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Design Approaches and Measuring Methods of Self-shading Buildings: Comprehensive Analyses

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Building envelope,
Facade Patterns,
Passive Design,
Simulation.

Abstract: Growing attention has been paid to different building shading strategies, especially self-shading techniques. Hence, researchers have explored various building design approaches for optimizing and evaluating self-shading performance. These approaches provide enormous potential for designers to express their creativity and adapt their designs to challenging climatic conditions. This paper introduces a comprehensive analysis of the most common self-shading design approaches and their studied variables, along with their associated evaluation metrics for assessing self-shading effects. Consequently, this study focuses on the analyses of solar radiation metrics and their simulation tools for evaluating self-shading performance. As a result, the findings show the capabilities and limitations of current self-shading design approaches, and their main design variables. Then, shading calculation methods and simulation tools for solar radiation metrics have been classified and evaluated. In addition, future directions for different applications in this field have been conducted, highlighting potential avenues for further exploration and optimization.

List of abbreviations

SR	Solar radiation
SRA	Solar radiation per area
ASR	Absolute solar radiation
SBE	Self-shading on building envelope

1. Introduction

Shading strategies for building envelopes, especially in hot climate zones, become increasingly significant in architectural design. Self-shading, as a passive solar design technique, offers a solution by incorporating and designing building forms or facades that cast shades on its envelope [1]. Unlike traditional shading devices or reliance on surrounding

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buildings, self-shading strategies aim to directly block solar radiation (SR) from reaching the building envelope for reducing insolation on both opaque and glazed elements during critical periods. Self-shading on building envelope (SBE) can effectively reduce cooling loads; consequently, enhance visual comfort [2]. A wide range of studies on SBE are available, offering potential to understand various design approaches and measurement methods. These studies provide valuable insights into optimizing SBE. However, there is a need for exploring the design variables associated with self-shading to achieve the desired performance outcomes. Also, there is a need to identify the critical metrics, how they measure and their efficiency.

This paper conducts comprehensive analyses of current design approaches for SBE, along with their associated evaluation metrics. Additionally, shading calculation methods and simulation tools for SR metrics are analyzed to identify the most effective tools and methods for applications in this field. The paper has been structured to start collecting SBE studies for outlining design variables of SBE in section 2, then identifying of methods and tools for evaluating SR of SBE in section 3, the comprehensive analyses and discussion have been displayed in section 4. Finally, in section 5, the paper has ended with a conclusion and the potential direction of SBE research in the future. **Fig. 1** presents a research framework that has been conducted in this study.

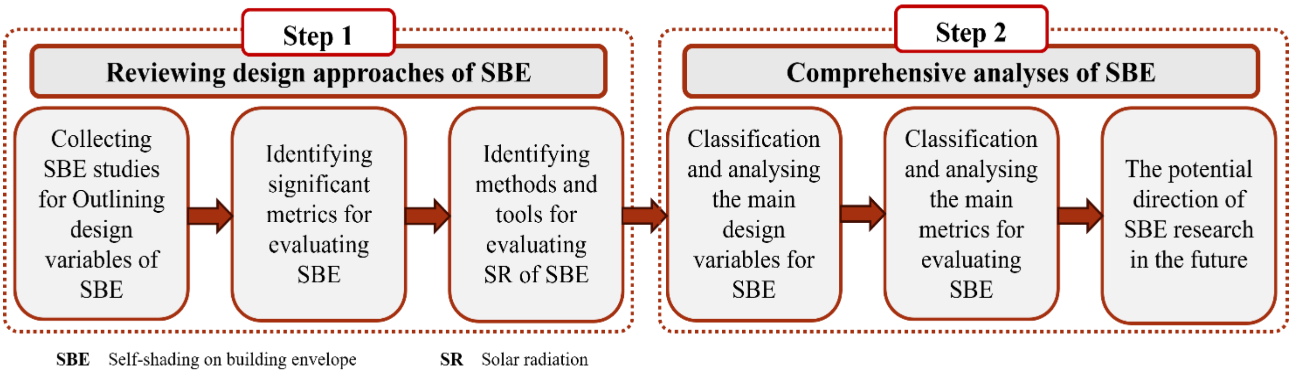


Fig. 1: Research framework of this study

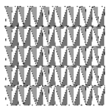
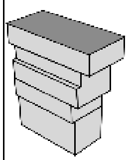
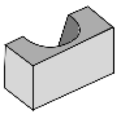
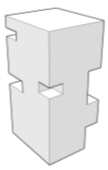
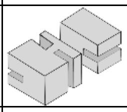
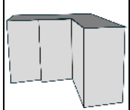
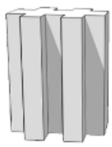
2. Collecting and reviewing SBE approaches from relevant literature.

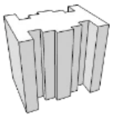
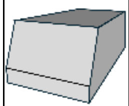
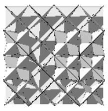
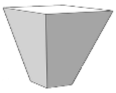
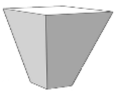
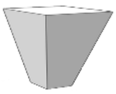
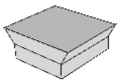
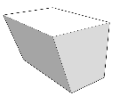
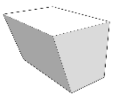
Collecting and reviewing related approaches have been achieved via a literature review methodology set based on the following main criteria:

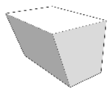
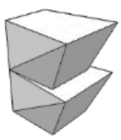
a) selecting the updated studies that were published between 2014 and 2025 to ensure relevance.
b) using Scopus, Web of Science, ScienceDirect, and Google Scholar as literature databases.
c) selecting research on self-shading achieved by either facade patterns as a component of facade surface or the overall building form.
d) excluding studies that investigated self-shading provided by green facades and external shading elements, also self-shading provided by surrounding buildings.
e) excluding studies that discussed self-shading between photovoltaic panels or shading on these panels by building components.

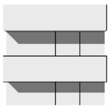
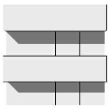
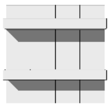
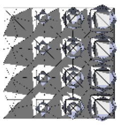
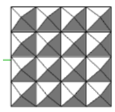
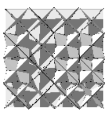
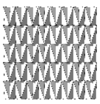
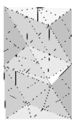
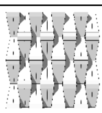
Based on these criteria, a set of publications was selected for review and analysis. This review on the literature showed two primary design approaches for optimizing SBE: a) building form designs which are characterized by their ability to create shade through building's shapes, b) self-shading facade designs which utilize aesthetic and functional patterns to create desired shading effects [3]. These approaches and their design variables are detailed in **Table 1**.

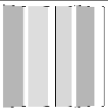
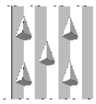
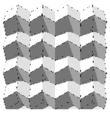
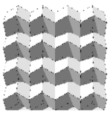
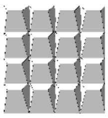
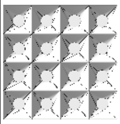
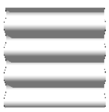
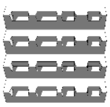
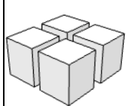
Table 1: SBE approaches and their variables

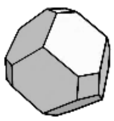
Reference	Year	Building or Façade design	Building forms: Extruded forms	Building forms: Building layouts	Building forms: Tilted forms	Building forms: Twisted forms	Façade design: Bricks	Façade design: Overhangs	Façade design: Folded patterns	Façade design: Curved patterns	Design variables/outlines	Façade orientation	Material	Type of façade surfaces
[2]	2025							×	×		■ Flat and folded façade units ■ Façade Unit depth: Between 0 to 10 cm ■ Influence of nanotechnological coatings	S	Alucobond panel, galvanized steel, Aluminum	Opaque
[4]	2021		×	×		×		×			■ Building shapes: square, rectangle, circle, triangle ■ Window-to-Wall Ratio: 30% ■ Four extended forms based on circle shape form using overhangs and twisting	Na	Window: Generic PYR B clear 3mm	Partially glaze
[5]	2024		×								■ Floors Horizontal scaling variations: 100 -150 % ■ Vertical motion variations: 4+ (0 to 2) m ■ Glazing parameters: sill level (0.2 to 1.2m), height (0.5 to 2.5m), window to wall ratio (0.2 to 0.9)	N, S, W, E	Wall: concrete and paint, window: normal glazing	Partially glazed
[6]	2023		×								■ Building form: subtractive voids, additive volumes, courtyards, and atriums	N, S, W, E	N/A	Opaque
[7]	2022		×								■ Number, position, and dimensions of each of the additive masses or subtractive voids. ■ Number of vertical shadings: 1 to 10 between columns ■ Spacing of horizontal shading panels: 0.3 to 1.5 m ■ Window-to-wall ratio: 0.1 to 0.9	N, S, W, E	N/A	Partially glaze
[8]	2022		×								■ Number, position, and dimensions of each of the additive masses or subtractive voids.	W, E	N/A	Opaque
[10]	2024			×							■ Plan layout: Rectangular; L, and U shapes ■ Surface area range: 570-590 m^2 ■ Volume range: 550-610 m^3 ■ Surface/volume ratio: around 1	E, W	Stone, Concrete	Partially glazed
[11]	2022			×							■ Reforming building layout shapes with fixing the height (15 stories), while modules' width was 8 m ■ Specific limitations such as shape area and shape circumference	N, S, W, E	N/A	Opaque

Reference	Year	Building or Façade design	Building forms				Façade design				Design variables/outlines	Façade orientation	Material	Type of façade surfaces
			Extruded forms	Building layouts	Tilted forms	Twisted forms	Bricks	Overhangs	Folded patterns	Curved patterns				
[12]	2021			×							■ Reforming building layout shapes with fixing the height (7 stories) ■ Window-to-Wall Ratio: 30%	N, S, W, E	Wall: brick, concrete Window: Double glazing	Partially glaze
[13]	2024				×						■ Slope of wall: from - 40 to 40° ■ Window-to-Wall Ratio: from 20 to 80% ■ Window type: Separate vertical, Continuous horizontal	S	Window: Single, Double, Triple Clear Air	Partially glazed
[14]	2024				×				×		■ Office dimension (H × D × W): 2.8× 8.5× 3.9 m ■ Window-to-Wall Ratio: 70% ■ Wall inclination degree: -30°, 0°, 30° ■ Façade Unit dimension: 1 × 0.5m ■ Opening percentage: Between 9% and 100%	S	Window: Single glazing Wall: Generic wall	Partially glazed
[15]	2024				×						■Field measurements for (weekdays when cooling systems were active and weekends when they were not in use), And for two different zones (the adjacent and the central zone).	S, W	Double low emissivity	Fully glazed
[16]	2019				×						■ The ratio between the inclined wall shading projection and the vertical height of the building.: 0, 25, 45, 70%	W	Low-E glass	Fully glazed
[17]	2016				×						■ Field measurements for inclined wall facades ■ Window-to-Wall Ratio: 60%	S, W	Low-E glass	Fully glazed
[18]	2022				×						■ Slope of wall: - 2 to 2 m ■ Window-to-Wall Ratio: 7 to 52% ■ Ranges of materials reflectance	N, NW, W, SW, S, SE, E, NE	N/A	Partially glaze
[19]	2015				×						■ The inclination angle of the south façade: from 90 to 140° ■ Window-to-wall ratio: 53% (south), 11%(east), 7% (north), and 0% (west)	N, S, W, E	Window: Triple glazing 13 mm argon-filled	Partially glazed
[20]	2022				×						■ Slope of wall: from 5 to 45° ■ Six different building forms	N, S	Window: Double glazing Wall: Concrete plaster, brickwork, thermal insulation	Partially glaze

Reference	Year	Building or Façade design	Building forms				Façade design				Design variables/outlines	Façade orientation	Material	Type of façade surfaces
			Extruded forms	Building layouts	Tilted forms	Twisted forms	Bricks	Overhangs	Folded patterns	Curved patterns				
[21]	2014				×						■ The inclination angles of the walls: 10, 20, 30, 40, 50° ■ Window-to-Wall Ratio: 60%	N, S, W, E	Wall: Mosaic tile, sand plaster, heavy concrete	Partially glazed
[22]	2021		×		×						■ The protrusion of the floors: from 0 to 1.2 m ■ The facade orientations towards the west and the east: from 0 to 60°	W, E	N/A	Opaque
[23]	2019				×						■ Shading height ■ Self-shading mass length ■ Depth of mass exceeding the original depth ■ Protrusion of mass exceeding the original length ■ Number of crystalline forms	N, S, W, E	Opaque cladding with glazing	Partially glazed
[24]	2024					×					■ Plan shape: Curved plan shape (Floor height 5m No. OF floors 50) ■ 3D transformation: Scaling and rotation for flooring	N/A	N/A	Partially glazed
[25]	2020					×					■ Floor-to-floor rotation angle: from 0° to 10° ■ Two different façade types: a) a continuous, smooth façade without overhangs, b) a discretized façade with all vertical surfaces and slabs. ■ Window-to-Wall Ratio: 40%	N, S, W, E	N/A	Partially glaze
[26]	2022						×				■ A brick wall dimensions: 3 × 2 m ■ Bricks dimensions: 11.5 ×24 ×5.2 cm ■ Rotation angle ranges from -15° to +15° ■ Translation value of bricks:0 to 11 cm	SW	Red brick	Opaque
[27]	2020						×				■ Room dimensions (H × D × W): 3 × 4 × 4 m ■ Window dimensions: 1.5 × 1.4 m ■ Brick patterns directions: Vertical ribs, and Horizontal ribs, and Staggered protruding bricks	S, W, E	Brick	Partially glaze
[28]	2018						×				■ Brick rotation angles ■ Brick protruding directions: Vertical and horizontal	W, E	Brick	Opaque
[29]	2016						×				■ Brick rows aligned on the same axis: from 1 to 9 ■ Spacing between bricks in each row: from 11 to 19 cm ■ Orient the openings of the brick screen 45° Stepping on the brick screen to inclined forward and backward ■ Brick screen inclination 5° forward and backward	S	Window: Double glazing Screen: Brick	Glazing with perforated shading

Reference	Year	Building or Façade design	Building forms				Façade design				Design variables/outlines	Façade orientation	Material	Type of façade surfaces
			Extruded forms	Building layouts	Tilted forms	Twisted forms	Bricks	Overhangs	Folded patterns	Curved patterns				
[30]	2019							×			■ Façade Unit dimension: 4 × 4 m ■ Façade Unit depth: from 1 to 2.5 m ■ Shaded devices: Fins, Louvers	N, S, NE, NW, SE, SW	Window mm: Double glazing Insulation: Fiber glass, Polyurethane	Fully glazed
[31]	2023							×			■ Façade Unit dimension: 4 × 4 m ■ Façade Unit depth: Between 1 to 4 m ■ Shaded devices: Fins, Louvers	N, S, NE, NW, SE, SW	Window: Double glazing Insulation: Fiber glass, Polyurethane	Fully glazed
[32]	2015							×			■ Balcony dimensions: 1.5 ×3 m ■ Balcony depth: 1.2 m ■ Different floor levels: from Ground to 20th floor	N, S, W, E	Structural steel, Stainless steel, Concrete	Partially glazed
[33]	2024								×		■ Pattern types: Cube, Pyramid and Tetrahedron ■ A modular façade unit dimension: 40 × 40cm ■ Tiling pattern, and Connectivity rules ■ Geometry transformation (variations in heights, openness, and closeness of the unit)	N/A	N/A	Partially glazed
[34]	2024								×		■ Folded pattern types: saw-tooth, and triangular pyramid ■ Façade Unit depth: 0.3, 0.5, 0.7 m ■ Fold line position: 1/2, 2/3, 1/3 ■ Saw-tooth unit direction: Vertical, and Horizontal ■ Number of modules: 1×1, 2×2, 4×4	S	Brick	Partially glazed
[35]	2023								×		■ Office dimension (H × D × W): 3× 8 × 4 m ■ Pleat folding movements: from fully closed to fully open	S	N/A	Partially glazed
[36]	2022								×		■ Façade Unit dimension: 35 × 20 cm ■ Façade Unit depth: Between 2 to 10 cm ■ Geometrical requirements of the nests	W	Ready-made ceramic body	Partially glaze
[37]	2019								×		■ Façade Unit dimension: 13.3 × 9 m ■ Façade Unit depth: Between 1 to 2.1 m ■ Distant between perforations	NW, SE	Insulated aluminum panels and double glazing	Glazing with perforated shading
[38]	2018								×		■ Façade Unit dimension: 4.4 × 4.5 m ■ Façade Unit depth: Between 0 to 1 m	S	N/A	Fully glazed

Reference	Year	Building or Façade design	Building forms: Extruded forms	Building forms: Building layouts	Building forms: Tilted forms	Building forms: Twisted forms	Façade design: Bricks	Façade design: Overhangs	Façade design: Folded patterns	Façade design: Curved patterns	Design variables/outlines	Façade orientation	Material	Type of façade surfaces
[39]	2015								×		■ Amplitude of the facade folds:0 to 1m ■ Vertical placement of the fold:0 to 1m ■ Blending effect: 0 to 1 m	NE, SE	7 types of windows glazing	Partially glazed
[40]	2014								×		■ Different clusters of folded patterns ■ Rotation and flipping of the folded pattern	N	White polypropylene sheets	Perforated shading
[41]	2016								×		■ Façade Unit dimension: 80 × 40 cm ■ Façade Unit direction: Vertical and horizontal ■ Compression states	S, W, E	Glass fiber reinforced polyester	Partially glazed
[42]	2016								×		■ Façade Unit depth: between 0.91 to .099 inch ■ Façade Unit direction: diagonal ■ Compression states: folded 10 ° to unfolded 79 ° ■ Opening percentage: from 6% to 84%	SW	Polymer sheets	Glazing with perforated shading
[43]	2022								×		■ Room dimension (H × D × W): 3.2× 6 × 4 m ■ Façade Unit dimension: 3.2 × 4 m ■ Façade Unit depth: 0.44 to 1.42 m	N, S, W, E	Window: Double glazing	Partially glaze
[44]	2024									×	■ Office dimension (H × D × W): 3× 4 × 3 m ■ 11 Material configurations ■ Façade Unit dimension: 1.4 × 1.4m (funnel patterns) ■ Hole rotation, hole tilt, and hole diameter ■ Openness factor: from 5% to 50%	S, W	Cement-textile composite	Partially glazed
[45]	2017									×	■ Shape amplitude of three basic wrinkle patterns: single sin-wave overhang, continuous unidirectional sin-wave, continuous bidirectional sin-wave ■ Undeformed tile shapes	S, W	Smart materials	Opaque
[58]	2015								×		■ Façade Unit depth: Between 1 to 3 m	N, S, W, E	Thin white cardboard	Perforated shading
[59]	2023			×					×		■ Building layout: rectangular (26×26 m), circular (12m radius) ■ Façade Unit dimension: width (0.4 to 1.2 m), height (0.6 to 2.4 m), depth (0.1 to 0.7 m), shift-x (0.3 to 1.1 m), shift-y (0.3 to 2.1 m)	N, E, S, SE, W	Selective cement activation	Partially glazed
[60]	2021			×							■17 building layouts with fixing floor area ($100m^2$), space volume ($600\ m^3$), and height (6 m): square, circle, I-shape, golden proportion, triangle, pentagon, hexagon, octagon, courtyard, and cluster.	N, S, W, E	Wall: Plaster render, brick	Opaque

Reference	Year	Building or Façade design	Building forms				Façade design				Design variables/outlines	Façade orientation	Material	Type of façade surfaces
			Extruded forms	Building layouts	Tilted forms	Twisted forms	Bricks	Overhangs	Folded patterns	Curved patterns				
[61]	2018				×						■ Eight prismatic building forms derived from isometric crystals with the same compactness (surface area per volume) ■ Degree of inclined surface: from 7 to 45°	N/A	Phenolic foam	Opaque
[62]	2018						×				■ Configurations: Running, English and Flemish bonds ■ Extrusion values: baseline, ¼ brick and ½ brick ■ Extruded bricks' area from the facade: 15% to 60% ■ Locations for attractor curved line	S	Brick	Opaque
[63]	2015							×			■ Room dimensions (H*D*W): 3 × 9 × 3.6 m ■ Façade Unit dimension: 3.6 × 3.6 m ■ Façade Unit depth: Between 0.6 to 3.6 m ■ Window horizontal locations left, middle, and right ■ Façade sheltering size: west/east-side, and double-side	S	Double-layer hollow glass window	Partially glazed
[64]	2014								×		■ Different window-to-wall area ratio ■ Inclination of the glass panels for south facade towards ground ■ Rotation of glass panels for east-west facades towards	NE, NW, S	Solid parts: Glossy ceramic tiles	Fully glazed
		Total	6	6	12	3	5	6	16	2				

N/A Not available **(H × D × W)** Height × Depth × Width **N, E, S, W** Northern, Eastern, Southern, Western facades **NE, SE, SW, SW** Northeastern, Southeastern, Southwestern, Northwestern facades

2.1. Self-shading building forms design

Based on the previous **Table 1**, several studies focused on building forms design as a component of the overall building morphology which influences SR [4]. Furthermore, the literature dealing with self-shading building forms design has been divided into four main approaches: a) extruded forms, b) building layouts, c) tilted forms and inclined walls, and d) twisted forms. For instance, some studies examined self-shading of one story over another via varying in stories' width and length to reduce thermal load [5]. Also, some design frameworks used EvoMass, as a massing design generation and optimization tool, to present an optimal design solution created by additive masses and subtractive voids for SBE [6], [7], [8], [9]. The best building shapes for energy and natural daylight were four extruded forms based on a circle shape that had the best SBE [4]. Some researchers studied various building forms, including rectangular, L-shaped, and U-shaped, and they found that U-shaped buildings showed the lowest air temperature due to its SBE [10]. Another optimization approach introduced how reshaping high-rise building layouts could develop better self-shaded alternatives, by considering shape area and circumference [11]. Also, deep learning methods could predict building energy use by utilizing self-shading by building layouts as training data [12]. Another study compared the designs of 17 building layouts with different utilizations of self-shading to assess solar heat gain, indoor temperature, and cooling requirements. In brief, these studies focused only on conventional regular building layouts to study SBE.

A considerable number of SBE studies focused on studying tilted form, inverted pyramidal form, and inclined walls. The inclined walls could enhance view quality by 75%, while they could simultaneously reduce energy consumption and glare [13]. Also, combining inclined walls and an adaptive facade could enhance visual comfort for employees in various latitudes [14]. Some studies employed field measurements to examine the self-shading impact of inclined wall on indoor air temperature [15], energy consumption for cooling [16], and the efficiency of daylighting [17]. Also, applying inclined walls with bilateral openings could improve visual comfort in classrooms [18] and reduce overheating in homes [19]. Others have investigated the thermal performance and energy consumption of various tilted angles in SBE to determine the optimal angle for achieving maximum shading [20], [21], [22]. Moreover, another study developed a tool for designing SBE that give full shading in summer with allowing winter solar heat gain [23]. These previous studies suggested that surface tilting could provide more effective SBE. A couple of design frameworks employed twisted forms, as a SBE technique, to minimize solar exposure with maintaining functionality and aesthetic appeal [24], [25]. Furthermore, most research focused on the overall building performance, while few studies explored the combined impact of SBE by forms and facades.

2.2. Self-shading Facade design

In contrast to building forms design, the design of a self-shading facade focuses on manipulating the elements of the building façade for achieving SBE [1]. The literature discussed simple and complex facade designs which have been divided into four main approaches: a) brick configurations, b) protrusions/ overhangs, c) folded patterns, and d) curved patterns. For instance, several studies investigated how shaded brick surfaces could reduce surface temperature, mitigate the impact of SR [26], improve thermal performance [27], reduce energy consumption [28], and maximize the spatial daylight autonomy value [29], these techniques aimed to optimize SBE through small protrusions on opaque solid walls. The pattern design of brick configurations could be applied to study larger facade protrusions. Also, numerous studies examined vertical and horizontal protrusions to create the SBE with a textured appearance. The integration between shading devices and overhangs, as a self-shading facade, could reduce annual energy consumption by 20.5% and the additional cost could be recouped within two years [30], as well as the impact of this technique was examined in different climates and locations [31]. Another research investigated the optimal floor level in residential buildings for incorporating balconies and explored their SBE [32]. These studies addressed the depth of protrusions required without altering the distribution pattern and disregarding aesthetic facade appeal.

Some studies guided the difficulties and opportunities of folded patterns selection in SBE. For example, some studies aimed to optimize folded and flat modules through a selection of assembly details, base materials, geometries, and finishing coatings to reduce temperatures and achieve cost efficiency [2]. The use of shape grammar concept in design folded facades showed various geometries with different self-shading patterns [33]. Thus, triangular folded patterns effectively provided better visual comfort and daylighting and reduced energy consumption [34]. Also, the movements and designs of folded plates provide self-shading geometries that improve visual comfort [35], provide potential bird nests [36], and minimize the temperature of cavity of the double-skin facades [37]. Other researchers examined structural efficiency of folded plates [38], their depth changes [47], and their variations by rotation and flipping [40] for better SBE. Turning to the types of folded patterns used, many studies had centered only on the Miura-ori pattern [35], [41], [42], exploring variations in compression states and directions. Other studies have investigated limited variables for patterns like rectangular pyramids [34], [43], triangulated linear patterns [2], [36], and other folded patterns [33], [37], [38]. Lastly, few researchers employed curved patterns in self-shading facades. For example, some study developed a genetic optimization algorithm for a complex curved shading system to improve the SBE with adequate daylight [44]. Others used curved patterns to enlarge the shaded area of the façade for reducing SR [45], [46]. The majority of earlier research, however, only examined a single pattern or a small number of variables. In brief, studying facade patterns is a good option for better SBE.

3. Measurement methods and tools for evaluating SR of SBE

According to previous research for self-shading, the performance of SBE is evaluated using various metrics as summarized in **Table 2**. SR is the most employed evaluation metric in literature. A variety of studies have developed methods to enhance shading calculations. For example, some studies used shadow calculation approaches to expedite the shadow calculation process of the surrounding environment [47], [48], [49] and improve the calculation of shadow geometry within a BIM authoring tool [50]. Another calculation framework for building shadows used the fundamental principles of shadow projection calculation to enable accurate energy consumption analysis [51]. Also, some shading calculation methods have been introduced to minimize the numerical gap between simulation and reality [52]. Then, a study improved an open-source method for calculating self-shading in fields of two-axis tracking solar collectors of arbitrary geometry [53], [54]. Furthermore, another study developed an approach for simulating complex surfaces via Grasshopper [55]. Additionally, a dynamic calculation technique studied calculating the shaded fractions of the shading elements in kinetic façades [56]. However, these approaches primarily assist designers in evaluating shading and solar aspects for specific cases or treatments or in assessing a particular parameter. **Table 2** provides classification of approaches, methods used for studied cases, objectives, evaluation metrics, and other elements that may create shading on building employed in research for SBE. Finally, the total number at the end of the table refers to how much the metric is common and scientifically used.

Table 2: Objectives and evaluation metrics of SBE studies

Reference	Design approach		Studied case				Study objective							Evaluation metric										Shading feature	
	Building forms design	Façade design	Existed building	Physical prototype	Simulation for a room model	Simulation for a structure	Exploration	Explanation	Investigation	Comparation	Evaluation	Optimization/ Improving	Developing	Solar radiation	Thermal performance	Daylight	Energy	Cost/ cost saving	Air Flow/ velocity	Humidity/ Relative humidity	Environmental impact	Wind façade pressure	Structural efficiency	Shading devices	Surrounding building
[2]		×		×	×		×			×	×	×	×	×	×			×			×				
[4]	×					×	×				×				×		×		×	×					
[5]	×					×	×		×	×	×				×	×	×								
[6]	×					×	×		×	×	×	×		×		×									×
[7]	×					×	×		×	×	×		×	×		×								×	×
[8]	×					×	×		×	×	×		×	×											×
[10]	×		×		×	×	×	×		×	×				×				×	×					×
[11]	×					×			×	×	×	×		×			×								
[12]	×					×			×	×	×						×								
[13]	×				×		×		×	×	×	×				×	×								
[14]	×	×			×				×	×	×					×									
[15]	×		×			×	×		×	×	×			×	×				×	×					×
[16]	×		×						×		×	×		×	×					×					
[17]	×		×				×				×				×	×				×					
[18]	×				×		×					×				×									
[19]	×					×			×	×	×				×	×	×								
[20]	×					×	×		×	×	×		×	×			×								
[21]	×		×				×	×		×	×				×		×								
[22]	×					×			×	×	×			×											
[23]	×					×		×					×		×										
[24]	×					×			×	×	×	×	×	×			×								
[25]	×					×			×	×	×			×											
[26]		×		×	×		×		×	×	×			×	×										
[27]		×			×					×	×	×		×	×										
[28]		×		×			×		×	×	×				×										
[29]		×				×			×	×	×		×			×									
[30]		×				×				×	×						×	×						×	
[31]		×				×				×	×						×								
[32]		×	×			×			×	×	×						×				×				
[33]		×		×			×		×	×	×		×	×	×				×	×					
[34]		×			×					×	×	×	×			×	×								
[35]		×			×						×	×				×									
[36]		×	×	×		×	×		×		×		×	×								×			×
[37]		×			×	×		×	×	×	×				×		×		×						
[38]		×	×			×		×	×	×	×			×									×		

Reference	Design approach		Studied case				Study objective							Evaluation metric										Shading feature	
	Building forms design	Façade design	Existed building	Physical prototype	Simulation for a room model	Simulation for a structure	Exploration	Explanation	Investigation	Comparation	Evaluation	Optimization/ Improving	Developing	Solar radiation	Thermal performance	Daylight	Energy	Cost/ cost saving	Air Flow/ velocity	Humidity/ Relative humidity	Environmental impact	Wind façade pressure	Structural efficiency	Shading devices	Surrounding building
[39]		×				×					×	×	×		×	×	×	×							
[40]		×		×	×		×		×		×		×	×	×										
[41]		×		×		×	×		×	×	×		×	×	×					×	×	×	×		
[42]		×				×	×			×	×		×			×									
[43]		×			×			×		×	×					×									
[44]		×		×	×			×	×	×	×		×			×					×			×	
[45]		×			×		×		×	×	×			×											
[58]		×		×		×	×	×	×		×		×	×		×									×
[59]		×		×		×			×	×	×	×		×	×										
[60]	×					×	×		×	×	×			×	×		×	×							
[61]	×		×				×		×	×	×			×	×		×								
[62]		×				×	×			×	×	×			×		×								
[63]		×				×	×		×	×	×						×		×						
[64]		×	×			×		×					×	×		×	×								×
Total	**23**	**27**	**10**	**10**	**14**	**31**	**21**	**9**	**32**	**38**	**46**	**10**	**17**	**24**	**22**	**17**	**20**	**4**	**6**	**7**	**4**	**2**	**2**	**3**	**8**

Incident SR, also sometimes called insolation, takes diffuse and direct radiation from the sun into account, but not the sunlight reflection [57]. The values of incident SR are examined for SBE via four metrics: a) absolute solar radiation (ASR), b) solar radiation per area (SRA), c) shading area, and d) sunlight hours. A lot of studies relied only on SRA values to study SBE buildings, since as it could be measured by calculating SR per unit area during a given time. For instance, some research explored the impact of varying folded pattern depths on SR [36], [38], [41]. However, they solely relied on SRA as an evaluation metric, neglecting the potential increase in surface area and, consequently ASR values. Other façade studies, such as [58], [40], also employed SRA to understand changes in rotations and flips of patterns, so the area of surface patterns hadn't been considered. Another study used SRA values to evaluate how different window-to-wall ratios and façade angles influenced solar gains and natural daylight. For self-shading building form designs, on the other hand, twisted forms [25] and inclined walls [16] significantly reduced SRA and improved energy efficiency. Few research relied only on ASR for evaluating SBE, as it could be measured by calculating total SR values across a defined period for a specific surface without considering the surface area. For example, one or two studies optimized SBE by reducing the value of ASR to minimize energy use intensity [24] and maximizing natural daylighting [6]. Other studies used this metric in self-shading facades to indicate the relationship between solar absorption, surface temperature [59], and shaded surface area [26].

Some studies used more than SR metric to check the effect of self-shading by considering shape circumference, area [11], and volume [60], [61]. For example, the best self-shaded alternative, which had less ASR and SRA values, had the best reduction in annual and summer energy consumption [11]. On the other hand, the cluster shape with the most shaded area had the highest values in ASR, SRA, and indoor temperature [60]. Furthermore, the prismatic building forms with larger shaded areas had lower SRA and reduced cooling loads in hot climates [61]. Other studies tried to achieve a balance between daylighting and solar heat gain reduction by reducing SRA and ASR [7] while maximizing natural daylight [8] to ensure sufficient daylighting in interior spaces. Along with other SR metrics, the impact of shaded areas on SBE was the focus of a lot of research. For instance, the analysis of SRA and shaded area for eight facade modules with varying shapes, materials, and surface finishes revealed a considerable impact on cost, environmental impact, and thermal performance [2]. Also, more shaded areas resulted in lower SRA and energy consumption as well as improved thermal comfort either for self-shading building forms [20] or façade designs [27]. Another study showed that varying protrusion depths and orientations affected SRA, while only different protrusions changed the average of shaded areas [22]. These studies showed that the investigation of SBE with more than one metric provided a comprehensive assessment. Also, it could help researchers to accurately assess the impact of design variations and enhance the design of effective SBE.

However, a variety of simulation tools, including Energy Plus, DIVA, DOE2, Design builder, Vasari, Revit, Grasshopper, and others, can be used to simulate SBE [1], where each tool has specific characteristics and advantages that allow the simulation's details to be extended to various edges. **Fig. 2** shows the number of studies using SR metrics as evaluation metrics to SBE and its simulation tools. For more details, **Table 3** presents studies that utilize SR metrics to evaluate SBE performance. Also, key information is summarized including study location, climate type, building type, building height, measurement period, SR metrics, reached optimization in SR performance, and SR simulation tool used.

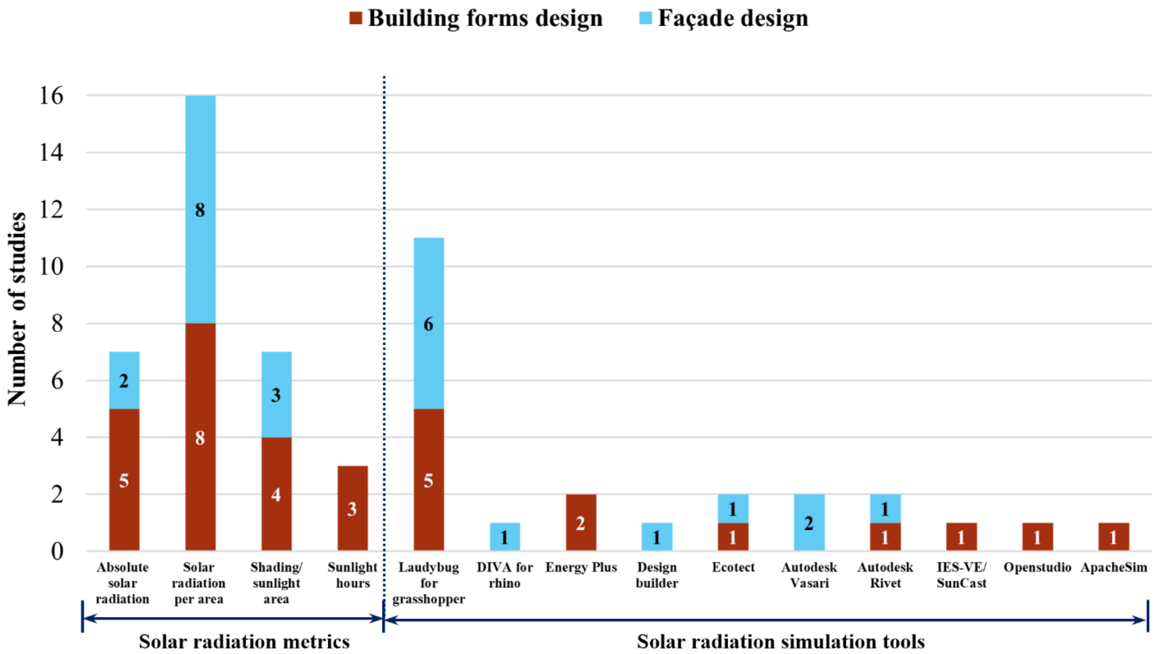


Fig. 2: Solar radiation metrics and simulation tools for self-shading buildings

Table 3: A review of SBE research on SR measurements, tools, and performance

Reference	Design approach		Climate Type	Country and city	Building	Building height			Study period			SR metric				SR simulation tool										Reached optimization in SR performance (%)			
	Building form	Façade				Low-rise	Middle rise	High-rise	Annual	month/ season	day/ hour	ASR	SRA	Shading area	Sunlight hours	Ladybug for grasshopper	DIVA for rhino	Energy Plus	Design builder	Ecotect	Autodesk Vasari	Autodesk Rivet	IES-VE/ SunCast	Openstudio	ApacheSim	ASR	SRA	Shading area	Sunlight hours
[2]		×	A humid subtropical climate	Italy, Ancona	A physical prototype					×	×		×	×								×					N/A	55%	
[6]	×		A hot summer, cold winter climate	Nanjing, China	Office buildings		×			×		×				×										87%			
[7]	×		A hot summer, cold winter climate	Wuhan, China	Educational buildings		×			×		×	×			×										40%	N/A		
[8]	×		A hot climate	Bushehr, Iran	A trade centre	×			×				×		×	×											N/A		N/A
[11]	×		A hot climate	Cairo, Egypt	Office buildings			×		×		×	×									×				N/A	**S:** 48% **W:** 38% **N:** 57% **E:** 44%		
[16]	×		A hot and humid climate	Malaysia	Office buildings		×		×				×												×		39%		
[20]	×		A hot, arid climate	Irbid, Jordan	Office buildings		×		×					×	×								×					77%	N/A
[22]	×		A hot and humid climate	Kish Island, Iran	N/A	×			×				×	×	×					×							51%	85%	N/A
[24]	×		A hot climate	Cairo, Egypt	Office buildings			×	×			×				×										84%			
[25]	×		Various	Various	Office buildings			×	×				×			×											76%		
[26]		×	A temperate Oceanic climate	Munich, Germany	A wall					×	×	×		×		×										N/A		85%	

Reference	Design approach		Climate Type	Country and city	Building	Building height			Study period			SR metric				SR simulation tool										Reached optimization in SR performance (%)			
	Building form	Façade				Low-rise	Middle rise	High-rise	Annual	month/ season	day/ hour	ASR	SRA	Shading area	Sunlight hours	Ladybug for grasshopper	DIVA for rhino	Energy Plus	Design builder	Ecotect	Autodesk Vasari	Autodesk Rivet	IES-VE/ SunCast	Openstudio	ApacheSim	ASR	SRA	Shading area	Sunlight hours
[27]		×	A hot climate	Cairo, Egypt	A single room					×	×		×	×					×								**S:** 36% **E:** 94% **W:** 30%	**S:** 75% **E:** 58% **W:** 64%	
[36]		×	A temperate Oceanic climate	Munich, Germany	A student residence	×				×			×			×											25%		
[38]		×	A hot summer, cold winter climate	Beijing, China	A mixed-Use building			×	×				×				×										85%		
[40]		×	A hot and arid climate	Melbourne, Australia	A physical prototype					×	×		×			×					×						45%		
[41]		×	A temperate climate	Copenhagen, Denmark	A physical prototype				×	×	×		×			×				×							**E:** 60% **S:** 59% **W:** 61%		
[58]		×	A hot and arid climate	Melbourne, Australia	A physical prototype				×	×			×			×											50%		
[59]		×	A temperate Oceanic climate	Braunschweig, Germany	Office buildings	×				×		×				×										50%			
[60]	×		A hot and humid climate	Bangkok, Thailand	A house	×			×			×	×	×				×						×		90%	71%	80%	
[61]	×		1-An equatorial climate 2-A hot climate 3-A humid, warm summer climate	1-Sao Luis 2-Cairo 3-Helsinki	Office buildings	×			×				×	×				×									1- 92% 2- 90% 3- 87%	N/A	
[64]		×	A warm summer climate	Stockholm, Sweden	A bank		×		×				×								×						N/A		

N/A Not available **SR** Solar radiation **ASR** Absolute solar radiation **SRA** Solar radiation per area **N, E, S, W** Northern, Eastern, Southern, Western facades

4. Comprehensive analyses and Discussion

While this study has highlighted a variety of approaches to developing and evaluating SBE, a comprehensive exploration of certain aspects has remained lacking, especially in certain aspects that will be further discussed in this section.

4.1. Main design variables for SBE

For analyzing the current SBE approaches deeply, their key design variables have been classified and analyzed in **Table 4;** this table reveals which aspects of design have been most explored and which remain under-researched. The results indicate that tilted building forms have yielded significant findings, especially in optimizing wall slope angles and evaluating their impact on various performance metrics. Studies on tilted buildings prioritize window and glazing variations over opaque material effects on SBE. Also, curved geometries in tilted buildings are overlooked, despite efforts to expand designs beyond inverted pyramids. On the other hand, more comprehensive studies are needed regarding the impact of twisted building forms on SBE. Furthermore, extruded form designs have utilized generative design techniques to achieve multi-objective optimization. Conversely, the building layout approaches have examined rectangular and traditional plan shapes. Both extruded forms and building layout approaches have limitedly explored the impact of window distributions, materials, height, and shading devices. Both research approaches have focused on generic cubic shapes and only four cardinal orientations. In brief, the most common design variables studied in different approaches are slope of wall for tilted forms, building geometries, depths of overhangs, window-to-wall ratios, and the four cardinal building orientations. It is obvious that variations of extruded forms are almost covered.

Table 4: A comprehensive analysis of SBE approaches and their variables

Design approach		Main studied design variables			The effect of altering these variables					Shading feature	
					Window-to-wall ratio	Materials	Building orientations	Building heights	Climate zones/ locations	Shading devices	Surrounding buildings
Building form	Extruded form	- Floor heights - Floor protrusion	- Additive masses	- Subtractive voids	√		√	√	√	√	√
	Building layout	- Layout shapes - Wall area - Floor area	- Building heights - Building Volume	- Shape circumference			√		√		√
	Tilted form	- Slope of wall	- Building geometries		√	√	√		√		√
	Twisted form	- Layout shapes - Floor heights	- Rotation angles - Scaling	- Rotated Façade types			√		√		

Design approach		Main studied design variables	The effect of altering these variables					Shading feature	
			Window-to-wall ratio	Materials	Building orientations	Building heights	Climate zones/ locations	Shading devices	Surrounding buildings
Facade	Brick	- Dimensions - Configuration bonds - Protruding direction - Rotation angles - Translation space - Attractor curved line - Aligned of rows - Screen inclination	√		√		√		
Facade	Overhang	- Depths - Overhang distribution - Dimensions		√	√		√	√	
Facade	Folded pattern	- Pattern types - Unit depths - Unit dimensions - Pattern flipping - Pattern rotation - Compression states - Fold line positions - Number of unit modules	√	√	√				√
Facade	Curved pattern	- Pattern types - Unit depths - Unit dimensions - Unit directions	√	√				√	

√ Examined variables

Moreover, research on self-shading façade designs has primarily focused on using folded patterns design considering various performance metrics for evaluation for a limited set of pattern types. For example, designs such as the Miura-ori, rectangular pyramids, and triangulated patterns had received attention while, a comprehensive comparison of different folded pattern types and their variables, especially for (unit dimensions, fold line positions, and the effect of pattern repetition), remains absent. Most reviewed studies on curved patterns for self-shading façades had focused on a single pattern type, typically generated through parametric generative design tools or derived from the behavior of smart or responsive materials. However, there is a lack of systematic exploration of curved pattern geometries that are manually designed or architecturally constructed, such as wavy linear, curved-crease Miura, winding, or mirror-inverted curved patterns. These systematically structured curved patterns have not been studied in terms of their self-shading performance. So, considering research on curved patterns in other domains offers valuable insights for generating curved-crease surfaces [65], [66] and expanding the design possibilities of curved-folding patterns [67]. Also, overhang approaches have often overlooked the distribution of protrusions, prioritizing depth as the primary factor for achieving self-shading and neglecting aesthetic considerations. While overhang patterns have been explored, an optimization of overhangs for SBE (e.g., through parametric analysis or multi-objective algorithms) remains unexplored. Conversely, brick design approaches have demonstrated an interest in exploring the impact of brick configurations, while these approaches have been limited to opaque walls. There is a lack of research on how bricks can be configured or integrated with openings (e.g., windows) to enhance self-shading. While some studies included contextual factors such as shading devices and surrounding buildings, others neglected them. This finding shows the need to consider the building's full environmental context.

4.2. Evaluation metrics for SBE

Based on **Table 5**, current research on self-shading façade approaches has focused on evaluating thermal performance based only on façade surface temperatures, less considering other thermal metrics (e.g., overall thermal transfer value, operative temperature) which affect the building's thermal performance. Hence, daylighting performance has received limited attention in the evaluation of building layout and overhang approaches for SBE. Also, curved patterns and twisted forms remain largely unexamined by many metrics since such forms are architecturally neither preferred nor common, while tilted forms were examined in different metrics due to the importance of orientation effect. Folded plates, although they are architecturally not common and used widely, have been focused on different studies based on many metrics. Furthermore, the reviewed studies reveal several limitations. A significant amount of research heavily depended on simulation-based approaches, which do not always reflect real-world building performance. Additionally, most of the reviewed studies focused on warm or hot climates, especially in specific regions (e.g., the Middle East and Southeast Asia), which may limit the applicability of findings to other climate zones. Hence, additional research is required to optimize self-shading strategies for dual effectiveness in summer cooling and winter heating load management. Also, there is an absence of real-world validation or post-occupancy data for numerous self-shading strategies. Addressing these gaps will require future studies to incorporate more field measurements and diverse geographic contexts.

Table 5: A comprehensive analysis of evaluation metrics of SBE studies

Design approach		Cases studied		SR metrics				Other evaluation metrics																								
								Thermal performance							Daylight							Energy										
		Simulation	Measurement	Absolute solar radiation (ASR)	Solar radiation per area (SRA)	Shading area	Sunlight hours	Surface temperature	Overall thermal transfer value	Wet-bulb temperature (WBT)	Dry-bulb (Air) temperature	Operative temperature (Op)	Solar heat gain (SHG)	Thermal comfort	Daylight factor (DF)	Useful daylight illuminance	Spatial daylight autonomy	Annual sunlight exposure (ASE)	Daylight glare probability	Daylight autonomy (DA)	Visual comfort/ Quality of view	Total or annual energy	Cooling load	Heating load	Lighting load	Energy use intensity (EUI)	Cost/ Cost saving	Air flow/ velocity	Humidity/ Relative humidity (RH)	Environmental impact	Wind façade pressure	Structural efficiency
Building form	Extruded form	√		√	√	√	√				√		√	√	√		√	√			√	√	√	√				√	√			
	Building layout	√	√	√	√	√					√	√	√	√	√							√	√				√	√	√			
	Tilted form	√	√		√	√	√	√	√	√	√	√	√		√	√	√	√	√	√	√	√	√	√	√	√		√	√			
	Twisted form	√		√	√																					√						
Facade	Brick	√	√	√	√	√		√			√						√	√				√										
	Overhang	√	√		√	√		√														√	√	√	√		√	√		√		
	Folded pattern	√	√	√	√	√		√						√	√	√	√	√	√	√	√		√	√	√	√	√	√	√	√	√	√
	Curved pattern	√	√			√									√	√	√		√	√										√		

SR Solar radiation √ Examined metrics

As a primary evaluation metric for SBE, SR and its metrics are crucial for comprehensive analysis; **Table 6** presents valuable insights into these metrics. Several studies have relied on SRA as an evaluation metric; this metric may be used when integrated with other evaluation metrics such as daylight, energy, etc. The accuracy of evaluations using this metric is maximized when comparing SBE for surfaces with similar or identical areas. Some studies of SBE have considered facade surfaces area via integrating SRA with other SR metrics and some research have tried not to change facade surfaces area for evaluation. Shading area and sunlight hours, as SR metrics, demonstrate expressive assessments of thermal building performance, especially to façade surface temperatures, however, these metrics possess limitations. For example, both metrics may not directly quantify the amount of SR received, require real visual analysis or detailed simulations, and are affected by seasonal variations and changing sun positions. Consequently, when evaluating SR for different building orientations, studies have observed only slight changes in both metrics despite significant variations in SRA values. Also, other studies have relied on measuring ASR or SRA with assessing shading area ratios to examine SBE. Complex façade geometries require detailed calculations when shading area and sunlight hours as evaluation metrics. So, the integration of ASR, which provides cumulative SR impacts, with SRA, which evaluates the efficiency of designs, offers a valuable approach to assessing SBE. The application of this integration between ASR and SRA has been primarily confined to building form designs, with its potential for application to complex façade pattern designs remaining unexplored. Also, few studies have explored how manipulating building façades with folded patterns and overhangs can enhance solar energy capture [68], [69] with achieving SBE [18]. This integration can open a future direction to study.

Table 6: A comprehensive analysis of SR metrics

SR metrics	Design approach		Study period			SR simulation tools										Relation with other evaluation metrics									Relation with SR metrics			
	Building forms design	Façade design	Annual	specific month/season	Single day/ hour	Ladybug for grasshopper	DIVA for rhino	Energy Plus	Design builder	Ecotect	Autodesk Vasari	Autodesk Rivet	IES-VE/ SunCast	Openstudio	ApacheSim	Thermal performance	Daylight	Energy	Cost/ cost saving	Air Flow/ velocity	Humidity/ Relative	Environmental impact	Wind façade pressure	Structural efficiency	Sunlight hours	Shading area	SRA	ASR
ASR	√	√	√	√		√		√				√		√		√	√	√	√							√	√	
SRA	√	√	√	√	√	√	√	√	√	√	√	√		√	√	√	√	√	√	√	√	√	√	√	√	√		
Shading area	√	√	√		√	√		√	√	√		√	√	√		√		√	√	√	√	√			√			
Sunlight hours	√		√			√				√			√					√										

SR Solar radiation **ASR** Absolute solar radiation **SRA** Solar radiation per area √ Examined elements

In brief, the most common and useful SR metrics studied are SRA, and their main outlines analyzed from the literature are an efficiency of utilizing SR metrics to evaluate SBE. Also, as a conducted result, the accuracy of evaluations is maximized when using more than one SR metric and integrating assessment with other evaluation metrics. However, it is obvious that Ladybug for Grasshopper, as a simulation tool for SR, has also been used extensively for analysis of the four SR metrics in several SBE studies.

5. Conclusion, results, and future directions

The research conclusion, main findings and possible directions for future works of the research will be further discussed in this section.

5.1. Conclusion

This paper presented a comprehensive analysis of design approaches for SBE, along with their associated evaluation metrics. First, the common design techniques for SBE were collected, studied, and analyzed. These techniques can be classified into two groups based on design methods to achieve self-shading: building forms design approaches and facades design approaches. Their variables, such as main design variables, window-to-wall ratios, materials, orientations, and climate zones, were collected and studied. Also, their related evaluation metrics, such as SR, thermal performance, daylight, energy, cost, etc., are demonstrated. Accordingly, a comprehensive analysis of design approaches and their variables has been considered. So, the key design variables with their related evaluation metrics have been determined, in addition to design and evaluation limitations for current SBE studies. Secondly, shading calculation methods and simulation tools for SR metrics have been evaluated to identify the most effective tools and methods for SBE applications. Also, this analysis highlights SR metrics in evaluating SBE performance.

5.2. Main results

Many solid outcomes of the analyses have been found. The most common design variables in self-shading studies are the slope of tilted walls, building geometries, depths of overhangs and folded patterns, window-to-wall ratios, and building orientation. Thus, the most common and useful SR metrics studied are SRA, while the accuracy of SRA values is enhanced when comparing designs with similar surface areas. As a conducted result, designs with different surface areas need the integration of two or more SR metrics for accurate analysis. Shading area and sunlight hours are valuable for assessing thermal performance. However, both metrics have limitations in quantifying SR and are influenced by seasonal variations. Hence, the integration of ASR and SRA provides an extended valuable evaluation, especially when applied to building form designs. However, it is obvious that further research is needed to explore the application of this integrated approach to complex façade patterns. Additionally, Ladybug for Grasshopper, as an SR simulation tool, has proven valuable for analyzing SR metrics in SBE studies. As limitations, this study does not consider: a) the efficiency of building materials that have been used on SBE studies, b) thermal, daylight, energy modelling methods and their calculations on SBE, c) analyses for optimization design methods (e.g., Strength Pareto Evolutionary Algorithm and Genetic Algorithm) for SBE, d) analyses for studies that considering surrounding building for self-shading or using kinetic facades.

5.3. Future research directions

However, these comprehensive analyses can provide a further extension in the future direction for SBE studies, such as: a) studying the integration between design approaches, b) studying SBE after the integration between building form designs and facade designs, c), exploring and comparing other building geometries like curved forms, d) exploring and comparing between different morphologies and variations of self-shading façade patterns, e) considering facade surfaces area within SR analysis, f) examining the impact of varying building heights and surrounding buildings, g) extending the study in the impact of the varying window-to-wall ratios, materials, building orientations, and locations, h) considering the aesthetic considerations within design processes, I) considering other evaluation metrics in more details such as exploring the self-shading effect on the building's thermal performance across all facade patterns, and specifically on energy consumption when using brick configurations and curved patterns, j) examining the integration between ASR and SRA to evaluate complex facade patterns with different surfaces area, k) exploring a potential of enhancing solar energy capture with achieving self-shading effect, l) developing a design framework for analyzing curved façade patterns, including their design variables, shading performance, and constructability, m) using comparative simulation-based and experimental analyses of folded and curved patterns to reveal new designs for enhancing passive solar control in warm climates by investigating their self-shading effects, n) incorporating real-world validation through field measurements and post-occupancy evaluations to assess the actual performance of self-shading strategies.

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