-Site [72] to perform dataset registrations, coloring, modeling, and most importantly, to facilitate the data transfer from scanner to the workstation in any designated format. Moreover, Cloud Compare (CC) [73] was used, not only for dataset preparation, but also for dataset pre-processing, such as attribute selection, dataset formatting, scalar field features, and the normal surface calculation. In alignment with that, Matlab [74] was specifically used to assist dataset correction (i.e., optimal normal values, intensity correction, and dataset subsampling), while Rhino [75] (coupled with Grasshopper [76] for visual scripting) was employed to develop a 3D geometric model of a proposed building and to perform solar simulation analysis by using a Ladybug [77] component in Grasshopper. Furthermore, a detailed task, dataset formats, and outputs of each step are addressed below.

5.8.1 Stage A – Input

5.8.1.1 Step A – Preparation of Input Parameters

As a starting point for the computational procedures, the input section refers to step A, which contains a series of parameters that are used to construct contextual settings of the subtractive shading envelopes. Specifically, it consists of climatic properties that correspond to coordinate location (i.e., longitude and latitude position based on World Geodetic System 1984, WGS84) and selected periods (i.e., month, year, day, and hours) (see Figure 5.16). The longitude and latitude coordinates influence the envelope's geometrical properties on the basis of sun position and solar angle. For example, high-latitude sites are characterized by a small angle of solar altitude and smaller degrees of solar radiation. Moreover, specific periods are required to obtain the number of critical hours of natural illumination that affects a proposed building and surrounding contexts.

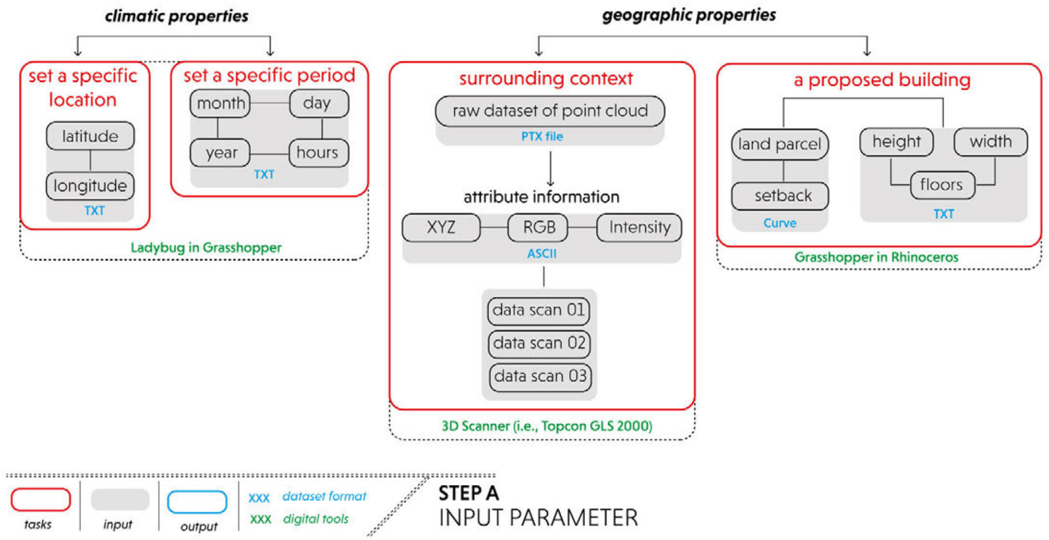

FIG. 5.16 Preparation of input parameters.

On the other hand, geographic properties include surrounding contexts (i.e., existing buildings and vegetation) and a geometric model of the proposed building. In this regard, the surrounding context contains a 3D point cloud data of the existing environment. As a raw dataset, its format properties often rely on the type of 3D scanner, but as long as the required attribute information (i.e., XYZ, RGB, and reflection intensity) is legible, any raw dataset formats are acceptable (i.e., PTX file). Meanwhile, several parameters, such as height, width, floors, setback, and building function, must be established to generate an initial 3D envelope for a proposed building. These inputs are then executed into the following Step B (dataset preparation) based on corresponding parameters and tasks.

5.8.2 Stage B – Simulation Process

This section focuses on translating the raw datasets into a simulation model by examining three main steps (i.e., dataset preparation, selection criteria, and form generation process of shading envelopes). Each step serves specific actions that are performed sequentially based on specific computational tasks. As illustrated in Figure 5.15, this section adopts several workflows that are partially implemented from previous works. For example, pre-processing point cloud datasets and the calculation of material properties (i.e., albedo values) are indicated with a green text

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[67]. These works focused on developing a material database of existing contexts and solar radiation analysis based on a small sample of point cloud data. Next, 3D polyhedra and sun visibility analysis are illustrated in the blue text [49,50]. These works primarily investigated a voxel-based generative design of subtractive solar envelopes based on 3D and parametric modeling. Last, the ray-tracing analysis between a proposed building and point cloud data of surrounding contexts is illustrated in the red text [56]. This work refers to a form generation of subtractive solar envelopes that consider surface properties of existing contexts based on geometric and radiometric information of point cloud data. While these previous works address different objectives, some features are still relevant for supporting an integrated design concept and computational workflow for establishing the subtractive shading envelopes.

To illustrate specific tasks in this stage, a detailed discussion of each proposed step is presented below.

5.8.2.1 Step B – Dataset preparation

This step aims to prepare all the necessary datasets to be readily used in the simulation model. After establishing the input from climatic and geographic properties, five tasks are required to perform. Two of these tasks (i.e., sun vectors calculation and the initial envelopes generation) can be run in parallel while the other three tasks (i.e., pre-processing datasets, dataset correction, and subsampling dataset) can be executed sequentially (see Figure 5.17).

Task 1, sun vectors refer to the number of sunlight hours that must be preserved on surrounding facades during the required period. As compared with cut-off times, which refer to a fixed period, sun access duration can be selected from a range of available hours for a specific façade on a specific day or for each day during a specific period. In doing so, sun visibility plays a crucial role when determining the relevant sun vectors.

Task 2, the initial envelope of a proposed building, is generated based on the predefined criteria. In this case, the functional program of a proposed building is projected as a public library, as well as communal space for the local community. To support the main activities, some spaces are established, such as a reading room, meeting room, toilet, and exhibition areas. Accordingly, the building needs to be accessible, and its indoor environment should be thermally comfortable for supporting the daily activities.

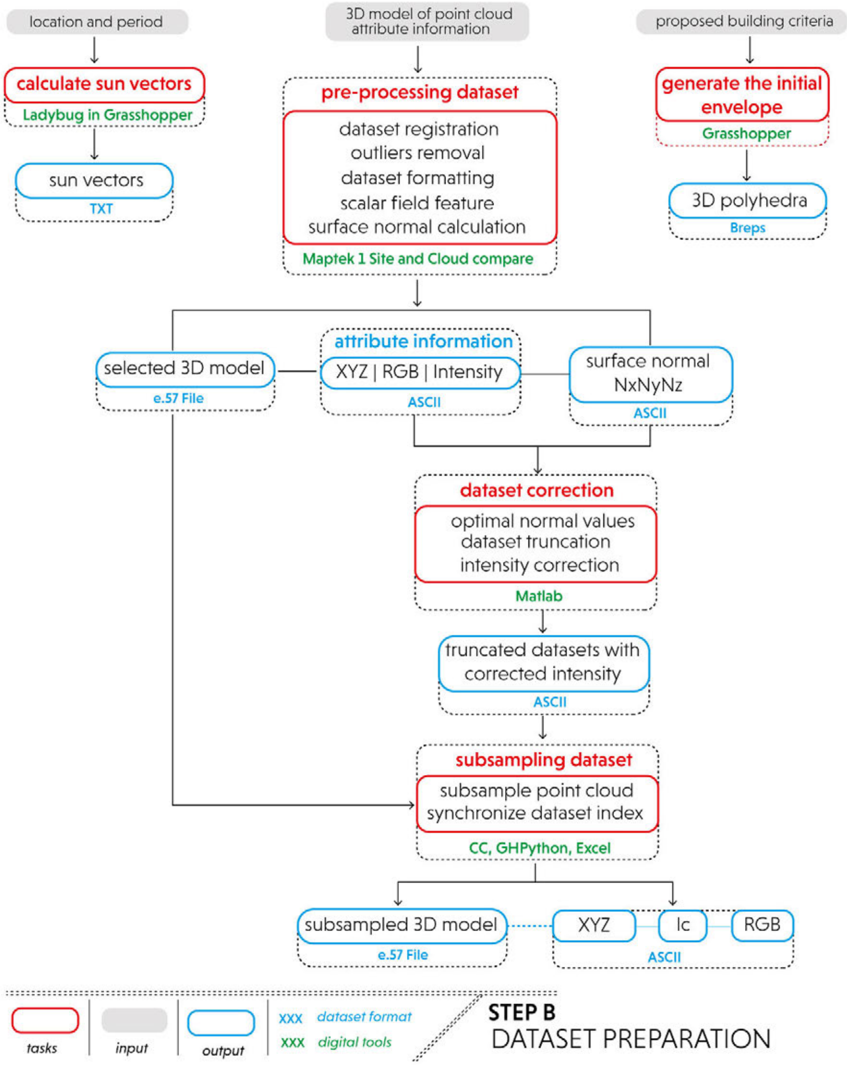

FIG. 5.17 Detailed procedures for the dataset preparation.

Task 3, the pre-processing tasks start with the dataset registration. This process aims to locate recorded datasets into a standard coordinate system based on the reflector position and GPS orientation. Afterwards, the outlier (unnecessary cloud of points) removal is performed not only to clean the boundary of selected datasets, but also to filter noises created during scanning. The dataset formatting also plays an important role in compensating for interoperability issues during the simulation process. In this case, the initial format of 3D raw point clouds (i.e., PTX) and its

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metadata are converted to E57 and ASCII files, respectively, in order to be accessible for various digital processing tools. In addition to this, the scalar field of the dataset is activated to identify the attached values' scale in each attribute. Last, normal surfaces (NxNyNz) of the dataset are calculated to find the appropriate normal values of each projected point during scanning. As normal values of the raw point cloud are excluded in the typical attribute properties, various angles of incidence, ranging from the sample of 10° to 90°, are firstly computed to each data scan. This is done by using the Hough Normal plugin [78] in CC, due to the original form of unstructured raw point cloud data. In this regard, each point within each data scan has different preliminary normal values. Ultimately, task 3 results in several outputs, such as a 3D model of selected datasets, attribute information of point cloud data with raw intensity values, and the normal surface of each data scan at various incidence angles.

Task 4, the dataset correction, is performed to compensate for the scattering condition of unstructured point clouds during scanning, specifically for amending radiometric properties of the dataset. It is worth noting that this procedure can only be applied on a single scan, due to the potentiality of mixing a reference point of the scanner and intensity values on the merge datasets [54]. The correction step starts with finding the average distribution of optimal projection points from the preliminary normal values. This achieves a reliable normal surface on each applied angle in the data scan. To do so, the following equation [79] is applied with an assumption that the original position of a 3D scanner located at (0,0,0).

$$i = \cos^{-1}\left(\frac{\overline{dn}\cdot\overline{dl}}{\left|\overline{dn}\right|\cdot\left|\overline{dl}\right|}\right) \tag{1}$$

where:
i = incident angle (α)
$\overline{dn}$ = direction of surface normal
$\overline{dl}$ = direction of the laser pulse

After configuring the point distribution from a various range of cosinus products, an evaluation is conducted to the standard deviation of each registered cosine value within the dataset. It aims to identify the pattern of point density to reduce scattered and coarse point clouds through the dataset truncation. Afterwards, the truncated datasets can be used for the intensity correction. In this regard, the angle of incidence becomes a relevant factor for correcting the dataset's acquisition geometry, given that instrumental effects highly affect the raw intensity value of TLS datasets. This procedure is executed based on the following equation [54].

$$I_c = I_{raw} \cdot \frac{1}{\cos\alpha} \quad (2)$$

where:
I_c = corrected intensity
I_{raw} = original intensity
α = angle of incidence

Task 5, the subsampling dataset, is performed in CC to reduce the density of points during the simulation. However, this procedure creates interoperability issues when the resulting dataset is matched and visualized to the initial 3D model in Rhino. Specifically, the 3D model cannot directly recognize the input of subsampled datasets, due to different units and scales of the attribute information. Therefore, synchronizing the initial index between the two datasets identifies metadata information in the geometric 3D model. This further permits the extraction of certain areas in the 3D dataset based on selected attributes values.

5.8.2.2 Step C – Selection criteria

After preparing the corrected datasets from climatic and geographic properties, this study sets two environmental performance criteria that support the geometric generation: sun visibility and material properties (see Figure 5.18). Sun visibility plays a crucial role in filtering the sun vectors that have direct access to the dataset of surrounding contexts. To do so, sun vectors generated from the indicated period are multiplied with normal vectors extracted from subsampled datasets. The resulting normal irradiance values are then evaluated on the basis of the projected angle. In this case, irradiance values with equal and larger than 90° are eliminated as they consist of zero and negative cosine values. Accordingly, these values are then excluded within the list of visible sun vectors because the surface of the datasets does not properly absorb their solar energy. Afterward, the resulting values can be used to select the corresponding points within the dataset.

On the other hand, material aspects are used to measure the performance behavior of the existing site’s surface properties. This allows architects to identify susceptible areas that may affect the geometrical performance of the proposed design. This study specifically computes albedo values to detect the absorbance percentage of solar energy on surrounding contexts by considering the RGB color and corrected intensity (Ic) of contextual datasets. A detailed procedure regarding the calculation of albedo values can be found in our previous research [67]. Furthermore, the resulting albedo values are filtered based on the threshold below 0.3. Although this setting indicates the low albedo, it can be used not only to identify areas that contain a high level of heat absorbance, but also to analyze and mitigate microclimatic impacts of the surrounding areas especially related to thermal issues and urban heat island (UHI) effect. In order to avoid that, these areas need to be blocked from direct sun exposures by excluding the indicated surfaces with high albedo values. Afterward, the resulting indexes of low albedo values (below 0.3) are synchronized not only with selected normal vectors from the sun visibility to register the corresponding normal surface of the dataset, but also with XYZ attributes to select the matching points within the dataset.

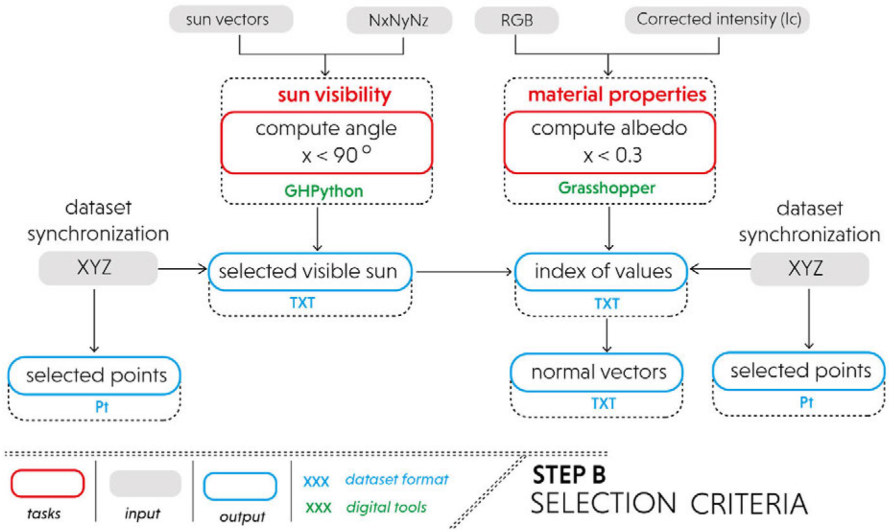

FIG. 5.18 Selection procedures based on the criteria of sun visibility and material properties.

5.8.2.3 Step D – Form generation process of shading envelopes

After establishing all the required parameters from the selection criteria, this step focuses on developing the simulation workflow (see Figure 5.19). It starts with the first ray-tracing analysis that requires input from visible sun vectors, selected corresponding points from sun visibility, and 3D polyhedra of a proposed building. This procedure principally applies a Boolean expression to assign true or false conditions on selected voxels within the 3D polyhedra array. The ray-tracing analysis-01 generates intersecting rays that are then evaluated based on the predefined criteria of direct sun access. In this case, voxels that are not blocking sun access to the proposed buildings or are categorized as an unsuccessful intersection with the 3D polyhedra will be considered part of the shading voxels (refer to voxels-02 in Figure 5.19). This workflow can also be called as a reverse solar envelope. Meanwhile, voxels that receive sun access will be forwarded to a later step in the second ray-tracing analysis (refer to voxels-01 in Figure 5.19).

Furthermore, reference points are generated from the voxels-02 to be used in the simulation of ray-tracing analysis-02. As a follow-up to the previous procedure, the ray-tracing analysis-02 aims to maximize the geometric generation of shading voxels. In doing so, by changing the basis projection of initial reference points originated from surrounding buildings to the voxels-02 may compensate for geometric obstruction of polyhedra at a certain projection angle in the ray-tracing analysis-01. Instead of applying this procedure to the original 3D polyhedra, it is used to re-evaluate voxels-01 based on reference points of voxels-02 so as to identify additional voxels (refer to voxels-03) that fulfill the criteria of receiving shading condition. As for the input for material properties, a similar procedure of ray-tracing analysis is also performed by considering the lowest albedo values (ranging from 0 to 0.3) applied to surround contexts. These results in voxels-04 so that in total, three groups of voxels (i.e., voxels-02, voxels-03, and voxels-04) are generated to shade surrounding buildings. These voxels are then combined into one group, voxels-05. To ensure that a shading condition also applies to a proposed building, the self-shading workflow is performed in the following stage.

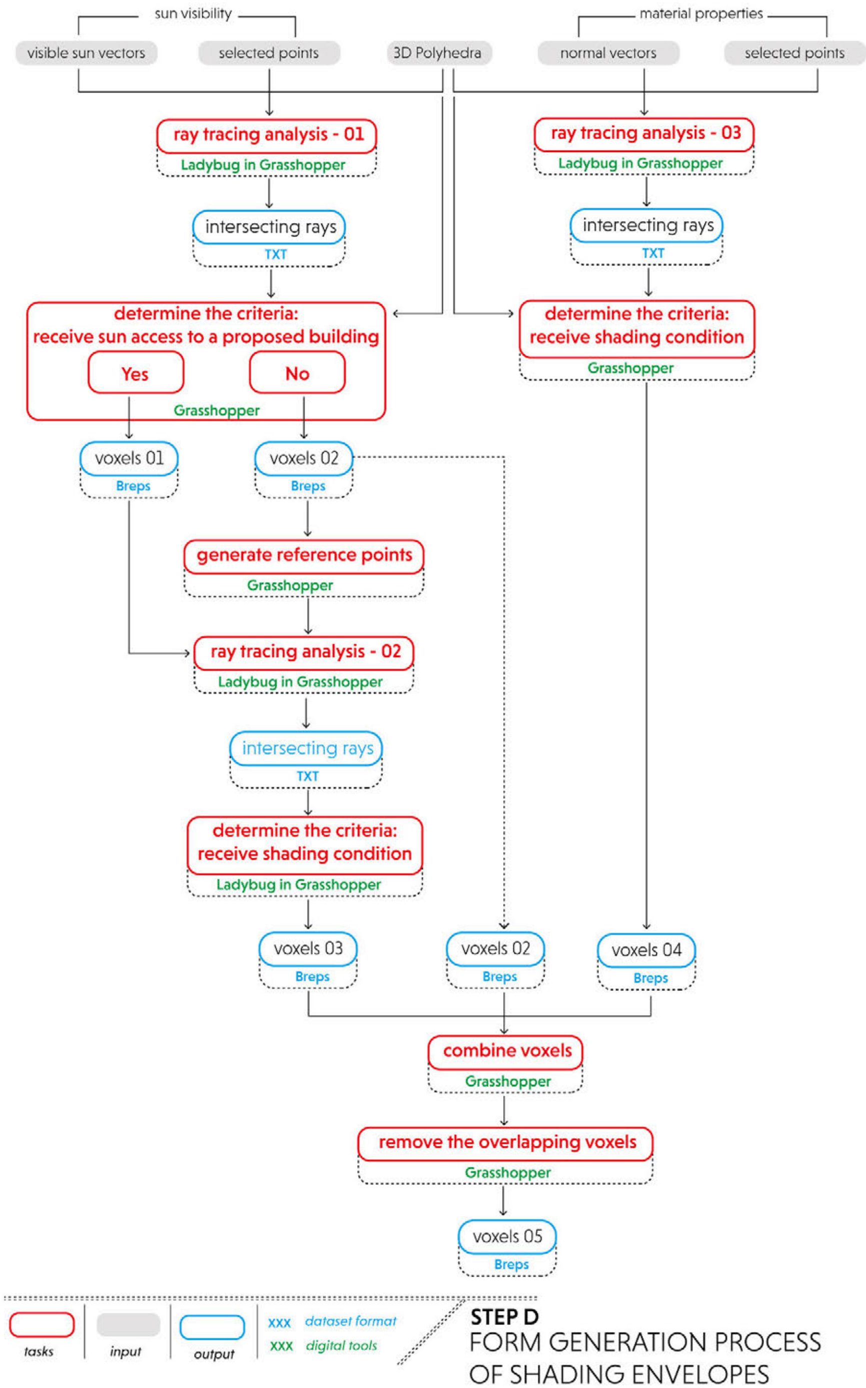

FIG. 5.19 Detailed procedures for the design simulation.

5.8.3 Stage C Output

5.8.3.1 Step E – Form Generation Process of Self-Shading Envelopes

As a last stage of the computational workflow, the output contains final tasks to generate a geometric configuration of self-shading envelopes (see Figure 5.20). The first task begins with selecting the upper part of the stacking voxels. This upper part acts as a roof or shelter to guarantee a shading condition for all properties under its envelope within a predefined period. Afterward, a solar protection plane can be applied on the bottom surfaces of the upper part of the voxels. It aims to establish reference points that are used as the basis for ray projections. Furthermore, the ray-tracing analysis-04 is performed by considering inputs from reference points of the upper voxels, the remaining stacking voxels (i.e., bottom part), and initial sun vectors calculated for the analysis period under consideration. This simulation will evaluate the remaining voxels by maintaining the one that receives a shading condition while removing the unshaded voxels. The resulting voxels (refer to voxels-06) are then combined with the upper voxels to establish the geometric envelope for each data scan (refer to voxels-07 and voxels-08). After identifying self-shading voxels for each data scan, the final step is to combine all these voxels into a final geometric envelope that represents a final configuration of envelopes (refers to voxels-09).

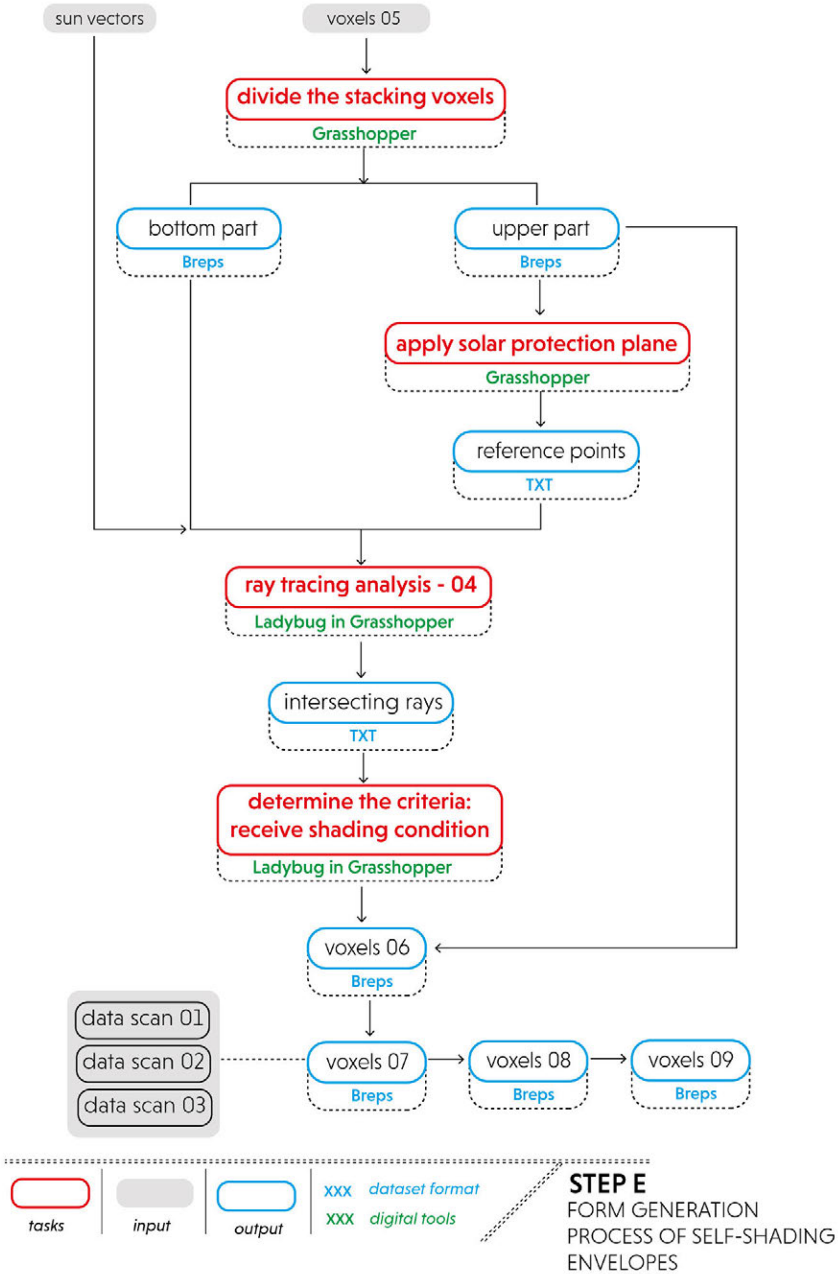

FIG. 5.20 Detailed procedures for generating the final output of self-shading envelopes.

5.9 Dataset collection

In regards to the dataset collection of on-site scanning, this study needs to fulfill at least two major aspects, as also mentioned in our previous study [56]. First, the collected point clouds should consist of Terrestrial Laser Scanning (TLS) datasets. It aims not only to accommodate more accurate geometric properties and better reality-based representation than Airborne Laser Scanning (ALS), but also to capture specific areas with various contextual elements, such as vegetation, temporal objects, material, and other elements, that may potentially contribute to the simulation model. Second, metadata information stored in a point cloud should at least contain typical attributes, such as XYZ, RGB, and reflection intensity. Geometric and radiometric properties within these attributes are used to identify material properties of the existing context and to conduct environmental performance analysis.

Furthermore, to demonstrate the proposed workflow, this study collaborates with SHAU, an architectural firm located in Bandung, West Java, Indonesia, to collect 3D point cloud data to design a new public library. This project is located in Citarip, West Java, Indonesia, (6°56'18.4"S 107°35'15.1"E, with ellipsoid reference WGS84) and surrounded by some vegetation and massive walls of neighboring buildings. The collected dataset was gathered using Topcon GLS-2000M incorporated with reflectors and GPS devices to achieve an accurate position during the registration process. As a light-weight and high-speed 3D laser scanner, this tool is also featured with a rugged design instrument (for use in the field) and full-dome field of view (FOV) with a selectable laser class, enabling the user to scan in extreme work environments and eye-safety concerns in dense areas. A detailed specification of the tool can be observed below (see Table 5.2):

TABLE 5.2 Detailed specifications of 3D scanner [71]

Parameters	Performance specification unit
System performance	
Maximum range (at 90% reflectivity) GLS-2000M	350 m (standard)
Single point accuracy Distance Angle	3.5 mm (1-150m), 1 sigma 6”
Tilt sensor Type Range	Liquid 2-axis tilt sensor +/- 6
Target detection accuracy	3” at 50 m
Laser scanning system	
Type	Pulse (time-of-flight) precise scan technology
Laser class	3R (high speed/standard) 1 M (low power)
Field of view (per scan)	Horizontal - 360° Vertical - 270°
Spot size	4 mm at 20 m (FWHM)
Scan rate	High Speed: Up to 120,000 points/sec
Physical and environmental	
Operation temp	-5°C to 45°C
Dust/humidity	IP54
Scanning control	
Scan time and resolution	Interval 12.5mm: High Speed: 01:46 Standard: 03:31 Low Power: 04:22

This tool’s performance specifications allow the dataset collection with only three single scans to capture a sufficient scene for the selected site (see Figure 5.21). With these three single scans, the dataset’s computational performance simulation can also be more manageable and relevant to the currently proposed workflow. Given that this approach is part of the exploratory study, architects need to select not only important information, but also a degree of detailed properties that are relevant to the simulation. In this regard, the setting of each scan approximately consists of four million points per scan within five minutes with a resolution 12.5 × 12.5 mm @10m. The distance between scanners and the designated objects are principally determined based on the approximate coverage of the scanner capacity, which may cover 360° of the horizontal field of view (FOV) with the distance for single-point accuracy 1–150 m. In this case, Scan 2 reaches the closest distance between the scanner and the object with 2.75 m. This is because data scan coverage areas need to capture the surrounding wall and corner spots behind the temporary shelters. Meanwhile, the longest distance is obtained by Scan 01 with 34.9 m, due to the diagonal position of the scanner to the corner of the site. Besides, in this dataset collection, it is worth noting that as long as the entire scenes of the selected site and relevant objects are covered, the scanner can be located at any appropriate distances.

FIG. 5.21 Dataset collection with different views captured in relation to the scanner position

5.10 Results and discussion

After establishing the selected dataset, this section presents the analysis results of the implemented workflow. It follows the five aforementioned steps as follows:

5.10.1 Step A – Input parameters

As previously described in the section about presenting the proposed workflow, input parameters consist of climatic and geographic properties. As for climatic properties, due to a constant temperature over the year in Indonesia [80], this study sets April 21st, 2019, as a sample of the selected period that represents a starting date for a dry season. Although the selected time range is limited, this simulation takes place as an exploratory study that focuses on exploring the feasibility of integrated computational workflow for shading envelopes based on attributes information of point cloud data. This specific duration is furthermore defined for four hours, starting from 11 am to 3 pm, which is averagely representing the highest temperature during the daylight hours. In parallel, a time-step for the simulation is set smaller than one hour to improve the simulation accuracy. This setting ultimately yielded four sun vectors that are simulated on each point of the dataset. Meanwhile, for a proposed building, the 3D polyhedra are extruded from the plot by considering predefined criteria of the buildings and local regulations, such as a 10 m height and 4–6 m setback requirement (see Figure 5.22). Each polyhedron is set to 2 × 2 × 2 m with the total number 690 units, including the generated asymmetrical shape, due to irregular order of the plot's boundary. In principle, this polyhedron's dimension can be vary depending on the architectural concept and functional program of the proposed building.

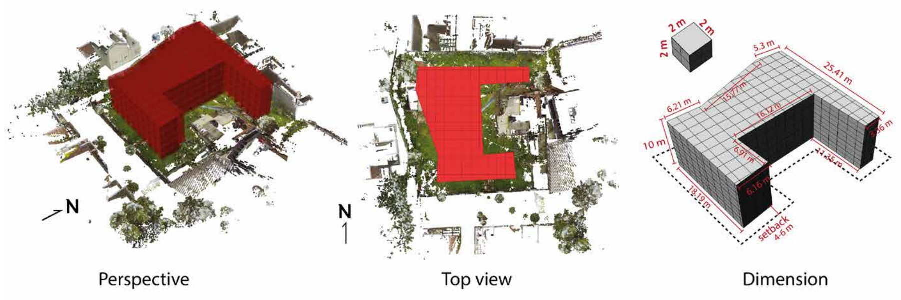

FIG. 5.22 Selected dataset and 3D polyhedra for a case study

5.10.2 Step B – Dataset preparation

While tasks (such as sun vectors calculation and 3D polyhedra generation) have been addressed previously, this section primarily discusses the result of sequential tasks, which consist of dataset correction and dataset subsampling. The dataset correction can be performed after establishing normal values with various incident angles for each selected data scan. According to Figure 5.23-A, all points are plotted on the basis of the cosine values of each incident angle. The pattern shown by all data scans is that points are distributed and assemble at a certain angle. This means that the laser beam projection may correspond very well at certain areas of the dataset during scanning, depending on the position of the scanner and geometric properties of the building surfaces (i.e., roughness). Afterward, to find the optimal normal values within this pattern, a standard deviation of cosine values is calculated based on a sample of points (see Figure 5.23-B). This becomes a basis for truncating the relevant datasets based on their distribution density.

In order to determine a threshold value of the dataset truncation, a standard deviation of the whole population of the dataset is plotted (see Figure 5.23-C). This facilitates us to generate the cosine values pattern resulting in Figure 5.23-B so that the number of points with a high distribution level of density can be identified reliably. As a result, ground areas of the plot (refer to blue-coded pattern in Figure 5.23-B) that mostly contain grass are automatically removed, due to irrelevant properties with the predefined criteria, while datasets with a red pattern are used for the intensity correction (See Figure 5.24).

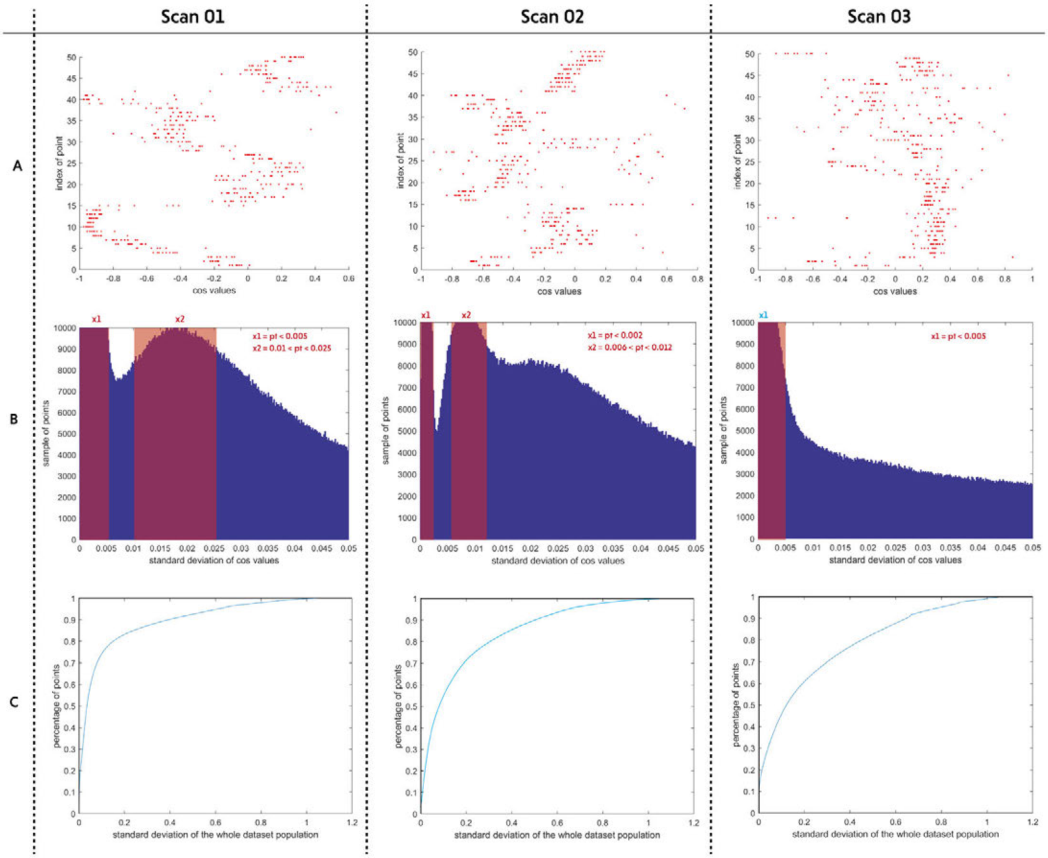

FIG. 5.23 Dataset correction (A). Point distributions based on cosine values of each incident angle (B). The standard deviation of cosine values based on a group sample of points (C). The standard deviation of the whole dataset population.

Figure 5.24 specifically demonstrates the result of intensity correction from the raw attributes to the corrected one through the scalar field of intensity and intensity distribution values. The dataset transformations of each scan are plotted based on four-color steps, ranging from blue to yellow, which represent the lowest and the highest intensity values. The threshold between these values is represented by light and dark green. The trend clearly shows that the raw intensity of all data scans contains yellow areas (refers to the “before” part), representing high reflective surfaces. However, these areas predominantly assign incorrect surface materials as it should be. For example, some parts of the buildings, such as wood façade and clay roof tiles, are attributed to yellow intensity. In fact, these materials principally contain a high level of emissivity value or low intensity, which means that the return incident energy from these materials to the scanner is highly decreased, due to its spectral reflectance mechanism on rough, dark, and dull surfaces [81]. In addition, the intensity correction also compensates for scanned areas around the scanner, due to the impact of the brightness level of intensity. These areas are massively indicated with yellow-coded values, due to the high level of intensity produced by the scanner at a very short distance. In this case, the scanner's brightness reducer is assumed not entirely and comprehensively applied in these areas, especially within the distance range of 10 m from the scanner position. This is because some local constraints, such as atmospheric variables (i.e., humidity and temperature pressures) and surface roughness of the objects, may influence specular and diffuse reflection of the laser pulse during scanning [54]

The corrected datasets are then performed with the subsampling procedure in CC in order to control the unstructured point density when it comes to the simulation. In this case, the distance between points is set to 0.05 or equal to 5 cm, which results, on average, in a decrease point, up to 70% of the truncated datasets. This procedure, however, only works on position information (XYZ) because it can cause interoperability issues when it transforms into the 3D model in Rhino, due to the different nature of the algorithmic operation. To tackle this issue, index information of each point (refers to ID in Figure 5.25) needs to be extracted beforehand during the truncation process and then used to synchronize the original attributes (i.e., XYZ and RGB) with the corrected ones in the 3D model. The workflow of this dataset transformation is illustrated further in Figure 5.25.

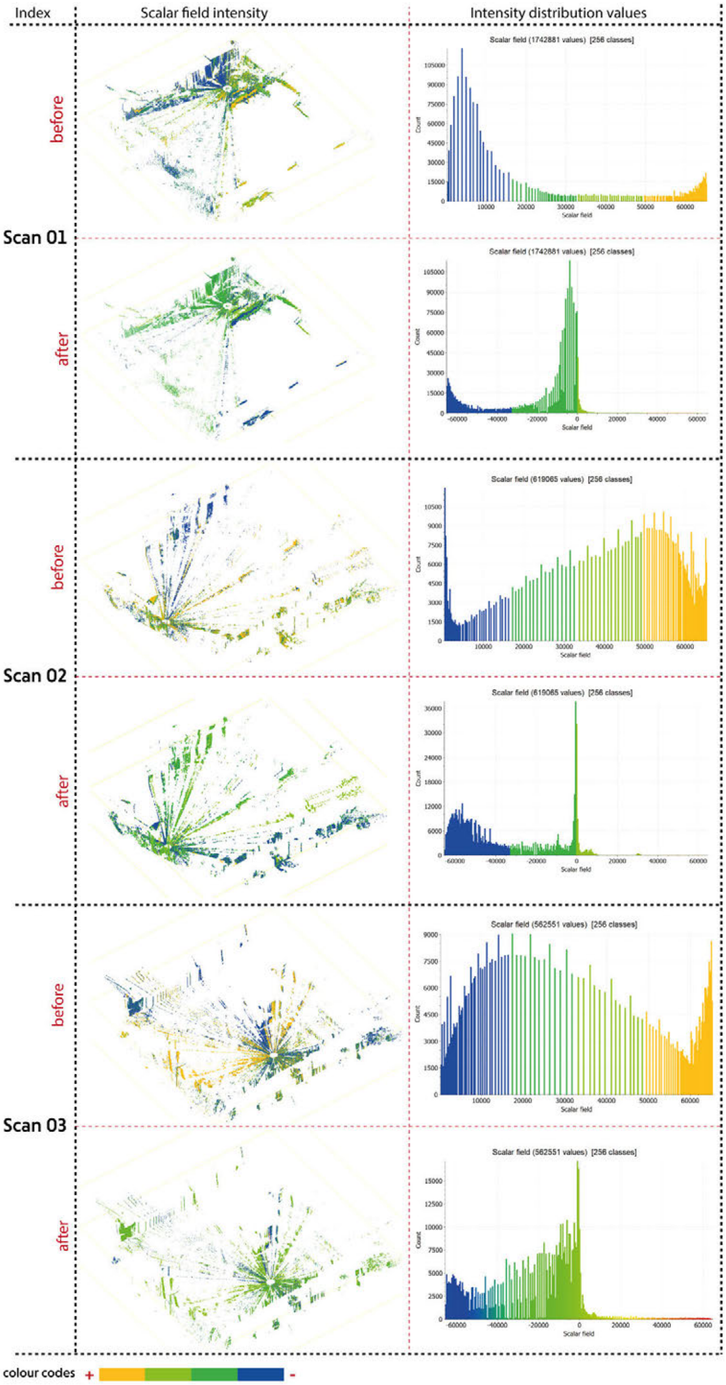

FIG. 5.24 Intensity correction on each data scan.

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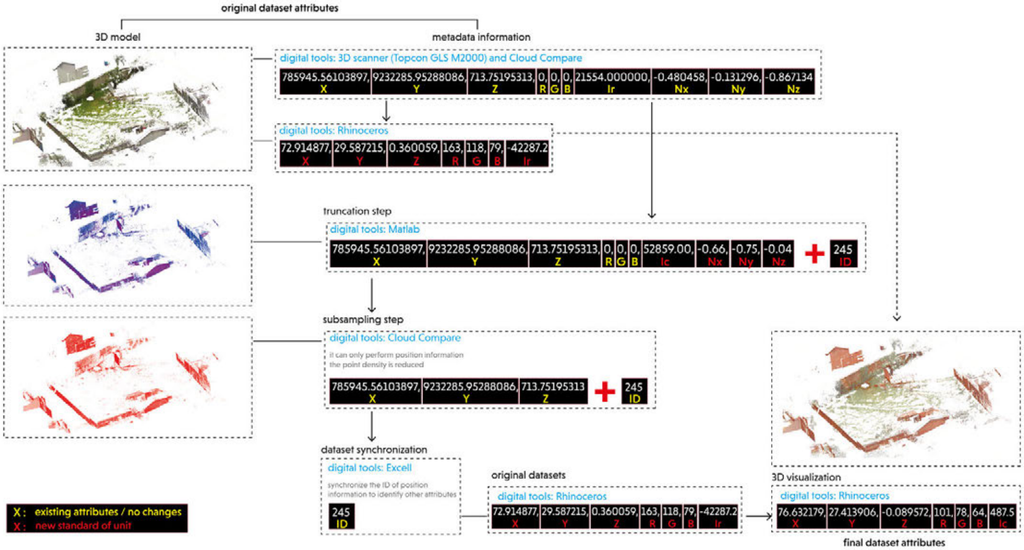


FIG. 5.25 Transformation of the dataset attributes.

In general, Figure 5.25 demonstrates a unit conversion of the dataset attributes that take place according to the step and digital tool used, starting from the raw data scan to the final stage of the workflow. A major transformation principally occurs when converting the original datasets from the 3D scanner to the 3D model in Rhino, which changes the unit of position (XYZ), color (RGB), and the raw intensity values (Ir). Therefore, the interoperability aspect plays a critical role not only to support the simulation analysis on the metadata information of the dataset (i.e., correction, truncation, and subsampling step), but also to help the visualization of geometric configuration based on the selected attributes.

5.10.3 Step C – Selection criteria

Before running the simulation, the subsampled datasets are evaluated based on the criteria of sun visibility and albedo values. These criteria identify relevant points that will be used for the voxels generation of shading envelopes. According to Figure 5.26, the resulting points for both criteria are significantly decreased as compared to the total points from the subsampled datasets. This is because a majority of subsampling points on the ground areas contain zero and negative sun vector values, which do not fulfill the sun visibility criteria. Accordingly, these points are automatically isolated, while successful ones are used as the basis datasets to perform the criteria of albedo values and the ray-tracing analysis.

In general, the trend in Figure 5.26 shows that the majority of selected points both for albedo values and the visible sun are similar and overlapping in a certain spot, such as the surrounding areas of the scanner position. On the other hand, each data scan also illustrates different specific areas for point distribution. For example, points for Scan 01 are primarily detected on the edge of the building's roof, while Scan 02 and Scan 03 are partially distributed in the brick wall and clay roofs of the surrounding houses, respectively. Furthermore, the selected datasets for each data scan are then used in the simulation process. This will be presented in the following step.

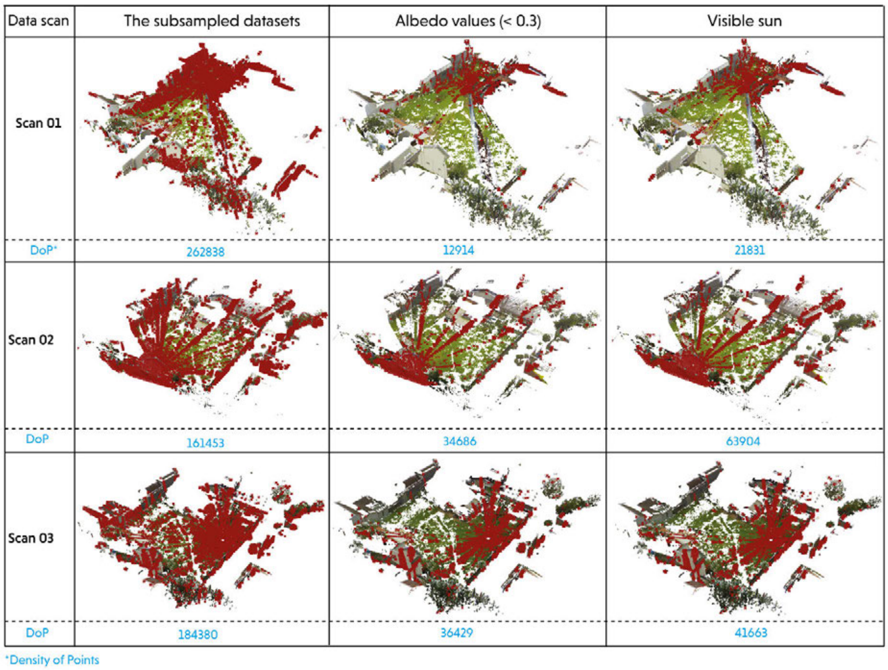
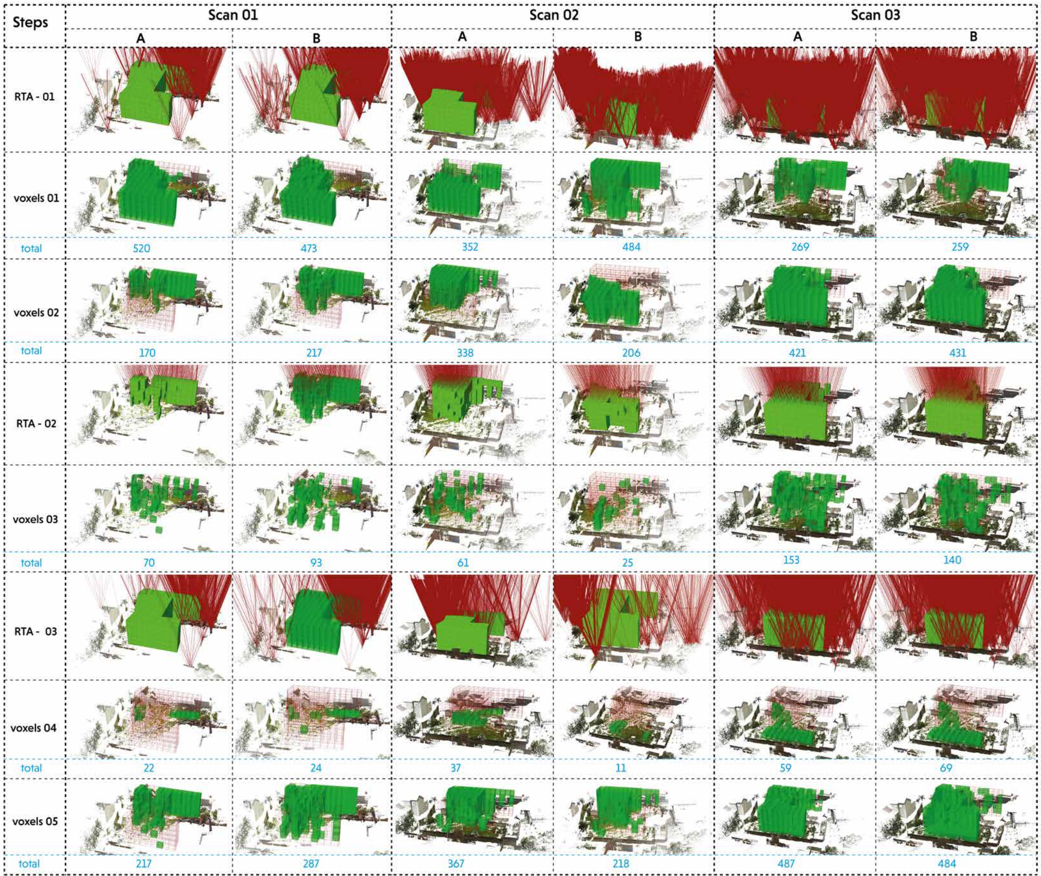


FIG. 5.26 The resulting points after performing the selection criteria

5.10.4 Step D – Form generation process of shading envelopes

The resulting datasets that successfully fulfill the predefined criteria in the previous step are used in the simulation by following a series of tasks illustrated in Figure 5.19. The outputs of these tasks are demonstrated in Figure 5.27. It consists of five steps to generate volumetric shapes and three steps to simulate the ray-tracing analysis. Beforehand, each data scan is divided into two parts in order to minimize the high computational cost during the simulation. According to Figure 5.27, some analysis can be further discussed as follows:

- The ray-tracing analysis (see part RTA-01) shows the intersection lines that occur between visible sun vectors, selected points of the existing site, and 3D polyhedra. The result of these intersections is then illustrated in voxels-01, which indicate a group of voxels that fulfill the criteria of receiving direct sun access. In this case, the simulation of Scan 03 yields a lower number of voxels-01 as compared with other scans, due to the density and position of each point to the 3D polyhedra. Specifically, the existing datasets of Scan 03 approximately cover all sides of the 3D polyhedra during the simulation, while Scan 01 only intersects a certain part of the polyhedra because the existing points are predominantly distributed on one side. Conversely, the resulting voxels-02 show a contrasting number of voxels, due to the different sun access criteria.
- Voxels-03 illustrate a simulation result of shading criteria. A major trend is shown by Scan 02, which results in a significantly decreasing number of voxels from the voxels-02. This is because sun vectors originated from the reference points of voxels-02 are massively intersected with the geometric shape of voxels-01.
- Voxels-04 represent a group of polyhedra that block the direct sun access to certain areas of surrounding properties. Each data scan consists of a different voxel configuration depending on the selected areas that have been identified below the albedo values 0.3. On the other hand, voxels-05 constitute as concatenating polyhedra gathered from the resulting voxels-02, voxels-03, and voxels-04. Although the volumetric size of voxels-05 shows a significant improvement, especially for Scan 03, unfortunately, the resulting voxels can only compensate for the shading condition of the surrounding properties and still lack in protecting the proposed building from the direct sun access within a certain angle. Accordingly, a self-shading envelope workflow needs to be applied afterwards.



RTA - 01 : ray tracing analysis between visible sun vectors, selected points and 3D polyhedra
RTA - 02 : ray tracing analysis between voxels 01, selected vectors and reference points obtained from voxels 02
RTA - 03 : ray tracing analysis between 3D polyhedra, normal vectors and selcted points gathered from material properties
voxels 01 : the resulting volumetric shapes (voxels) that receive sun access criteria
voxels 02 : the resulting volumetric shapes (voxels) that block direct sun access to surroundings
voxels 03 : the resulting volumetric shapes (voxels) that fulfill shading condition criteria
voxels 04 : the resulting volumetric shapes (voxels) that fulfill shading condition criteria gathered from albedo values
voxels 05 : the resulting volumetric shapes (voxels) after combining voxels 03, 02, 04 and removing the overlapping geometries

FIG. 5.27 The geometric configuration of subtractive shading envelopes based on sequential steps of design simulation.

5.10.5 Step E – Form generation process of self-shading envelopes

In order to perform self-shading envelopes, solar protection planes are applied on the voxels-05 by excluding voxels located on the upper part of the 3D polyhedra. This is because the upper voxels are considered as the roof or shelter for the remaining voxels located on the bottom envelopes. To do so, the upper voxels in each data scan are firstly separated from the set of 3D polyhedra (see Figure 5.28 step 02), while performing the ray-tracing analysis (see step 03) on the remaining voxels. As a result (see steps 04), voxels-06 illustrate the resulting envelopes that fulfill the criteria of a self-shading mechanism. The trend shows that the resulting voxels-06 for Scan 03 reduce, on average, 50% of the volumetric 3D polyhedra (refers to voxels-05 bottom part), while other data scans also decrease nearly a half of the initial 3D polyhedra. In this case, most of the reducing voxels are located on the edge of the 3D polyhedra or voxels that act as an exterior wall of the 3D polyhedra.

Voxels-06 of each data scan is combined with the upper part voxels that are previously separated in the previous step (refers to voxels-05 step 02). This process results in voxels-07 (refers to step 05), which are then used to perform the merging procedure in step 06—voxels-08. This step also includes elimination procedures for the voxels located in the same location. In so doing, the total number of polyhedra represented by voxels-08 shows the core geometry for each data scan. For example, the initial amount of voxels-08 after combining Scan 1A and 1B is 366 polyhedron, but after eliminating the overlapping polyhedron, it yields 259 polyhedra.
Thus, 107 voxels are indicated as overlaps during the merging procedure. Afterward, the voxels-08 of each data scan are merged using the same steps in order to generate the final geometry of self-shading envelopes. Ultimately, the total number of voxels that fulfill the shading criteria for surrounding contexts and the 3D polyhedra is 514 of 690 (see Figure 5.28)

Furthermore, the resulting geometries of self-shading envelopes can be identified as a core geometry that fulfills the building's main activities based on the daylight condition. For example, architects may plot voxels located on the ground level as a communal space, workshops, and playing areas for children as it requires more open activities while the upper floor can be fulfilled with a reading room or any other activities that match with the required shading. In addition, the roof of this upper floor can be utilized as a solar collector for PV panels that may produce supplementary solar energy for the buildings. This is relevant because Indonesia's geographical condition is located in the Equator can support the electricity production around 1,534 kWh/year for each installed solar panel based on 4.5 kWh/m^2 average daily radiation [82].

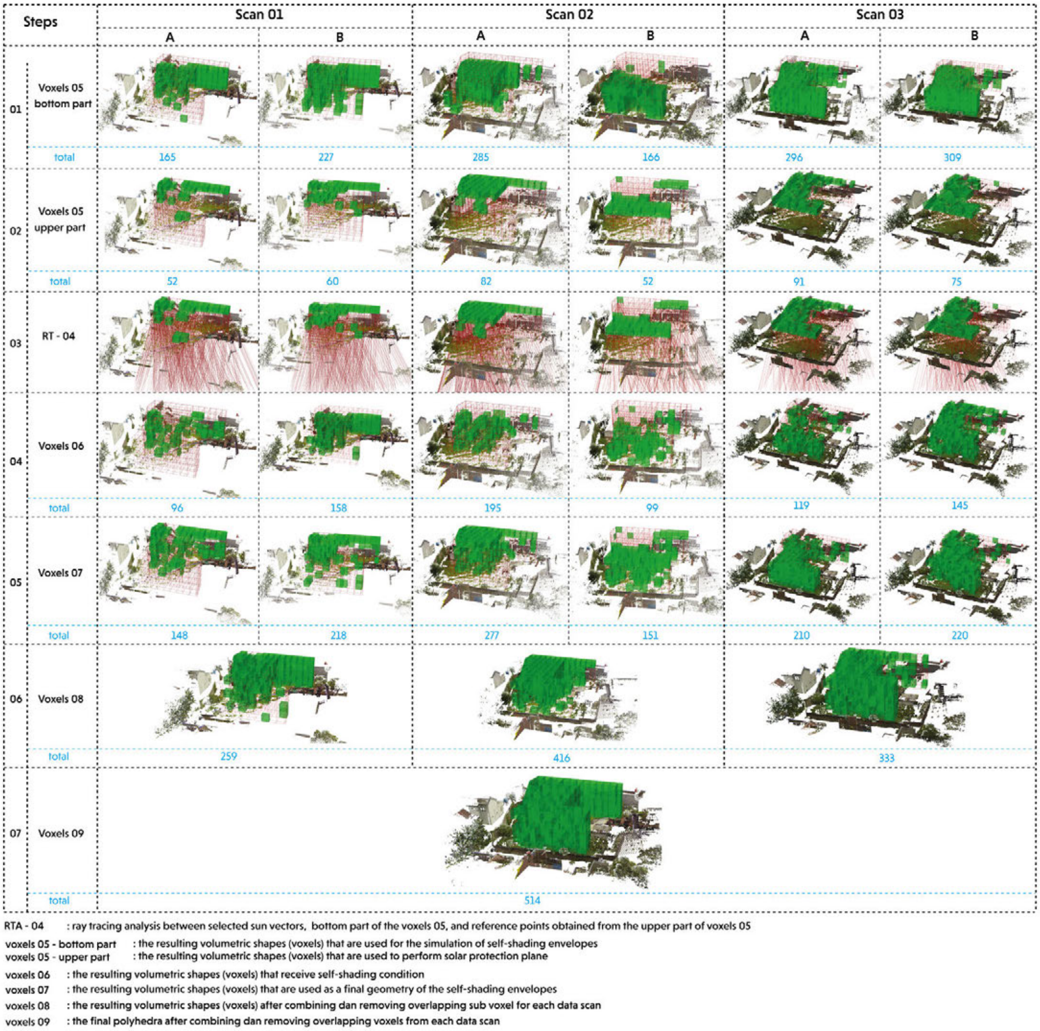


FIG. 5.28 Geometric configuration of subtractive shading envelopes

As compared to the existing method of self-shading envelopes proposed by Capeluto [36], this approach not only creates potential shading that merely comes from the roof of the envelopes, but also originates from a dynamic form of the envelope facades that correspond to different solar vectors. For these reasons, geometrical configurations of the final envelopes in this study show more variations in different orientations.

In design practices, the proposed approach can be adopted by architects as a further step for designing and analyzing high performing envelopes both for new and existing development areas. The Dutch architecture and urban design firm, MVRDV, has been implemented the basic design principles of this approach into several projects based on solar-oriented designs. As a new development area, for example, the P15 Ravel Plot, which is located in the Zuidas district, 1082 LC, Amsterdam was constructed based on the idea of the optimal line of sight integrated with the three-dimensional landscape and greenery [83]. Meanwhile, in urban scale, MVRDV proposed the idea of solar energy as a part of design intervention for zero energy neighborhoods to the existing historic infrastructures in Bordeaux, France [84]. These examples clearly show a stepping-stone for architectural design practices to explore further the relevance and potential application of a voxel-based design approach in supporting sustainable environmental design. In this regard, point cloud data can be a powerful instrument that fortifies environmental performance simulation of design context during the early design phase.

5.11 Conclusion

This study investigates the potential application of attribute information stored in point cloud data to support a new computational method for a voxel-based design approach based on shading performance criteria. As a part of the contextual design strategy, the proposed workflow specifically presents form generation based on subtractive shading envelopes and material properties of existing contexts that are used to generate a new method for self-shading envelopes in tropical countries. Ultimately, this integrated approach may support architects in taking a comprehensive design decision during the early stage of the design process based on real contextual datasets. As an exploratory study, this work presents several concluding remarks as follows:

- The attribute information of point cloud data (i.e., XYZ, RGB, and reflection intensity) contributes not only to calculate material properties of existing context, but also to be a part of selection criteria for generating voxel-based subtractive shading envelopes.

- The dataset preparation includes pre-processing and correction steps that help architects minimize the environmental effects of the dataset measurement during scanning and to select reliable and relevant information for the contextual analysis and the simulation process.

- The proposed workflow enables architects to produce more variation of geometrical facades, especially related to the final geometry of self-shading envelopes that are not only depending on the roof perimeters, but also considering reference points that attach to the upper part of each generated voxel.

- The ray-tracing analysis between 3D polyhedra and selected points of surrounding contexts permits one to identify specific areas and voxels that fulfill shading performance criteria during a predefined period.

- As a contextual design approach, self-shading envelopes not only receive environmental performance responses from surrounding buildings to the proposed design, but also deliver feedback from the new building to the existing contexts.

Despite the findings mentioned above, there still some limitations. For example, first, the implementation of this proposed workflow in design practice may require a collaboration with the field of remote sensing, especially related to the dataset collection and preparation. This is because some specific tasks need prior knowledge regarding the dataset pre-processing and particular digital tools. Second, the limitations of simulating highly dense datasets imply the number of solar vectors that need to be reduced, especially when dealing with the ray-tracing analysis procedure. Third, normal surface of the datasets and voxels of the proposed building should be evaluated by each solar vector, but as a consequence, it requires high computational processing that is currently lacking in our 3D modeling tools. Therefore, further research is expected to consider these issues in order to enhance the quality of the simulation results. It is also recommended to implement this study in different urban settings with multiple building functions, such as high-rise or new development areas, so that various urban forms can be further explored.

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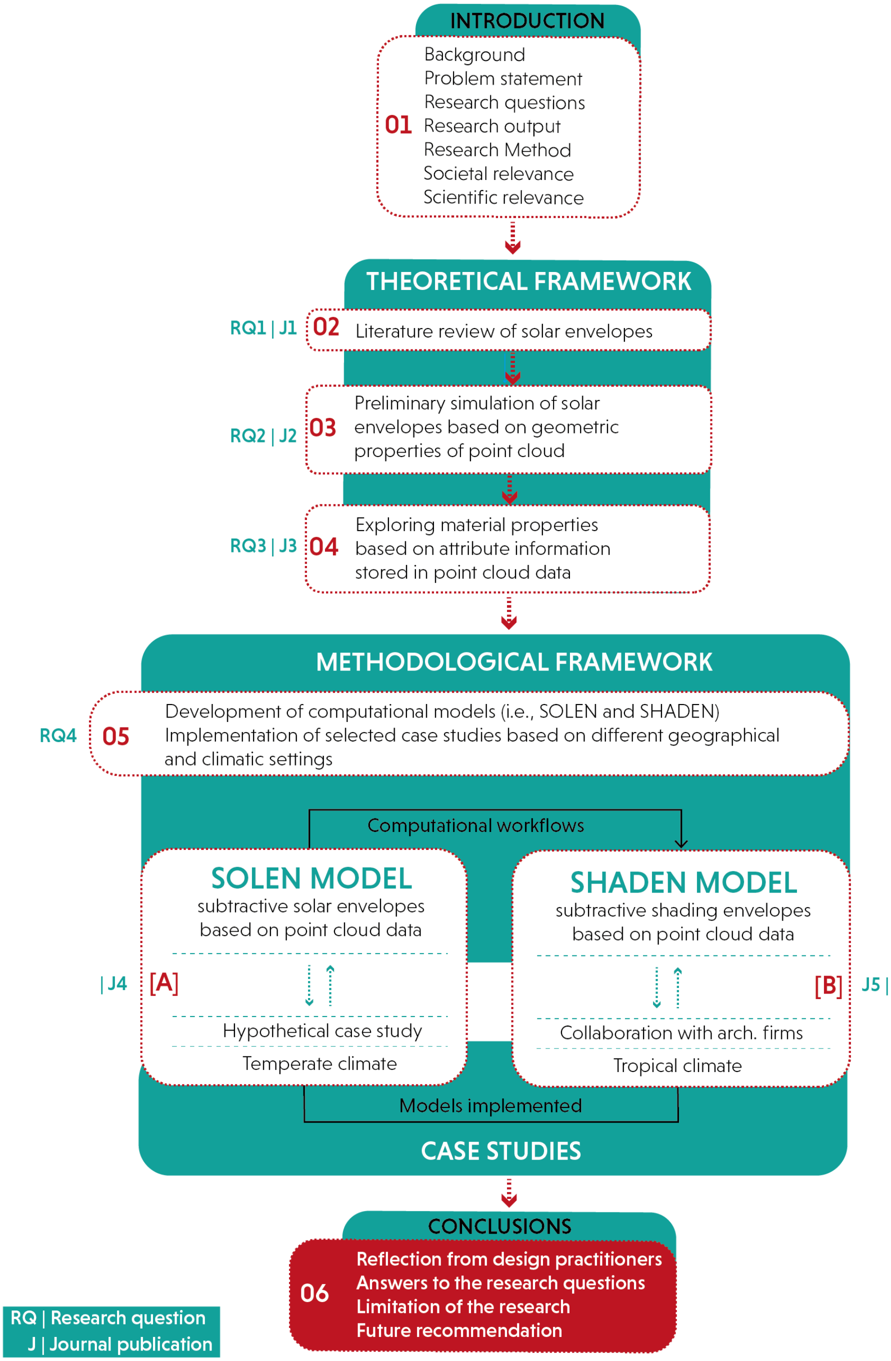
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6 Conclusions

6.1 Introduction

In this thesis, an integrated computational design method was developed for establishing solar geometry by making use of solar and shading performance aspects between the new building and its local contexts based on attribute information stored in point cloud data. In particular, two computational models consisting of SOLEN (Subtractive Solar Envelopes) and SHADEN (Subtractive Shading Envelopes) were developed, which were applied to temperate and tropical climates, respectively. In design practice, these models help architects to produce informed-design decisions during the conceptual design stage.

This thesis was carried out through a series of studies including a mixed-methods of deductive and inductive reasoning with quantitative and qualitative analysis, such as literature reviews to identify relevant references related to the topic, field studies for surveys and collection of raw datasets, environmental design simulations, project collaboration with an architectural design firm to demonstrate the developed method, and interviews with design practitioners (i.e., architects, urban designer, developer, city planner) to obtain constructive feedback on the proposed computational method.

Before answering each research question, this chapter will first discuss a summary of the constructive feedback obtained from design practitioners regarding the practical application of the proposed method in design practice. Afterward, comprehensive answers to sub-research questions will be presented in each chapter and will, proceed with the main research question to provide an inclusive response to the findings of the thesis. Furthermore, the limitations of the study and future recommendations will be presented to draw both scientifically and socially significant contributions to the body of knowledge in the context of the built environment.

6.2 Reflections from design practitioners

As an exploratory study, this research aimed at demonstrating the proposed computational method into design practices. This is a matter of not only identifying the level of practical application of the workflows proposed in existing design schemes, but also of gaining critical responses from architects, developers, and urban designers for future implementation. In doing so, interviews were conducted with selected participants. These participants were selected according to their scope of work, experience, and current office positions. In total, around ten participants from different specific backgrounds (i.e., developers, design consultants, urban designers, local governments) and countries (i.e., Indonesia, Qatar, The United Kingdom, The Netherlands) participated in this interview.

Furthermore, this interview was started with a brief presentation from the researcher about the research background and was followed by a booklet containing computational procedural steps of the workflow (see Appendix 6A). The booklet also includes a sample of datasets so that participants can explore the simulation steps shown. In order to drive comprehensive feedback, this study establishes nine questions (see Appendix 6B) that help participants raise critical points during the discussion.

As a result, participants generally confirmed positive feedback regarding this study, especially with regard to the potential application of 3D scanning technology that instantly enables one to convert existing contexts into 3D digital models. Despite the current complexity of processing datasets, incorporating point clouds into the architectural design process shows great interest for architects, especially related to radiometric properties stored in point cloud data. Potential features such as material properties, solar radiation simulation, and ray tracing analysis can be used to further explore the geometric envelope. These features significantly extends the main contribution of point clouds into architectural design that are predominantly used only for 3D reconstruction. The results of the interview are summarized into the following points:

Computational environments

Although the proposed model was demonstrated with clear sequential procedures and were largely based on open source tools, the main barrier for participants laid not only in the operation of the tools but also the technical knowledge of dataset processing. Given that participants mostly used different computing platforms during the design process in current working environments, technical issues such as digital interoperability between architectural tools and remote sensing equipment require some adjustments during demonstration.

Project cost

When it comes to design application, the budget aspect raises two main concerns, namely dataset preparation and design features. These aspects particularly apply the terms and conditions agreed between the architect and client. First, dataset preparation requires not only a high-cost investment to use 3D scanners but also a labor management task that usually demands specific skills to handle dataset processing and extraction of relevant information. Second, the integration of the proposed method into existing design workflows may stretch the time and cost slots for the client. In practice, this can be another trade-off between architects and clients when making design decisions for a project.

Local regulations

Although the study presented potential applications for integrating environmental performance analysis into existing design processes, unfortunately, it poses difficulties in dealing with architectural design practices due to lack of local regulations. Consequently, architectural design firms often put aside environmental parameters and focus merely on the geometric properties of design forms. For example, parameters such as shadow fences and sun access quantity were not listed yet in the Indonesian building regulations. Specific consideration regarding direct sun access in the new building in relation to surrounding contexts rests solely with the architect. That is why this aspect often causes contextual conflicts between new buildings and existing sites. To some extent, the concept of sustainable architecture simply becomes marketing jargon when bidding on a project or during the building permit appraisal process.

6.3 Answer to the research questions

6.3.1 Sub-research questions

What is a state-of-the-art review of computational design methods for establishing solar envelopes? (chapter 2)

This question aimed to identify background studies, knowledge gaps, and potential developments on the topic of solar envelopes. To answer this question, a systematic review study was conducted. Several criteria were determined to narrow the relevant findings of the research scope such as selecting three topics and sub-topics (i.e., conceptual themes: solar architecture, solar envelopes, and solar access, design workflows: computational design, solar design, and solar simulation, and contextual settings: urban planning, urban design, and architectural design), establishing a search span between 1960 and 2019, and exploring three-wide citation literature databases (i.e., Web of Science, Scopus, and Google Scholar). The search results were then analyzed comparatively based on various design parameters, digital tools, and case studies taken from 58 selected references. Although the growing number of references related to the proposed topics has increased moderately over the course of the study, the research objectives focus on relevant references that specifically employ the solar envelope simulation concept. Accordingly, the studies related to solar-form findings that only investigated generative architectural forms [1] [2] [3] and solar radiation analysis [4] [5] were not further considered in the main discussion of the research.

After formulating the framework of the review, this chapter resulted in three conceptual issues that correspond to knowledge gaps and future directions of the study. First is the 3D contextual model. It is currently lacking in understanding the site characteristics information, including the necessity to present the geometric properties of the contextual model. By exploring the potential applications of 3D scanning technologies (e.g., ALS, TLS datasets) providing a reality-based dataset may bring further possibilities to mitigate missing features in current 3D site models. The second is the climatic properties. The climatic settings from the existing literature were found merely in four-season countries and were predominantly based on the cut-off times parameter. These conditions will be different when it comes to tropical climates due to different design objectives. The third is geometric configuration. Due to limited performance criteria, the resulting geometric envelopes from the existing solar envelope's methods are also limited. Thus, exploring and integrating new features such as multi-objective optimization and multi-performance criteria (i.e., material properties, floor plan layouts) can bring a variety of geometric configurations to the final solar envelope.

Although the results of this chapter may need a quantitative evaluation analysis for future work, the resulting conceptual reviews were sufficiently robust to identify new parameters and develop new computational methods for establishing the solar envelope.

How do geometric properties of point cloud data contribute to the simulation of solar envelopes? (chapter 3)

According to the preliminary simulations of solar envelope discussed in chapter 3, the geometric properties of the point cloud collected from the ALS dataset present new features that contribute to the generation of solar envelopes, such as surrounding site elements (i.e., vegetation) and surface properties of the surrounding building contexts. These elements were used not only to generate 3D contextual models based on the existing site but also to perform environmental simulations on the final geometry of solar envelopes such as sunlight hours and insolation analysis. A comparative analysis between the manual 3D model (used by the existing solar envelope) and the TIN model (generated from the point cloud data) was examined to identify significant discrepancies between these models. In this regard, although the geometric representation of the TIN model is still far from being an ideal model that presents reality-based datasets, the simulation results of the TIN model at least contribute to capturing relevant information for further consideration in solar envelope simulations, especially with regard to parameters such as vegetation and surface morphology of the existing building.

Given that this chapter focused on exploratory studies of geometric properties stored in ALS datasets, some potential features such as material properties and high accuracy datasets [6] [7], were yet to be explored. In this regard, the potential application of TLS datasets offers a relevant match to these aforementioned features. Through the radiometric information, surface material properties of existing contexts can be further investigated.

What are potential features that can be developed further from attribute information of point cloud data? (chapter 4)

The simulation results in chapter 3 successfully presented the contribution of geometric properties stored in ALS datasets, not only to generate contextual 3D models but also to support the generation of solar envelope geometry. Further consideration of these results was carried out in chapter 4 through an exploration of geometric and radiometric information stored in TLS datasets. More specifically, a series of computational workflows was developed to conduct environmental simulations based on the point cloud of existing contexts. These workflows started with correcting the raw dataset based on the angle of incidence. It was aimed to select relevant information during site analysis and minimize erroneousness of the dataset measurement during scanning. The corrected dataset was then used to calculate material properties and perform insolation analysis. For material exploration, geometric (position-XYZ) and radiometric (color-RGB and reflection intensity-I) information of point clouds were used to calculate thermal properties (i.e., albedo, emissivity) and optical properties (i.e., reflectivity, translucency) of the dataset. These properties serve as input parameters for developing a database of surface materials from the existing site. On the other hand, insolation analysis aimed at calculating the solar energy absorbed by the site surface, especially the façade of surrounding buildings. This enables one to identify potential impacts from surrounding sites regarding solar radiation analysis.

As a final result of this chapter, material properties and insolation analysis were essential features used to develop an integrated computational workflow for contextual analysis. This workflow is essential for architects as it supports not only in revealing the specific characteristics and performances of the existing context but also in integrating the design simulation of solar envelopes based on real contextual datasets. While these features demonstrated positive results in performing environmental simulations, the list of materials stored in the developed database should be updated in order to be relevant to the design context.

How can new computational models for constructing solar geometry in temperate and tropical urban contexts integrate attribute information stored in point cloud (i.e., position-XYZ, color-RGB, and reflection intensity-I)? (chapter 5)

According to the simulation results presented in chapter 5, the attribute point cloud information through geometric and radiometric properties strongly supported the demonstration of the SOLEN and SHADEN model into case studies. These properties particularly contributed not only to dealing with geographic parameters but also to addressing features missing in existing solar envelope methods, such as sun visibility analysis, ray-traced obstructions, and material properties of the existing context. In this regard, sun visibility was performed to identify sun vectors that are not blocked by existing buildings, ray-traced obstructions were used to capture more elements in surrounding buildings during the simulation process, and the last, material properties were used to examine surface performance behaviors of the existing context through thermal (i.e., albedo, emissivity) and optical (i.e., reflectivity, translucency) properties. In addition to these features, environmental performance aspects such as glare analysis, surface material database, and solar radiation simulation were integrated as performance criteria into both models. However, the two models used these aspects differently in computational workflows. In SOLEN models, these aspects were used to assess the potential and impact of the final geometry of subtractive solar envelopes while in SHADEN model, they were used to generate the final geometry of subtractive shading envelopes.

Regardless of the integrated environmental aspects, the computational workflow of SOLEN model in chapter 5-Part A demonstrated a comprehensive design and analysis for establishing subtractive solar envelopes. It has been successfully applied in temperate climates based on a hypothetical case study in Delft, The Netherlands. However, different climatic settings (e.g., tropical climate) of course require different adjustments, especially with regard to design objectives, methods, and local parameters. For example, typical buildings in a tropical context are predominantly designed to minimize penetration of direct sunlight access, due to high temperatures in almost all year round. Thus, instead of applying solar envelopes, shading envelopes become relevant concepts for maintaining energy consumption and building thermal conditions.

Chapter 5–Part B focuses on developing computational workflows for establishing subtractive shading envelopes suited to the context of tropical climates. The computational workflow of SHADEN model not only considers the shading performance criteria of surrounding contexts but also takes into account the shading condition of the building itself through a solar protection plane. It aims to maximize self-building protections from overheating conditions by maintaining the geometric configuration of envelope’s roof areas. The SHADEN model has also been successfully demonstrated in a selected project in Bandung, Indonesia, in collaboration with an architectural firm, SHAU. This case study not only demonstrated the great feasibility of implementing a new method to subtractive shading envelopes in design practice but also presented a good starting point for a collaborative approach between architectural design and the field of remote sensing.

6.3.2 Main research-question

How can we develop a computational design method of solar geometries as a decision-making support for architects based on solar and shading envelopes and attribute point cloud information?

This research aims to address critical aspects of environmentally sustainable design by investigating a reciprocal relationship between the new building design and the local context without causing an adverse impact on the built environment. The first step started by exploring a theoretical framework of solar envelopes through a systematic review study. It aims not only to identify scopes and knowledge gaps of existing studies but also to highlight future directions of computational solar envelopes based on 3D contextual models, climatic properties, and geometric configurations. For example, existing methods for establishing solar envelopes provide an insufficient understanding of site characteristic information in the simulation model. In most cases, their 3D contextual model merely focuses on the building-oriented context so relevant parameters such as vegetation, materials, and other site properties are often neglected during the simulation process. To some extent, this can lead to a misinterpretation of simulation results and fewer comprehensive conclusions for the research problem.

The review studies simultaneously provides a theoretical underpinning for new technologies relevant to the specific gaps mentioned above, such as point cloud data gathered from 3D laser scanning technology. A preliminary simulation of solar envelopes was performed using geometric properties of point cloud based on ALS datasets. In this regard, the contextual dataset of point clouds has successfully contributed to capturing various site elements (e.g., vegetation) to support the geometric simulation model but still lacks to further identify the performance behavior of the existing context surfaces. On the other hand, attribute information stored in TLS datasets shows great relevance to deal with material properties of the existing context. Through geometric and radiometric information (i.e., XYZ, RGB, I), thermal (i.e., albedo and emissivity) and optical properties (i.e., reflectivity, translucency) of existing surface's dataset were computed in parallel with the development of environmental features such as glare analysis, surface material database, and solar radiation simulation based on existing context datasets.

As a result, two computational models for solar geometry (i.e., SOLEN, SHADEN) were developed based on the integration of the environmental performance features from the point cloud and subtractive design principles of solar envelopes. Although these models consisted of similar environmental features, they were different in terms of design objectives, computational workflow, geographic and climatic properties, and case studies. The SOLEN model was applied in Delft, The Netherlands based on temperate climates and performance assessment features to the final geometry of subtractive solar envelopes. Meanwhile, the SHADEN model was applied in Bandung, Indonesia based on a tropical climate and performance generation features to produce the final geometry of subtractive shading envelopes.

After applying the models developed to each corresponding case study, this research confirmed positive results regarding the simulation workflow and the feasibility of applying them into architectural design practice. The proposed method of solar geometry not only allows architects to receives the environmental performance responses from surrounding buildings to the proposed design, but also delivers feedback from the new building to the existing context. In order to gain technical and conceptual feedback comprehensively, interviews with design practitioners in section 6.2 were conducted. Within this section, oral (i.e., presentation) and written descriptions of the proposed model (i.e., a booklet containing detailed computational steps) were presented in a comprehensive manner. In summary, the method developed has contributed significantly to the following particular facets:

- To better understand the existing context before starting design exploration. Thanks to the attribute information stored in the point cloud data, comprehensive site analysis can be performed based on real contextual datasets, not only identifying microclimatic conditions of the existing site but also highlighting potential impacts that may happen between new buildings and local contexts.

- To assist architects in making better design decisions during the conceptual design stage. The exploration of material properties and insolation analysis play a crucial part as design features, functioning not only as a performance evaluator assessing environmental impacts on the final geometry of solar envelopes, but also as a form generator producing the final configuration of the solar envelopes geometry.

- To organize a collaborative and interdisciplinary approach between the field of remote sensing and architectural design. This brings further opportunities for the two disciplines to explore relevant new features such as expanding the functional properties of the 3D point cloud data to contribute not only to 3D reconstruction but also to the architectural design process through environmental performance simulations.

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6.4 Limitation of the research

Although the study presented a comprehensive answer to each research question and some considerations regarding the practical implementation of the proposed method mentioned in section 6.3, this research acknowledges some critical aspects that can benefit from further considerations. For example, as a collaborative research project that integrates technical knowledge from remote sensing with computational design in architecture, this study realized that dataset collection cannot be conducted and treated as individual surveys by architects. This is not only due to the technical operation of the 3D scanner but is also a matter of processing the dataset which requires a prerequisite knowledge in selecting the relevant information for the project. In addition, the tool cost affordability may also be a major constraint for many architectural design practices in using these support tools during the conceptual design stage, especially for small architectural firms.

This study also identified several limitations regarding the computational workflow of the models developed during the simulation. First, the currently proposed workflow predominantly employed an angle of incidence's (α) parameter as the main feature for the raw dataset correction, especially for the reflection intensity (I) attribute. As for the range (R) which is also included as part of acquisition geometric parameters, it is yet to be further explored due to technical preparation issues during scanning such as the reflector's placement in specific areas and the noises dataset created by the object's movement on site.

Second, the number of solar vectors used during the ray tracing analysis was on average limited due to the use of very dense datasets. As a consequence, high computation time and cost continue to cause major problems during the simulation process. This study solves this issue by selecting a small range of simulation periods with the subsampling dataset but on the other hand, this may affect the robustness of simulation results.

Third, this research mostly applied case studies based on specific building functions with simple urban forms. Therefore, the exploratory section regarding the geometric analysis between a new building and its local context was limited. In fact, the existing site located in urban areas usually consist of high and complex urban density.

6.5 Future recommendations

With further developments to future research, the scope, objectives and research findings can be extended to explore new features and approach of solar geometries. The following aspects are highlighted according to the thesis framework:

Theoretical framework

As discussed in chapter 2, this study investigates a literature review that focuses on understanding computational methods for establishing solar envelopes based on design parameters, tools, and case studies, taking into account the selected references timeframe from 1960 to 2019. While this study has developed a new computational method, future reviews could be of further benefit to include additional methods from this study by performing quantitative analysis of various methods and using a similar set of parameters. In addition, a review that specifically investigates the shading envelope may complement a comprehensive approach database for solar envelopes.

Further developments on material properties also play a crucial role as part of the theoretical framework of this study. Chapter 4 presented a computational workflow for developing a material properties database from existing contexts, computed from attribute information of point cloud data. Additional integrated devices such as thermal cameras enable one to calibrate and verify temperature parameters when calculating reflectance values of the dataset. This will improve the identification of solar potential collection on existing datasets.

Methodological framework

The methodological section generally consists of two developed models, namely SOLEN model (see chapter 5-Part A) and SHADEN model (see chapter 5–Part B). At least three potential features were identified for future study development. First is the geometric configuration. As a voxel-based generative design, this study explored geometric shapes for solar and shading envelopes based on environmental performance criteria (i.e., direct sun access). In principle, the final geometric configuration represents the best possible compromise between the volumetric envelope and the selected environmental parameters. Since the option to select the optimized envelope was not yet available in this study, further consideration of multi-

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objective optimization may allow for the generation of optimized solutions regarding geometric envelopes with the best environmental performance values. This may attract new environmental variables for future optimization research such as thermal comfort, wind, and acoustics.

Second is the ray-tracing analysis. Due to the heavy simulation dataset consuming high computational costs, this study can benefit further by investigating machine learning approaches, especially AI (Artificial Intelligence) to simulate ray tracing analysis between 3D polyhedra of the proposed building and the dataset of existing contexts. This can not only reduce the simulation time and increase the accuracy of result but also identify new configurations of performance analysis such as solar radiation and material performance behaviors.

Third are the computational design tools. This study developed an integrated computational method involving the interoperability of various digital tools and workflows from 3D laser scanning technology to environmental performance analysis. When it comes to design practice, this part becomes critical to help architects in making design decisions during the conceptual design process. Accordingly, during the reflection part, architects highlighted two specific points that may contribute to the future model of this study, namely the familiarity of design tools and the level of computational skills. Due to the lack of these factors in most common architectural practices, the development of customized design tools that specifically perform the model proposed in this study can be a potential option for future research. This tool can be components or plugins that embed into the existing digital tools environment or a new digital platform that can be used independently. In this regard, architects only need to input parameters that are relevant to their context and projects.

Case studies

This study applied the developed method into two case studies based on the context and climatic properties. The case study predominantly focuses on specific urban forms and building functions. By exploring more urban properties in densely populated areas with a variety of existing building functions enables one to understand in depth the complexities of existing urban forms in relation to new buildings. In addition, incorporating functional utility into the shading envelope simulation, especially during the ray tracing analysis makes it possible to integrate the geometric shape of each resulting voxel with a specific function meeting predefined criteria. This will significantly help architects to configure the 3D space layout of a new building based on the environmental performance simulations generated in the early phase of architectural design.

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Appendix 6A

1 What is your educational and professional background?

2 What is your current position at the office?

3 What are your computational skills? What computational tools do you use in your daily practice?

4 How do you deal with performance-based architecture during the conceptual design process?

5 What do you think about the interdisciplinary (i.e., engineering and architecture) design approach to design practice?

6 To what extent can the presented method be adopted in your daily practice?

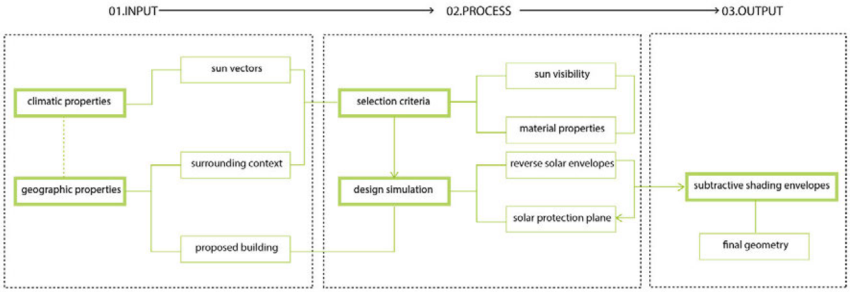
7 What are the pros and cons of using the method presented?

8 What are the future recommendations for the method presented ?

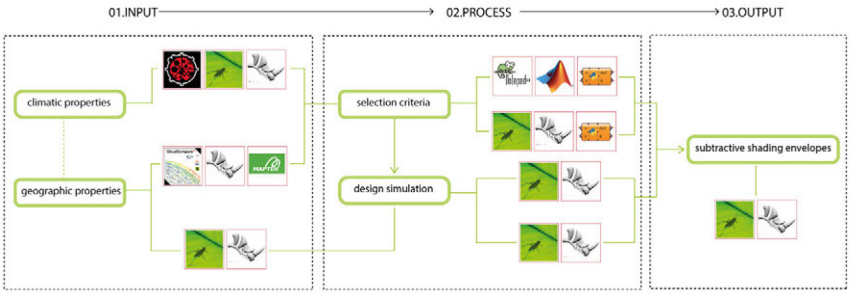
Appendix 6B

Procedural steps of the computational workflow

Step 1



Step 2



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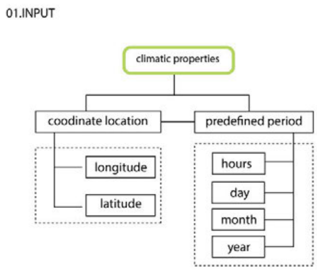

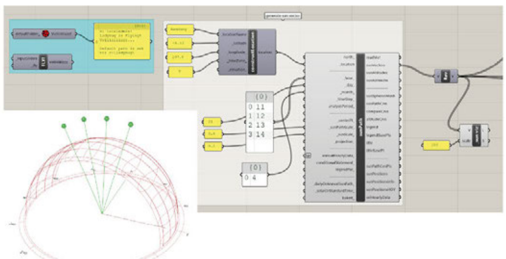

Step 1
Generate sun vectors from the predefined period.

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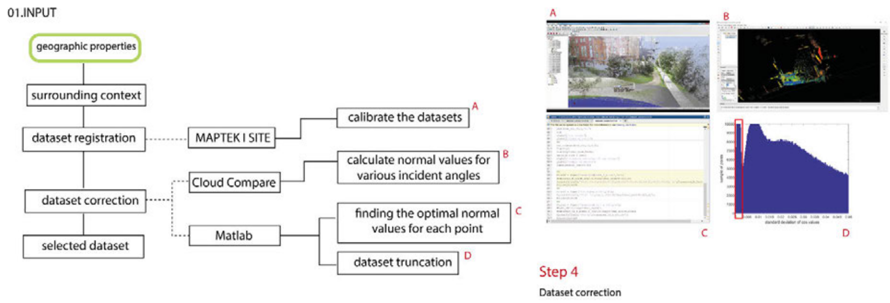
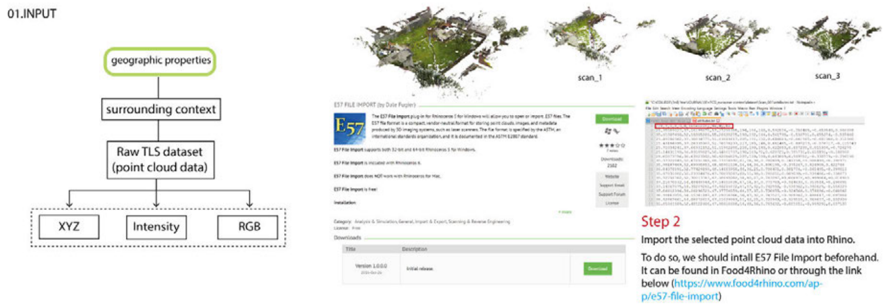
Step 4



Step 4b



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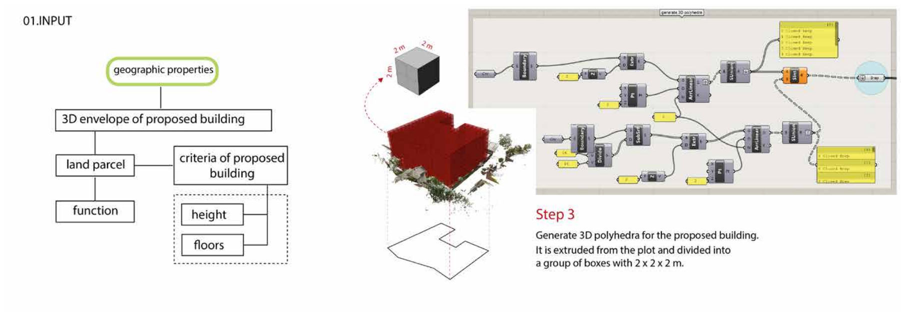

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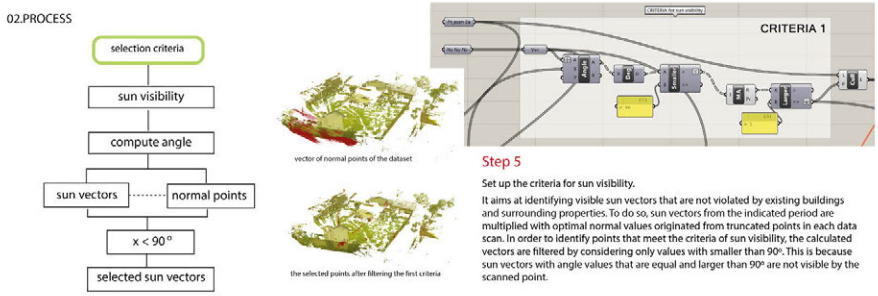
Step 6



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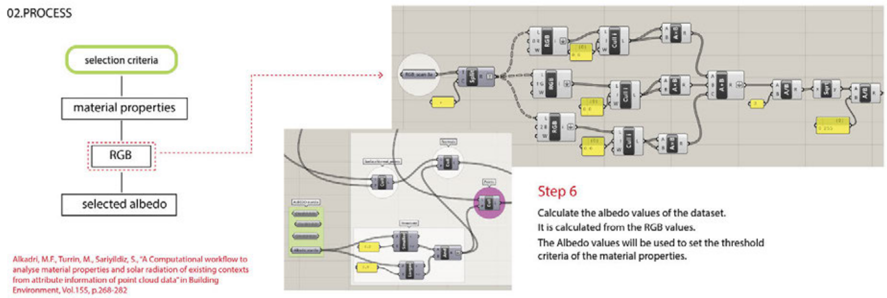

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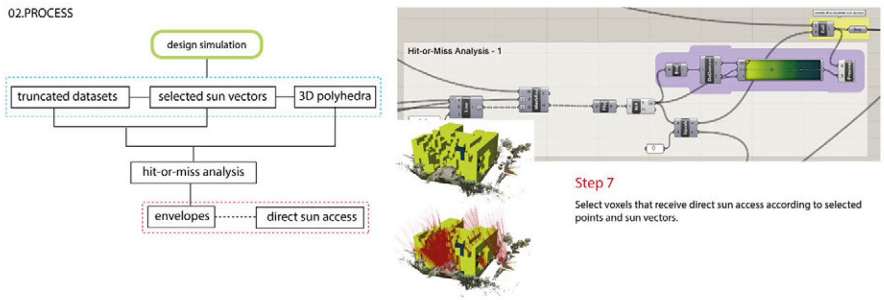

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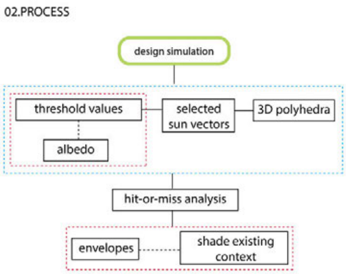
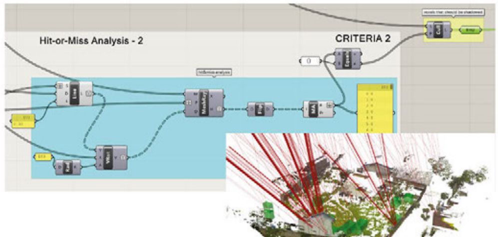
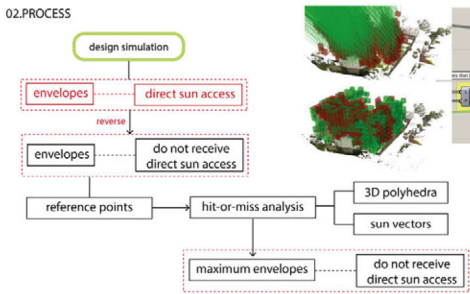


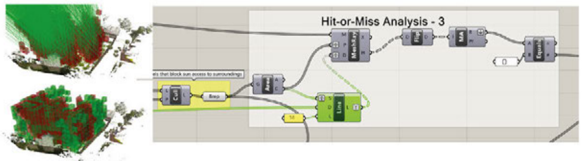


Step 8

Select voxels that will shade existing context according to threshold of material properties within the criteria 2.

Step 10

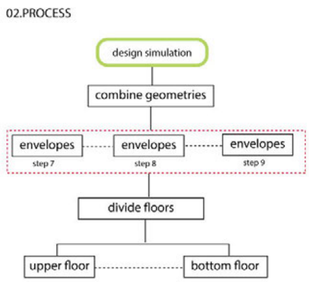


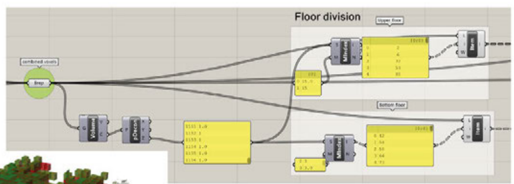


Step 9

- Generate a reverse mechanism (to create shading envelopes instead of solar envelopes).
- Maximmize the involvement of voxels of shading envelope that fits to the border of the plot (3D polyhedra). It is done by running again the hit-or-miss analysis with the initial shape of 3D polydera

Step 11





Step 10

- Combine voxels from the step 8 and 9. Afterwards, we will apply solar protection plane by dividing upper and bottom floor of the combined voxels. This aims to generate self-shading envelopes for the proposed building.

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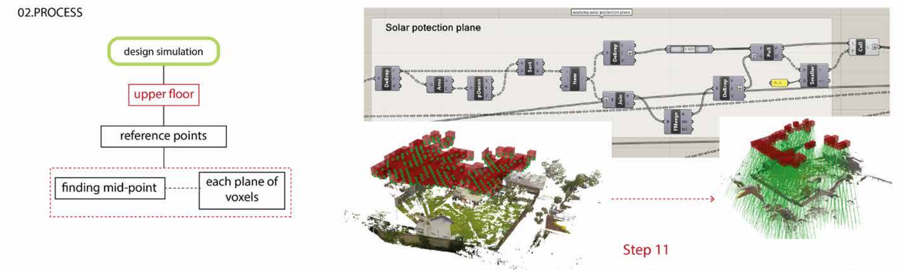
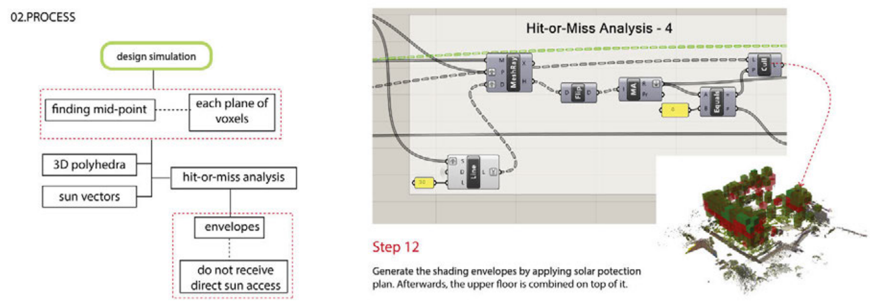
Step 12



Step 11

Generate base for the solar protection plane. It will be used to place solar vectors for running hit-or-miss analysis of the bottom voxels.

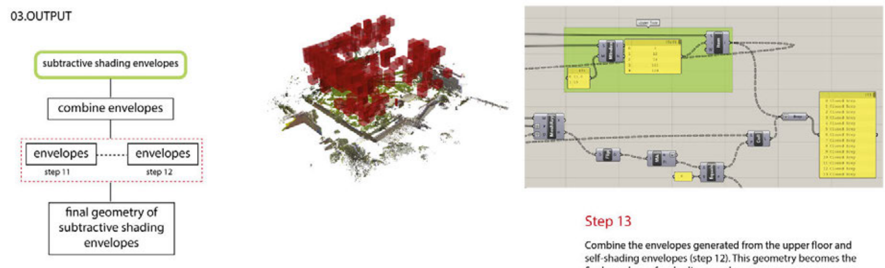
Step 13



Step 12

Generate the shading envelopes by applying solar potection plan. Afterwards, the upper floor is combined on top of it.

Step 14



Step 13

Combine the envelopes generated from the upper floor and self-shading envelopes (step 12). This geometry becomes the final envelopes for shading envelopes

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Curriculum Vitae

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Selected Academic Activities

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Since 10.2020	Reviewer in CAADRIA – PROJECTIONS 2021 The Chinese University of Hong Kong
Since 05.2020	Reviewer in Journal of Renewable and Sustainable Energy Reviews
Since 05.2020	Reviewer in Journal of Information Processing in Agriculture
08.2019	Workshop Coordinator Digital fabrication: Robotic weaving using bio-composites materials University of Indonesia, Indonesia
11.2019	Presenter In International LDE-Heritage Conference Delft, the Netherlands
01.2019	Presenter In Conference Child in the City, Children in the Sustainable City Antwerp, Belgium
01.2018	Workshop Organizer Computational method of solar envelopes and solar collection Chair of Design Informatics, TU Delft

List of Publications

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21#13

Solar Geometry in Performance of the Built Environment

An Integrated Computational Design Method for High-Performance Building Massing Based on Attribute Point Cloud Information

Miktha Farid Alkadri

As part of the passive design strategy, the development of computational solar envelopes plays a major role to construct a cooperative environmental performance exchange between new buildings and their local contexts. However, the state-of-the-art computational solar envelopes pose a great challenge in understanding site characteristics from a given context. Existing methods predominantly construct 3D context models based on basic architectural geometric shapes, which are often isolated from the surrounding properties of local contexts (i.e., vegetation, materials). Thus, they only focus on context-oriented buildings and energy quantities that unfortunately lack a contextual solar performance analysis. It is clear that this condition may result in a fragmented understanding of the local context during the design and simulation process.

With the potential application of attribute point cloud information, it is necessary to consider relevant parameters such as surface and material properties of existing contexts during the simulation of solar geometries, which are currently absent in computational frameworks. As such, the new method is required to enable architects not only to measure specific performances of the local context but also to identify vulnerable areas that may affect the proposed design. This research focuses on exploring an integrated computational design method for solar geometry based on solar and shading envelopes, and geometric and radiometric information from point cloud data. In particular, two computational models consisting of SOLEN (Subtractive Solar Envelopes) and SHADEN (Subtractive Shading Envelopes) are developed, which are applied to temperate and tropical climates, respectively. In design practice, these models help architects to produce informed-design decisions towards high-performed building massing.

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