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Optimizing Building Layouts for Proper Self-shading: A Computational Approach

Amr Mamdoh Ali Youssef *

KEYWORDS:
Self-shaded Buildings; Shape Grammar; Optimization; Building Envelope; Computational Approach.

***Abstract*— Self-shaded buildings receive great attentions especially in high-rise building in hot climate zones. This paper introduces a novel optimization approach for reforming high-rise building layout shapes (BLSs) towards better self-shaded alternatives for a given shape, along with the determination of different treatments for optimizing a given shape using shape grammar theory; their performance have been simulated by Autodesk Revit. Variables considered during the generation process include different treatments, range of treatments' ratios and orientations along with controlling shape area and circumference if required. High-rise buildings in Egypt are used to demonstrate/validate the approach applications. The study results, through many applications, show the generation possibility of better self-shaded BLSs along with controlling previous variables when required. This optimization has been also tested from energy consumption perspective through 12 alternatives, and the usefulness of the approach has been validated through a conducted survey on different architects. This approach can help architectural designers in achieving self-shaded BLSs for their design cases which cannot be handled directly via single simulations.**

LIST OF SYMBOLS

BLS/s	Building Layout Shape/s
SG	Shape Grammars
SI	Solar Irradiation (kWh/(m^2.summer))
ASI	Absolute Solar Irradiation (kWh /summer)
SC	Shape Circumference
SA	Shape Area
R.*x* or R.*y*	A group of SG rules; *x* or *y* denotes to a row number or a column letter respectively; rows were ordered as numbers (from 1 to 20), while columns were ordered as letters from (A) to (P). For example, R.F or R.5 refers to the rules illustrated in the whole column (F) or row (5), respectively.
R.*xy*	A SG rule; both *x* and *y* denote to a row number and a column letter that represent a specific rule, respectively. For example, R.5F refers to only one rule illustrated in row (5) and column (F).
Alt.i	Alternative Number (i)

I. INTRODUCTION

SHADING in general receives growing attention from designers while testing building envelopes, especially in hot climate zones. In high-rise buildings, reforming building layout shapes (BLSs) for maximizing shaded areas is sensitive due to the wideness of their facades. Self-shading can be defined/considered as one of the passive solar strategies to reduce incidence of direct solar radiation on buildings envelope, accordingly heat gain in its spaces; in which shades are created via the building shape/form itself, so the building envelope has to block out solar radiation instead of using limited shading devices or surrounded context [1]. The challenges in reforming BLSs towards better self-shaded ones are the other required parameters such as best treatments' orientations, shading duration, number of shaded surfaces and others; this is why optimizing BLSs towards better self-shading is a wider scope and not means only using types of shading devices. For example, cavities will provide self-shading in general and less solar exposure per m^2, but also it will increase the shape circumference (SC) of BLSs accordingly absolute solar exposure;

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studying SC of shapes is sensitive then and treatments should be classified in details. Hence, an automated method is required for reforming either a given or generic BLS towards better self-shaded ones using pre-defined orientations, areas, etc, with considering all relevant parameters.

Many previous studies focused on new techniques for buildings towards better self-shading. Nikpour et al [2] investigated the amount of overall thermal transfer value reduction in an actual model of self-shading buildings. Kandar et al [1] studied self-shading in buildings to provide efficient daylighting and energy consumption. Alhuwayil et al [3] assessed the impact of applying external shading strategy on the energy saving and relevant economics for a multi-story hotel building in hot-humid climate. Kandar et al [4] examines the effect of inclined wall self-shading strategy on heat gain in an office building; ambient temperature and relative humidity were the main variables used in the study. Shahda [5] presented proposals based on simulations to create self-shading on opaque solid walls using small protrusions to be compared with the basic wall. These techniques are aiming to optimize self-shading without changing the building envelope.

Unlike the focus of the previous studies, a lot of researches were found studying strategies and techniques of shading devices. For example, Sun et al [6] studied the effects of different shading-type cladding designs (such as orientations, inclinations and others) on the energy performance in BIPVs in Hong Kong. Vergauwen et al [7] gave an overview of the main parameters of adaptive shading components based on curved-line folding. Cho et al [8] presented an integrated approach for exterior shading design analysis by simulating 48 exterior shading devices applied on a simple window module in Korea. Bellia et al [9] conducted a critical analysis shading devices' effects on building thermal and/or lighting performances. Cheng et al [10] described a design approach for discerning solar gain to assign external shading devices. Fiorito et al [11] presented a critical review of the most recent smart morphing shade devices activated by solar radiation for reducing total building energy consumptions. Valladares-Rendón et al [12] conducted a comprehensive review for recommending the most effective and balanced solutions to increase energy savings including different shading devices in different orientation. Hraska [13] studied and classified adaptive solar shading systems of buildings. Al-Masrani and Al-Obaidi [14] conducted a critical review for assessing several systems of dynamic shading systems; design elements and evaluation strategies were studied. However, these research works were focusing the details of shading devices, not re-forming shapes of high-rise buildings under specific limitations; using shading devices is useful but optimizing the geometry is utilizing more surfaces' areas, accordingly more self-shading possibility.

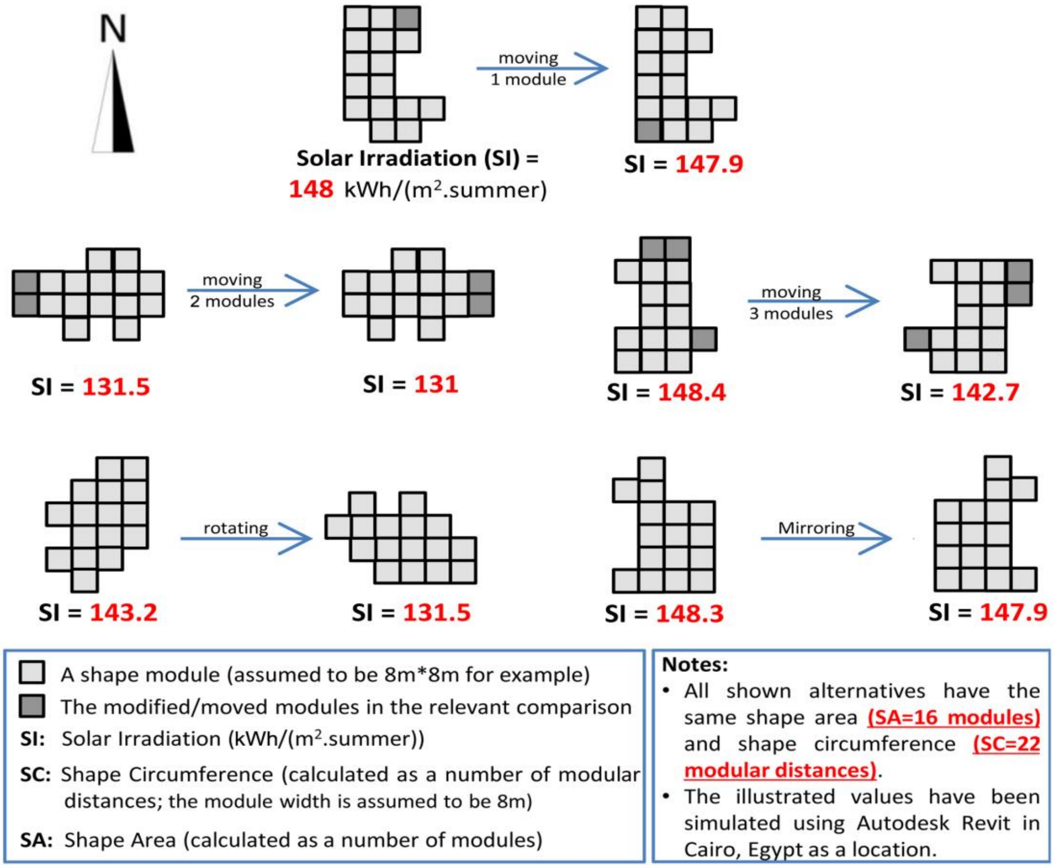
However, self-shading on building envelopes can be simulated using a lot of simulation tools/approaches, such as Energy Plus, DOE2, TRNSYS and others [15], where each tool has its own attributes and possibilities that extend the simulation details to different edges [16]. Other tools were developed to cover extended details of shading, for example, Hashemloo et al [17] presents a method for designing a shading algorithm that utilizes visual comfort metric; it accounts for building specific local conditions. Choi et al [18] developed a shaded area calculation tool for kinetic façades in irregular building shapes; it derived shaded fractions on different movement directions and orientations. Yi et al [19] developed an advanced daylight model to simulate, evaluate and analyze the performance of dynamic shading device. Abuimara et al [20] proposed an occupant-centric method for optimizing window and shading design that evaluates the impact of occupant-related assumptions in office buildings. Jensen et al [21] developed an open source method for calculating self-shading on two-axis tracking solar collectors; simulations were carried out with considering relevant layout parameters, i.e., aspect ratio, offset, rotation and others. However, these simulation tools and approaches help designers in testing shading and solar aspects on only single cases/treatments and/or to test a specific parameter, while these tools cannot provide a generation of a set of alternatives for a building form in the same perspective.

In the field of automating and optimizing building layouts/geometries for different purposes, Mashood et al [22] developed a hybrid system through a genetic algorithm to produce a set of optimal solutions of building layouts, and Doulgerakis [23] provided an approach for automating layout planning via genetic programing. Merrell et al [24] proposed an approach that automates generations of residential building layouts based on specific requirements. Lavafpour and Sharples [25] studied optimizing thermal comfort on building geometries using numerical thermal simulations in UK climates. Weng et al [26] proposed a practical methodology for optimizing complex building layouts and facades that explores/tests new design solutions on them. Lavafpour [27] examined the potential of self-shading in facades' geometries in dwelling designs in London to reduce summer overheating with outlining possible scenarios for dwelling facades. Guo and Li [28] implemented a multi-agent topologic finding system (EAATF) to generate designed architectural layouts that satisfy specific criteria. Koenig and Knecht [29] applied subdivision algorithm for generating satisfied architectural layouts based on proposed criteria. Kitchley and Srivathsan [30] provided a design tool for generating layout solutions of fishing settlements in India. Regarding the techniques used in such layout optimizations, Peng et al [31] proposed non-linear approaches to generate layouts towards flexibility, accessibility and aesthetic criteria, while Hua et al [32] acknowledged the automated generation process based on regular linear approach. Saligheh and Saadatjoo [33] addressed the impact of building form porosity on self-shading as an efficient passive cooling solution in hot and humid regions using simulations.

Few studies were found focusing on optimizing building envelope to fit or raise solar irradiation for different purposes. A computational tool “RADIANCE” can assist in optimizing urban geometric forms with analyzing solar irradiation of these forms [34]. Youssef et al [35] developed an optimization method that reforms given building shapes/envelopes to produce a set of better

Building Integrated Photovoltaics (BIPV) shape alternatives; used treatments are already providing self-shading that has been avoided not to affect PV panels negatively. Martinopoulos et al [36] compared the performance of shadings and PV system on buildings in achieving thermal comfort in office buildings; shading options can reduce energy requirements by 33% in the studied case. Jakica and Kragh [37] assessed self-shading benefits of twisting geometries using the correlation between floor-to-floor rotation and façade solar irradiation focusing on hot climates. However, such studies present why self-shading is not simply inversing such researches that aim at raising solar irradiation in envelope parts regardless relevant shading; the optimization of self-shading depends on using indentations for raising self-shading without increasing SC that accordingly increase absolute solar irradiation on surfaces; a new approach, more and detailed treatments' ratios are needed. Many approaches/tools are useful to study single cases of self-shading, while no approaches or tools were found for articulating self-shaded alternatives from a given form including shapes, dimensions, orientation, possible different treatments; a computational method should be developed to do so with considering solar irradiation.

This paper introduces a novel optimization approach for reforming the shape of high-rise BLSs towards better self-shaded alternatives as shown in Figure 1, either starting from a given initial one or specific limitations such as area, circumference and others. This can be achieved via determining best self-shading treatments that suits these limitations; these treatments can be applied in the generation processes using Shape Grammar (SG) theory as detailed in the following section; briefly, (SG) theory was invented by G. Stiny in 1980; it has been identified as "a set of shape rules that can be applied in a step-by-step way to generate a set, or language, of designs", according to Terry Knight [38]. Hence, better self-shaded BLSs can be generated computationally.



☐ A shape module (assumed to be 8m*8m for example)

■ The modified/moved modules in the relevant comparison

SI: Solar Irradiation (kWh/(m^2.summer))

SC: Shape Circumference (calculated as a number of modular distances; the module width is assumed to be 8m)

SA: Shape Area (calculated as a number of modules)

Notes:

- All shown alternatives have the same shape area **(SA=16 modules)** and shape circumference **(SC=22 modular distances)**.
- The illustrated values have been simulated using Autodesk Revit in Cairo, Egypt as a location.

Fig. 1: Different shape optimizations of building layouts towards better self-shading within the same area and circumference

The main variables that have been studied in the proposed approach are: a) Solar Irradiation (SI) per area in the summer months (kWh/(m^2.summer)) to be used to measure self-shading on building surface; b) Shape Circumference (SC) calculated as a number of modular spacing around BLS outline; c) Absolute Solar Irradiation (ASI) [] accordingly is also included as a directly proportional variable with SI and SC - this is why SC is very sensitive to be studied; d) Shape Area (SA); and e) Number of modifications to be applied. However, high-rise

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[] Absolute Solar Irradiation (ASI) (kWh/summer) = $SI \times SC \times i$

where:

SI: Solar Irradiation (kWh/ (m^2. summer)).

SC: Shape circumference of a BLS calculated as a number of modular distances (m).

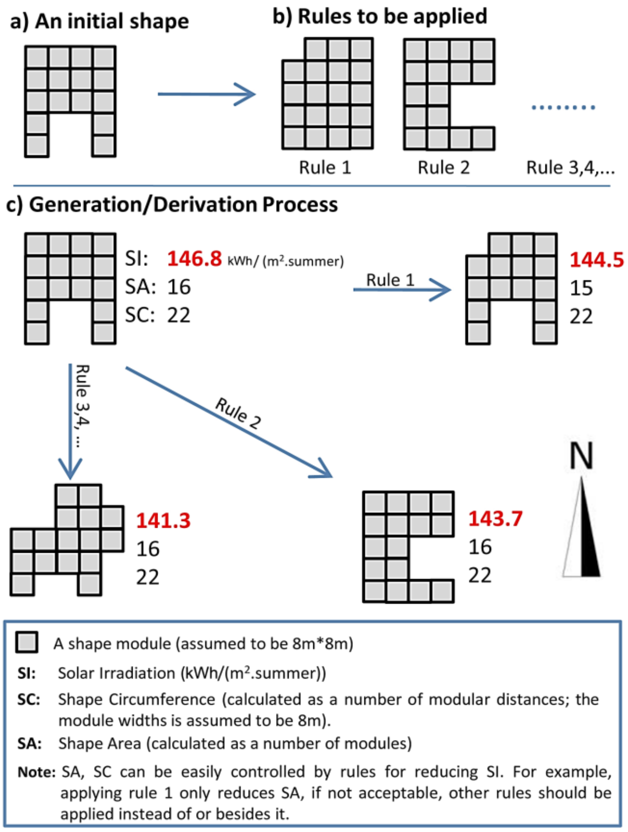
i = Building height x facade modules' width (both are constants in this study, since the approach re-forms BLSs with fixing the height of high-rise buildings (15 stories), while modules' width has been assumed to 8 m).

buildings in Egypt, as a hot climate zone, are used to demonstrate and validate the applications of the proposed approach. The paper has been structured to include SG principles in section 2, the framework of the proposed approach in section 3, and a set of applications and the relevant validation in sections 4 and 5, respectively, and ends with the discussion and conclusion in sections 6 and 7, respectively.

II. PRINCIPLES OF SHAPE GRAMMAR THEORY

As illustrated before, SG theory provides representations to generate alternatives for shapes to achieve a specific purpose, and it performs computations for these alternatives by the recognition of a particular shape and its possible replacements. These computations are applied using pre-developed rules that present the particular shape replacement [38]. This is necessary for automated generations as required in this approach. Many studies used SG towards achieve architectural goals computationally. For example, Halatsch et al [39] utilized SG to derive meaningful 3D city models, Ruiz-Montiel et al [40] for generating different designs to satisfy architectural requirements, Granadeiro et al [41] to produce better envelope alternatives with minimum HVAC demand.

However, Figure 2 presents how SG theory can be applied to optimize BLSs; each rule represents a specific treatment to be added/ replaced on the given initial shape to generate different alternatives. Based on the required variables' ranges, SG rules can be selected and/or each generated alternatives are checked accordingly.



☐ A shape module (assumed to be 8m*8m)

SI: Solar Irradiation (kWh/(m^2.summer))

SC: Shape Circumference (calculated as a number of modular distances; the module widths is assumed to be 8m).

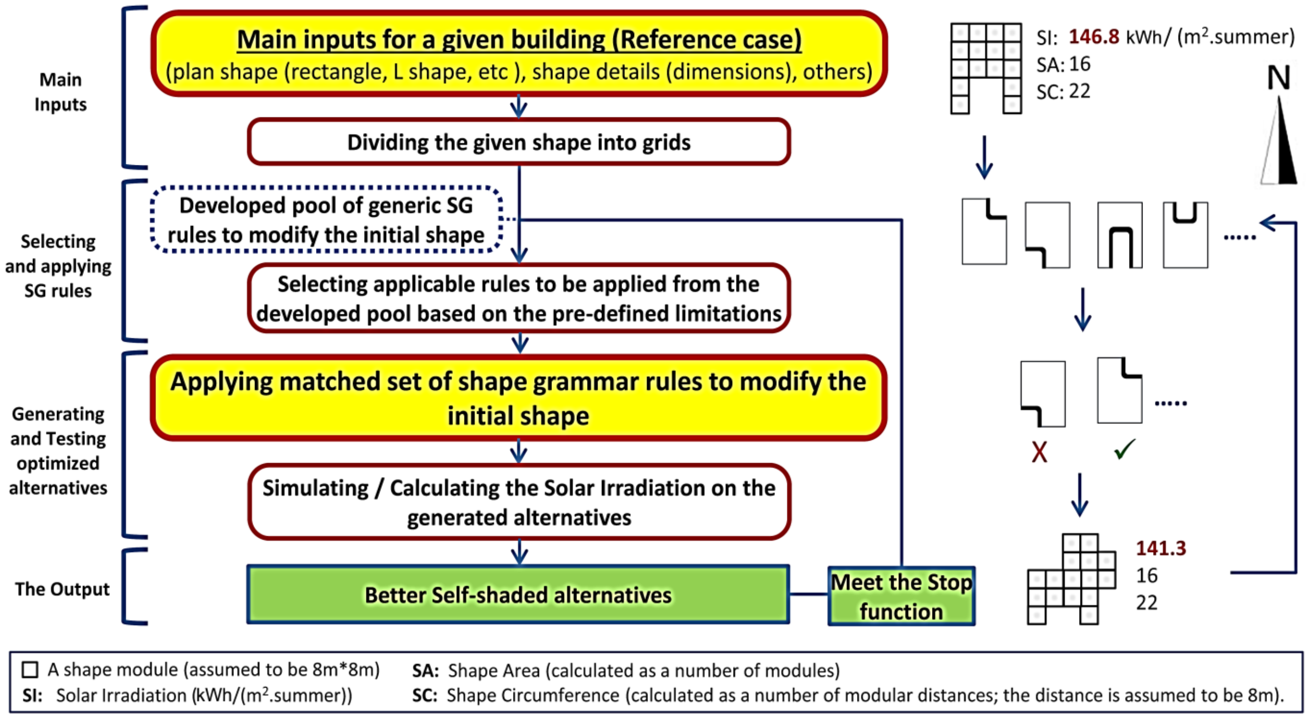
SA: Shape Area (calculated as a number of modules)

Note: SA, SC can be easily controlled by rules for reducing SI. For example, applying rule 1 only reduces SA, if not acceptable, other rules should be applied instead of or besides it.

Fig 2. Examples of applying shape grammar theory to reform building layout shapes towards self-shaded alternatives: a) an initial shape; b) rules to be applied; c) generation/derivation process

III. FRAMEWORK OF THE PROPOSED OPTIMIZATION METHOD

Figure 3 illustrates a summarized framework for the proposed optimization method that consists of five sections as detailed below. The framework employs SG to generate better self-shaded building shapes as detailed below.



☐ A shape module (assumed to be 8m*8m)

SI: Solar Irradiation (kWh/(m^2.summer))

SA: Shape Area (calculated as a number of modules)

SC: Shape Circumference (calculated as a number of modular distances; the distance is assumed to be 8m).

Fig 3. The proposed optimization framework

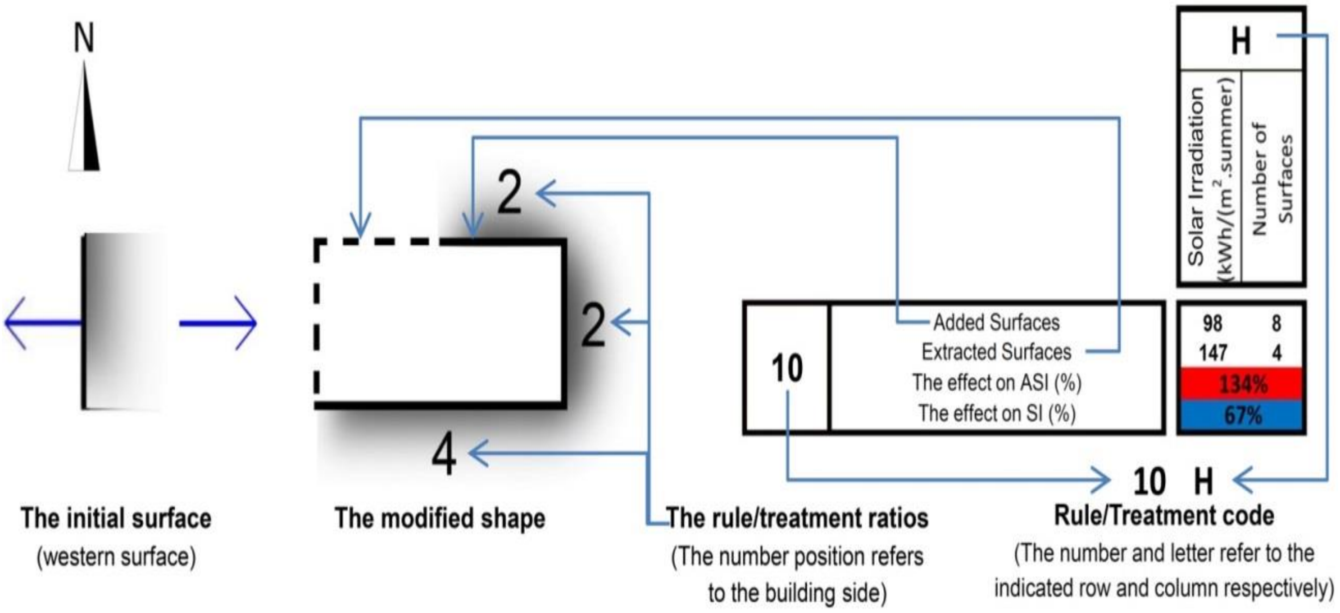
3.1. Main Inputs

The main input of the proposed framework is a given initial BLS to be optimized on a 2D modular grid (this represents dimensions, area, circumference, etc). If there is no specific initial BLS required, basic shapes can be used initially to generate a set of different alternatives. However, variables that can be controlled in each single generation and accordingly compared with the initial BLS are: SI, SC, ASI, SA, treatments' ratios, orientations and number of modifications (the number of applied rules); these variables' ranges can be also specified as inputs. SI of initial BLS can be simulated computationally with any suitable simulation tools.

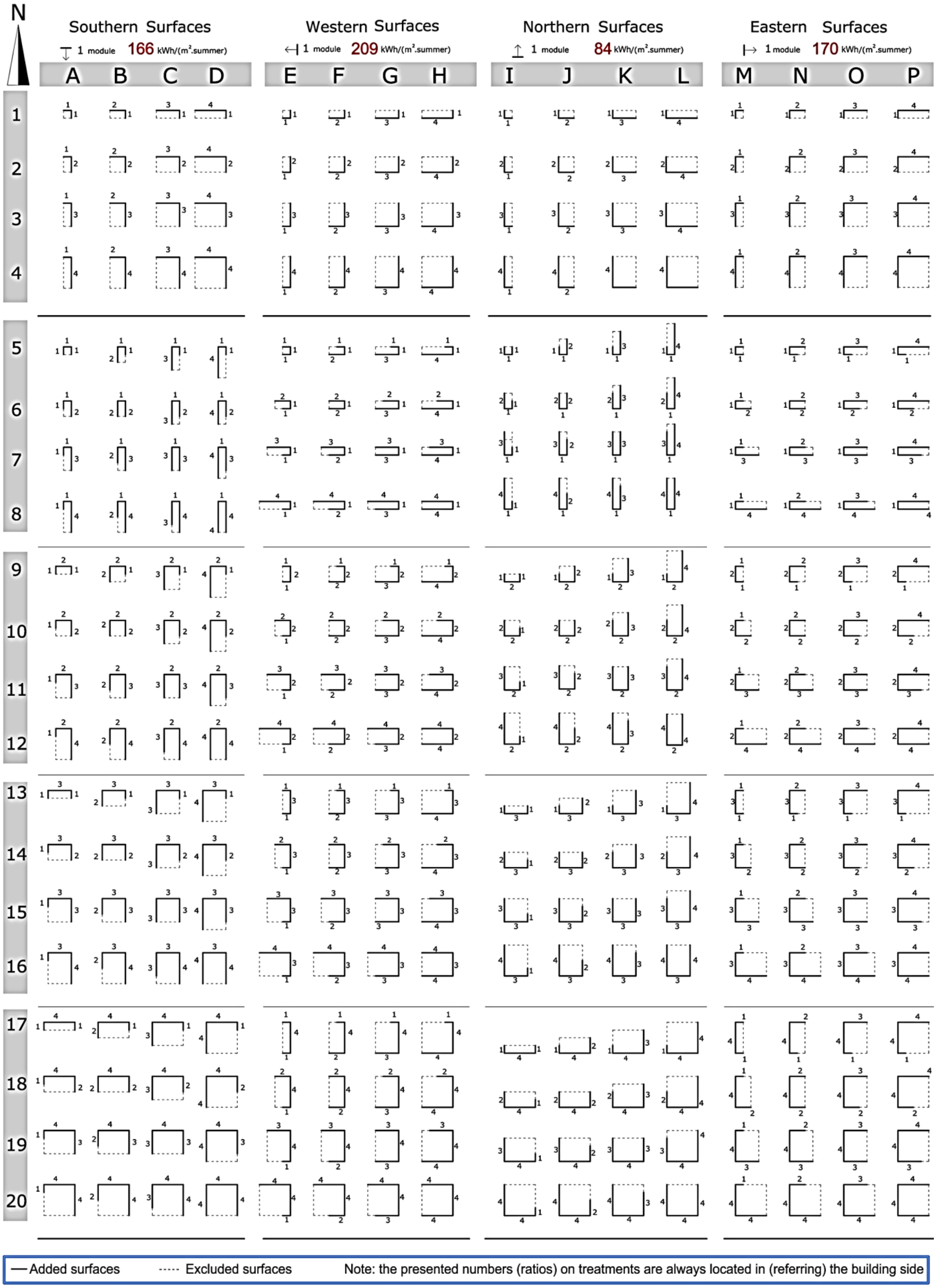
3.2. Selecting and Applying SG Rules on the Initial Shape

Cubic corner and edge indentations have been selected as main treatments that change the given BLS towards better self-shading. Accordingly, a pool with 320 SG rules has been developed on a 2D modular grid as shown in Figure 4 to yield a number of treatments' alternatives either for a given BLS and/or adapting specified variables; these rules have been classified to represent different ratios and orientations for different treatments that can be applied on any rectilinear/cubic BLS. Applying each rule or group of rules will affect building SI, ASI, SA and SC, and other rules to be applied afterwards. For example, R.10H is a protrusion on the western facades that extracts 4 surfaces with adding 8 ones as shown in Figure 4 (a), where the number and the letter denote the row and column, respectively; however, this causes 67% SI (kWh/ (m^2. summer)), while this increases ASI by only 134% although the added surfaces are double the extracted ones.

As detailed in Table 1, each proposed rule has been simulated using Autodesk Revit (using Insight Plug-in) during the summer months (8am - 5pm) and accordingly classified; some rules can decrease both SI and ASI compared with initial surfaces in different orientations, such as all corner indentations (R.1, R.2, R.3 and R4). However, the majority of top 15 rules reducing SI are in groups R.7 and R.8, while top 15 rules reducing ASI are in groups R.1, R.2 and R.3. On the other hand, the majority of other edge indentations (R.5 to R20) decrease SI and all of them increase ASI with different percentages due to the added surfaces. Also, R.L and R.K contains the majority of top and worst 15 rules that affect both SI and ASI, especially northern indentations with square ratios because of the low SI and SA of surfaces on northern facades; this refers to the sensitivity of these rules. However, rules that increase ASI and/or SI can still be utilized in the generation process of self-shaded alternatives by: a) replacing them from initial BLS with any other rules that have better effect; b) applying them in addition to better rules (such as R.1, R.2, R.3 and R4) to get alternatives with lower SI and ASI in total; c) applying them to decrease SI only, and accordingly other rules should be added as protrusions to compensates shape area.



(a)



(b)

Fig 4. The developed main SG rules for optimizing self-shaded building layout shapes: a) A specification of rules (R. 10H as an example); b) the developed rules.

TABLE (1)
THE DETAILS AND CLASSIFICATIONS OF THE DEVELOPED RULES

		A		B		C		D	
		SI (kWh/(m^2.summer))	Number of Surfaces	SI (kWh/(m^2.summer))	Number of Surfaces	SI (kWh/(m^2.summer))	Number of Surfaces	SI (kWh/(m^2.summer))	Number of Surfaces
1	Added Surfaces	164	2	157	3	157	4	158	5
	Extracted Surfaces	188	2	180	3	177	4	175	5
	The effect on SI or ASI(%)	87%		87%		89%		90%	
2	Added Surfaces	176	3	166	4	161	5	161	6
	Extracted Surfaces	195	3	188	4	183	5	180	6
	The effect on SI or ASI(%)	90%		89%		88%		89%	
3	Added Surfaces	184	4	173	5	167	6	165	7
	Extracted Surfaces	198	4	192	5	188	6	184	7
	The effect on SI or ASI(%)	93%		90%		89%		89%	
4	Added Surfaces	189	5	178	6	173	7	169	8
	Extracted Surfaces	200	5	195	6	191	7	188	8
	The effect on SI or ASI(%)	94%		91%		91%		90%	
5	Added Surfaces	97	3	107	4	120	5	126	6
	Extracted Surfaces	166	1	168	2	169	3	169	4
	The effect on ASI (%)	175%		127%		119%		112%	
	The effect on SI (%)	58%		64%		71%		75%	
6	Added Surfaces	115	4	87	5	95	6	105	7
	Extracted Surfaces	188	2	166	1	168	2	169	3
	The effect on ASI (%)	123%		262%		170%		145%	
	The effect on SI (%)	61%		52%		57%		62%	
7	Added Surfaces	133	5	102	6	82	7	88	8
	Extracted Surfaces	195	3	188	2	166	1	168	2
	The effect on ASI (%)	114%		163%		346%		210%	
	The effect on SI (%)	68%		54%		49%		52%	
8	Added Surfaces	145	6	116	7	93	8	79	9
	Extracted Surfaces	198	4	195	3	188	2	166	1
	The effect on ASI (%)	110%		139%		198%		428%	
	The effect on SI (%)	73%		60%		50%		48%	
9	Added Surfaces	123	4	121	5	128	6	133	7
	Extracted Surfaces	166	2	167	3	168	4	168	5
	The effect on ASI (%)	148%		121%		114%		111%	
	The effect on SI (%)	74%		72%		76%		79%	
10	Added Surfaces	129	5	111	6	113	7	118	8
	Extracted Surfaces	180	3	166	2	167	3	168	4
	The effect on ASI (%)	119%		201%		158%		140%	
	The effect on SI (%)	72%		67%		68%		70%	
11	Added Surfaces	141	6	129	7	129	8	108	9
	Extracted Surfaces	188	4	180	3	166	2	167	3
	The effect on ASI (%)	113%		167%		311%		194%	
	The effect on SI (%)	75%		72%		78%		65%	
12	Added Surfaces	150	7	129	8	113	9	104	10
	Extracted Surfaces	192	5	188	4	180	3	166	2
	The increase of ASI (%)	109%		138%		188%		313%	
	The increase of SI (%)	78%		69%		63%		63%	

		E		F		G		H	
		SI (kWh/(m^2.summer))	Number of Surfaces	SI (kWh/(m^2.summer))	Number of Surfaces	SI (kWh/(m^2.summer))	Number of Surfaces	SI (kWh/(m^2.summer))	Number of Surfaces
1	Added Surfaces	121	2	102	3	95	4	91	5
	Extracted Surfaces	147	2	126	3	115	4	109	5
	The effect on SI or ASI(%)	83%		81%		82%		83%	
2	Added Surfaces	149	3	124	4	116	5	105	6
	Extracted Surfaces	167	3	147	4	134	5	126	6
	The effect on SI or ASI(%)	89%		85%		87%		84%	
3	Added Surfaces	166	4	142	5	129	6	117	7
	Extracted Surfaces	178	4	159	5	147	6	138	7
	The effect on SI or ASI(%)	93%		89%		88%		85%	
4	Added Surfaces	173	5	151	6	137	7	128	8
	Extracted Surfaces	184	5	167	6	155	7	147	8
	The effect on SI or ASI(%)	94%		90%		88%		87%	
5	Added Surfaces	109	3	91	4	86	5	84	6
	Extracted Surfaces	209	1	147	2	126	3	115	4
	The effect on ASI (%)	156%		124%		114%		109%	
	The effect on SI (%)	52%		62%		68%		73%	
6	Added Surfaces	109	4	90	5	81	6	80	7
	Extracted Surfaces	188	2	209	1	147	2	126	3
	The effect on ASI (%)	116%		215%		166%		149%	
	The effect on SI (%)	58%		43%		55%		64%	
7	Added Surfaces	122	5	97	6	83	7	78	8
	Extracted Surfaces	180	3	188	2	209	1	147	2
	The effect on ASI (%)	113%		155%		278%		213%	
	The effect on SI (%)	68%		52%		40%		53%	
8	Added Surfaces	127	6	104	7	89	8	79	9
	Extracted Surfaces	177	4	180	3	188	2	209	1
	The effect on ASI (%)	108%		135%		190%		340%	
	The effect on SI (%)	72%		58%		47%		38%	
9	Added Surfaces	140	4	120	5	104	6	100	7
	Extracted Surfaces	209	2	167	3	147	4	134	5
	The effect on ASI (%)	134%		120%		106%		104%	
	The effect on SI (%)	67%		72%		71%		75%	
10	Added Surfaces	136	5	117	6	102	7	98	8
	Extracted Surfaces	195	3	209	2	167	3	147	4
	The effect on ASI (%)	116%		168%		142%		134%	
	The effect on SI (%)	70%		56%		61%		67%	
11	Added Surfaces	135	6	117	7	104	8	98	9
	Extracted Surfaces	188	4	195	3	209	2	167	3
	The effect on ASI (%)	108%		140%		199%		176%	
	The effect on SI (%)	72%		60%		50%		59%	
12	Added Surfaces	137	7	119	8	108	9	99	10
	Extracted Surfaces	183	5	188	4	195	3	209	2
	The increase of ASI (%)	105%		127%		166%		237%	
	The increase of SI (%)	75%		63%		55%		47%	

		I		J		K		L	
		SI (kWh/(m^2.summer))	Number of Surfaces	SI (kWh/(m^2.summer))	Number of Surfaces	SI (kWh/(m^2.summer))	Number of Surfaces	SI (kWh/(m^2.summer))	Number of Surfaces
1	Added Surfaces	102	2	89	3	85	4	84	5
	Extracted Surfaces	127	2	113	3	106	4	101	5
	The effect on SI or ASI(%)	80%		79%		81%		83%	
2	Added Surfaces	123	3	105	4	95	5	93	6
	Extracted Surfaces	141	3	127	4	118	5	113	6
	The effect on SI or ASI(%)	87%		83%		80%		83%	
3	Added Surfaces	135	4	117	5	105	6	101	7
	Extracted Surfaces	149	4	136	5	127	6	121	7
	The effect on SI or ASI(%)	91%		86%		83%		84%	
4	Added Surfaces	142	5	125	6	115	7	109	8
	Extracted Surfaces	153	5	141	6	133	7	127	8
	The effect on SI or ASI(%)	93%		88%		86%		86%	
5	Added Surfaces	69	3	96	4	121	5	133	6
	Extracted Surfaces	84	1	147	2	167	3	178	4
	The effect on ASI (%)	246%		131%		121%		112%	
	The effect on SI (%)	82%		66%		72%		75%	
6	Added Surfaces	86	4	69	5	88	6	105	7
	Extracted Surfaces	127	2	84	1	147	2	167	3
	The effect on ASI (%)	135%		411%		180%		146%	
	The effect on SI (%)	68%		82%		60%		63%	
7	Added Surfaces	104	5	81	6	70	7	83	8
	Extracted Surfaces	141	3	127	2	84	1	147	2
	The effect on ASI (%)	123%		191%		583%		227%	
	The effect on SI (%)	74%		64%		83%		57%	
8	Added Surfaces	113	6	93	7	78	8	71	9
	Extracted Surfaces	149	4	141	3	127	2	84	1
	The effect on ASI (%)	114%		154%		246%		761%	
	The effect on SI (%)	76%		66%		61%		85%	
9	Added Surfaces	78	4	94	5	115	6	126	7
	Extracted Surfaces	84	2	126	3	147	4	159	5
	The effect on ASI (%)	186%		125%		118%		111%	
	The effect on SI (%)	93%		75%		78%		79%	
10	Added Surfaces	86	5	82	6	95	7	106	8
	Extracted Surfaces	113	3	84	2	126	3	147	4
	The effect on ASI (%)	127%		293%		176%		145%	
	The effect on SI (%)	76%		98%		76%		72%	
11	Added Surfaces	100	6	89	7	85	8	94	9
	Extracted Surfaces	127	4	113	3	84	2	126	3
	The effect on ASI (%)	118%		184%		405%		224%	
	The effect on SI (%)	79%		79%		101%		75%	
12	Added Surfaces	108	7	97	8	89	9	87	10
	Extracted Surfaces	136	5	127	4	113	3	84	2
	The increase of ASI (%)	112%		153%		237%		518%	
	The increase of SI (%)	80%		76%		79%		104%	

		M		N		O		P	
		SI (kWh/(m^2.summer))	Number of Surfaces	SI (kWh/(m^2.summer))	Number of Surfaces	SI (kWh/(m^2.summer))	Number of Surfaces	SI (kWh/(m^2.summer))	Number of Surfaces
1	Added Surfaces	145	2	144	3	148	4	150	5
	Extracted Surfaces	168	2	167	3	167	4	167	5
	The effect on SI or ASI(%)	86%		86%		89%		90%	
2	Added Surfaces	150	3	146	4	147	5	148	6
	Extracted Surfaces	169	3	168	4	168	5	167	6
	The effect on SI or ASI(%)	89%		87%		88%		88%	
3	Added Surfaces	155	4	150	5	149	6	149	7
	Extracted Surfaces	169	4	168	5	168	6	168	7
	The effect on SI or ASI(%)	92%		89%		89%		89%	
4	Added Surfaces	157	5	152	6	150	7	150	8
	Extracted Surfaces	169	5	169	6	168	7	168	8
	The effect on SI or ASI(%)	93%		90%		89%		89%	
5	Added Surfaces	96	3	103	4	114	5	120	6
	Extracted Surfaces	170	1	168	2	167	3	167	4
	The effect on ASI (%)	169%		123%		114%		108%	
	The effect on SI (%)	56%		61%		68%		72%	
6	Added Surfaces	82	4	83	5	91	6	99	7
	Extracted Surfaces	127	2	170	1	168	2	167	3
	The effect on ASI (%)	129%		244%		163%		138%	
	The effect on SI (%)	65%		49%		54%		59%	
7	Added Surfaces	78	5	75	6	78	7	84	8
	Extracted Surfaces	113	3	127	2	170	1	168	2
	The effect on ASI (%)	115%		177%		321%		200%	
	The effect on SI (%)	69%		59%		46%		50%	
8	Added Surfaces	78	6	75	7	74	8	75	9
	Extracted Surfaces	106	4	113	3	127	2	170	1
	The effect on ASI (%)	111%		155%		233%		397%	
	The effect on SI (%)	74%		67%		58%		44%	
9	Added Surfaces	116	4	117	5	122	6	126	7
	Extracted Surfaces	170	2	169	3	168	4	168	5
	The effect on ASI (%)	136%		116%		109%		105%	
	The effect on SI (%)	68%		69%		73%		75%	
10	Added Surfaces	100	5	101	6	106	7	110	8
	Extracted Surfaces	141	3	170	2	169	3	168	4
	The effect on ASI (%)	118%		178%		147%		131%	
	The effect on SI (%)	71%		59%		63%		65%	
11	Added Surfaces	92	6	91	7	94	8	99	9
	Extracted Surfaces	127	4	141	3	170	2	169	3
	The effect on ASI (%)	109%		150%		221%		176%	
	The effect on SI (%)	72%		64%		55%		59%	
12	Added Surfaces	89	7	88	8	89	9	92	10
	Extracted Surfaces	118	5	127	4	141	3	170	2
	The increase of ASI (%)	105%		139%		189%		271%	
	The increase of SI (%)	75%		69%		63%		54%	

(continued on the next page)

(TABLE 1: continued)

		A		B		C		D	
		SI (kWh/(m^2.summer))	Number of Surfaces	SI (kWh/(m^2.summer))	Number of Surfaces	SI (kWh/(m^2.summer))	Number of Surfaces	SI (kWh/(m^2.summer))	Number of Surfaces
13	Added Surfaces	133	5	130	6	133	7	135	8
	Extracted Surfaces	166	3	167	4	168	5	168	6
	The effect on ASI (%)	**134%**		**117%**		**111%**		**107%**	
	The effect on SI (%)	**80%**		**78%**		**79%**		**80%**	
14	Added Surfaces	137	6	124	7	124	8	127	9
	Extracted Surfaces	177	4	166	3	167	4	168	5
	The effect on ASI (%)	**116%**		**174%**		**149%**		**136%**	
	The effect on SI (%)	**78%**		**75%**		**74%**		**76%**	
15	Added Surfaces	144	7	129	8	120	9	121	10
	Extracted Surfaces	183	5	177	4	166	3	167	4
	The effect on ASI (%)	**110%**		**146%**		**217%**		**181%**	
	The effect on SI (%)	**79%**		**73%**		**72%**		**72%**	
16	Added Surfaces	151	8	136	9	125	10	119	11
	Extracted Surfaces	188	6	183	5	177	4	166	3
	The effect on ASI (%)	**107%**		**134%**		**177%**		**263%**	
	The effect on SI (%)	**81%**		**74%**		**71%**		**72%**	
17	Added Surfaces	141	6	136	7	137	8	139	9
	Extracted Surfaces	166	4	167	5	167	6	168	7
	The effect on ASI (%)	**127%**		**114%**		**109%**		**107%**	
	The effect on SI (%)	**85%**		**82%**		**82%**		**83%**	
18	Added Surfaces	144	7	135	8	133	9	134	10
	Extracted Surfaces	175	5	166	4	167	5	167	6
	The effect on ASI (%)	**115%**		**163%**		**144%**		**133%**	
	The effect on SI (%)	**82%**		**81%**		**80%**		**80%**	
19	Added Surfaces	149	8	138	9	132	10	131	11
	Extracted Surfaces	180	6	175	5	166	4	167	5
	The effect on ASI (%)	**110%**		**142%**		**199%**		**173%**	
	The effect on SI (%)	**83%**		**79%**		**80%**		**79%**	
20	Added Surfaces	154	9	142	10	135	11	131	12
	Extracted Surfaces	184	7	180	6	175	5	166	4
	The effect on ASI (%)	**107%**		**131%**		**170%**		**237%**	
	The effect on SI (%)	**84%**		**79%**		**77%**		**79%**	

		E		F		G		H	
		SI (kWh/(m^2.summer))	Number of Surfaces	SI (kWh/(m^2.summer))	Number of Surfaces	SI (kWh/(m^2.summer))	Number of Surfaces	SI (kWh/(m^2.summer))	Number of Surfaces
13	Added Surfaces	151	5	132	6	121	7	113	8
	Extracted Surfaces	209	3	178	4	159	5	147	6
	The effect on ASI (%)	**120%**		**111%**		**107%**		**103%**	
	The effect on SI (%)	**72%**		**74%**		**76%**		**77%**	
14	Added Surfaces	140	6	129	7	111	8	111	9
	Extracted Surfaces	198	4	209	3	178	4	159	5
	The effect on ASI (%)	**106%**		**144%**		**125%**		**126%**	
	The effect on SI (%)	**71%**		**62%**		**62%**		**70%**	
15	Added Surfaces	144	7	129	8	112	9	111	10
	Extracted Surfaces	192	5	198	4	209	3	178	4
	The effect on ASI (%)	**105%**		**130%**		**161%**		**156%**	
	The effect on SI (%)	**75%**		**65%**		**54%**		**62%**	
16	Added Surfaces	145	8	130	9	120	10	112	11
	Extracted Surfaces	188	6	192	5	198	4	209	3
	The effect on ASI (%)	**103%**		**122%**		**151%**		**196%**	
	The effect on SI (%)	**77%**		**68%**		**61%**		**54%**	
17	Added Surfaces	161	6	143	7	132	8	123	9
	Extracted Surfaces	209	4	184	5	167	6	155	7
	The effect on ASI (%)	**116%**		**109%**		**105%**		**102%**	
	The effect on SI (%)	**77%**		**78%**		**79%**		**79%**	
18	Added Surfaces	155	7	140	8	129	9	122	10
	Extracted Surfaces	200	5	209	4	184	5	167	6
	The effect on ASI (%)	**108%**		**134%**		**126%**		**122%**	
	The effect on SI (%)	**77%**		**67%**		**70%**		**73%**	
19	Added Surfaces	153	8	139	9	129	10	121	11
	Extracted Surfaces	195	6	200	5	209	4	184	5
	The effect on ASI (%)	**105%**		**125%**		**154%**		**145%**	
	The effect on SI (%)	**79%**		**69%**		**62%**		**66%**	
20	Added Surfaces	152	9	138	10	129	11	122	12
	Extracted Surfaces	191	7	195	6	200	5	209	4
	The effect on ASI (%)	**103%**		**118%**		**142%**		**175%**	
	The effect on SI (%)	**80%**		**71%**		**64%**		**58%**	

		I		J		K		L	
		SI (kWh/(m^2.summer))	Number of Surfaces	SI (kWh/(m^2.summer))	Number of Surfaces	SI (kWh/(m^2.summer))	Number of Surfaces	SI (kWh/(m^2.summer))	Number of Surfaces
13	Added Surfaces	82	5	95	6	111	7	120	8
	Extracted Surfaces	84	3	115	4	134	5	147	6
	The effect on ASI (%)	**163%**		**124%**		**116%**		**109%**	
	The effect on SI (%)	**98%**		**82%**		**83%**		**82%**	
14	Added Surfaces	88	6	88	7	99	8	108	9
	Extracted Surfaces	106	4	84	3	115	4	134	5
	The effect on ASI (%)	**125%**		**244%**		**172%**		**145%**	
	The effect on SI (%)	**83%**		**105%**		**86%**		**81%**	
15	Added Surfaces	99	7	94	8	94	9	100	10
	Extracted Surfaces	118	5	106	4	84	3	115	4
	The effect on ASI (%)	**117%**		**178%**		**336%**		**217%**	
	The effect on SI (%)	**84%**		**89%**		**112%**		**87%**	
16	Added Surfaces	105	8	99	9	96	10	97	11
	Extracted Surfaces	127	6	118	5	106	4	84	3
	The effect on ASI (%)	**110%**		**151%**		**227%**		**423%**	
	The effect on SI (%)	**83%**		**84%**		**91%**		**115%**	
17	Added Surfaces	85	6	93	7	105	8	116	9
	Extracted Surfaces	84	4	109	5	126	6	138	7
	The effect on ASI (%)	**152%**		**119%**		**111%**		**108%**	
	The effect on SI (%)	**101%**		**85%**		**84%**		**84%**	
18	Added Surfaces	88	7	93	8	100	9	109	10
	Extracted Surfaces	101	5	84	4	109	5	126	6
	The effect on ASI (%)	**122%**		**221%**		**165%**		**145%**	
	The effect on SI (%)	**87%**		**111%**		**92%**		**87%**	
19	Added Surfaces	95	8	96	9	99	10	105	11
	Extracted Surfaces	113	6	101	5	84	4	109	5
	The effect on ASI (%)	**112%**		**171%**		**295%**		**212%**	
	The effect on SI (%)	**84%**		**95%**		**118%**		**96%**	
20	Added Surfaces	102	9	101	10	101	11	103	12
	Extracted Surfaces	121	7	113	6	101	5	84	4
	The effect on ASI (%)	**109%**		**149%**		**220%**		**368%**	
	The effect on SI (%)	**84%**		**90%**		**100%**		**123%**	

		M		N		O		P	
		SI (kWh/(m^2.summer))	Number of Surfaces	SI (kWh/(m^2.summer))	Number of Surfaces	SI (kWh/(m^2.summer))	Number of Surfaces	SI (kWh/(m^2.summer))	Number of Surfaces
13	Added Surfaces	126	5	126	6	128	7	131	8
	Extracted Surfaces	170	3	169	4	168	5	168	6
	The effect on ASI (%)	**124%**		**112%**		**106%**		**104%**	
	The effect on SI (%)	**74%**		**75%**		**76%**		**78%**	
14	Added Surfaces	112	6	112	7	115	8	117	9
	Extracted Surfaces	149	4	170	3	169	4	168	5
	The effect on ASI (%)	**113%**		**154%**		**136%**		**125%**	
	The effect on SI (%)	**75%**		**66%**		**68%**		**69%**	
15	Added Surfaces	102	7	102	8	104	9	108	10
	Extracted Surfaces	136	5	149	4	170	3	169	4
	The effect on ASI (%)	**105%**		**137%**		**184%**		**160%**	
	The effect on SI (%)	**75%**		**69%**		**61%**		**64%**	
16	Added Surfaces	98	8	99	9	100	10	102	11
	Extracted Surfaces	127	6	136	5	149	4	170	3
	The effect on ASI (%)	**103%**		**131%**		**168%**		**220%**	
	The effect on SI (%)	**77%**		**73%**		**67%**		**60%**	
17	Added Surfaces	135	6	133	7	133	8	135	9
	Extracted Surfaces	170	4	169	5	169	6	168	7
	The effect on ASI (%)	**119%**		**110%**		**105%**		**103%**	
	The effect on SI (%)	**79%**		**79%**		**79%**		**80%**	
18	Added Surfaces	121	7	120	8	121	9	123	10
	Extracted Surfaces	153	5	170	4	169	5	169	6
	The effect on ASI (%)	**111%**		**141%**		**129%**		**122%**	
	The effect on SI (%)	**79%**		**71%**		**72%**		**73%**	
19	Added Surfaces	112	8	112	9	113	10	115	11
	Extracted Surfaces	141	6	153	5	170	4	169	5
	The effect on ASI (%)	**106%**		**132%**		**166%**		**150%**	
	The effect on SI (%)	**79%**		**73%**		**66%**		**68%**	
20	Added Surfaces	106	9	106	10	107	11	109	12
	Extracted Surfaces	133	7	141	6	153	5	170	4
	The effect on ASI (%)	**102%**		**125%**		**154%**		**192%**	
	The effect on SI (%)	**80%**		**75%**		**70%**		**64%**	

SI: Solar Irradiation (kWh/ (m^2. summer) simulated within the period between 8am to 5pm.

ASI: Absolute Solar Irradiation (kWh /summer)

SI (%) or ASI (%): The percentage represents the increase of SI (kWh / (m^2. summer)) or ASI (kWh/summer) on rule surfaces compared with their initial surfaces.

R.i: Rule code, where i denotes to a row number or/and a column letter that refer to a group of rules or a specific one.

Notes:

- Top 15 rules reducing SI (%) are: 8H, 7G, 6F, 8P, 7O, 12H, 8G, 8D, 6N, 7C, 8C, 7P, 11G, 7F, 5E (the majority are in groups 7, 8)
- Worst rules that increase SI (%) are (only 10 rules): 20L, 19K, 16L, 15K, 18J, 12L, 17I, 11K, 20K (the majority in group K, L)
- Top 15 rules in reducing ASI (%) are: 1J, 1I, 2K, 1K, 1F, 1G, 1E, 2J, 2L, 3K, 1L, 1E, 3L, 2H, 2F (all are in groups 1, 2, 3, and the majority are in groups K, L)
- Worst 15 rules that increase ASI (%) are: 8L, 7K, 12L, 8D, 16L, 6J, 11K, 8P, 20L, 7C, 8H, 15K, 7O, 12D, 11C (the majority are in groups K, L)

🟩 These rules reduce both SI and ASI without increasing the number of surfaces (R.1 to R.4)

🟩 These rules reduce SI (R.A to R.H and R.M to R.P)

🟦 =< 100%

🟥 > 100%

3.3. *Generating and Testing Optimized Alternatives:*

The performance of applying previous rules individually on basic BLSs can be directly judged and controlled, while the performance of applying group of rules on generic BLSs cannot be judged first due to the different effects of adjustments, BLS compatibilities and orientations of rules in addition to the other variables (SA and SC); this is why a mathematical formula may not fit all cases and meet all criteria, instead, SI of generated alternatives should be simulated individually or calculated using the SI of its partial treatments.

3.4. *Calculating SI of Alternatives:*

One of the basic outcomes of pre-simulating SI (kWh/ (m^2. summer)) on the previous indentations and the main orthogonal surfaces is to calculate the SI average of any BLS (either given or optimized). Figure 5 presents the processes of SI calculation that can be applied only if the BLS surfaces are presenting the previous treatments/orientations with no self-shading on them, otherwise individual simulation should be conducted.

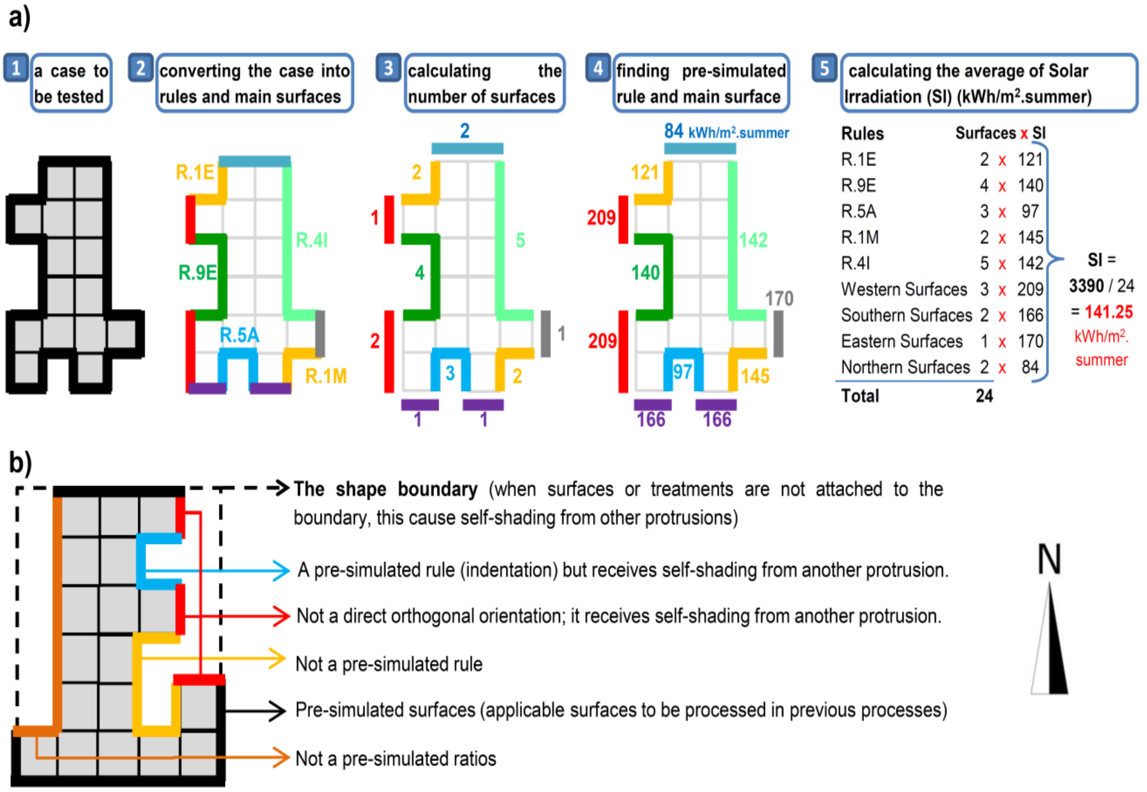


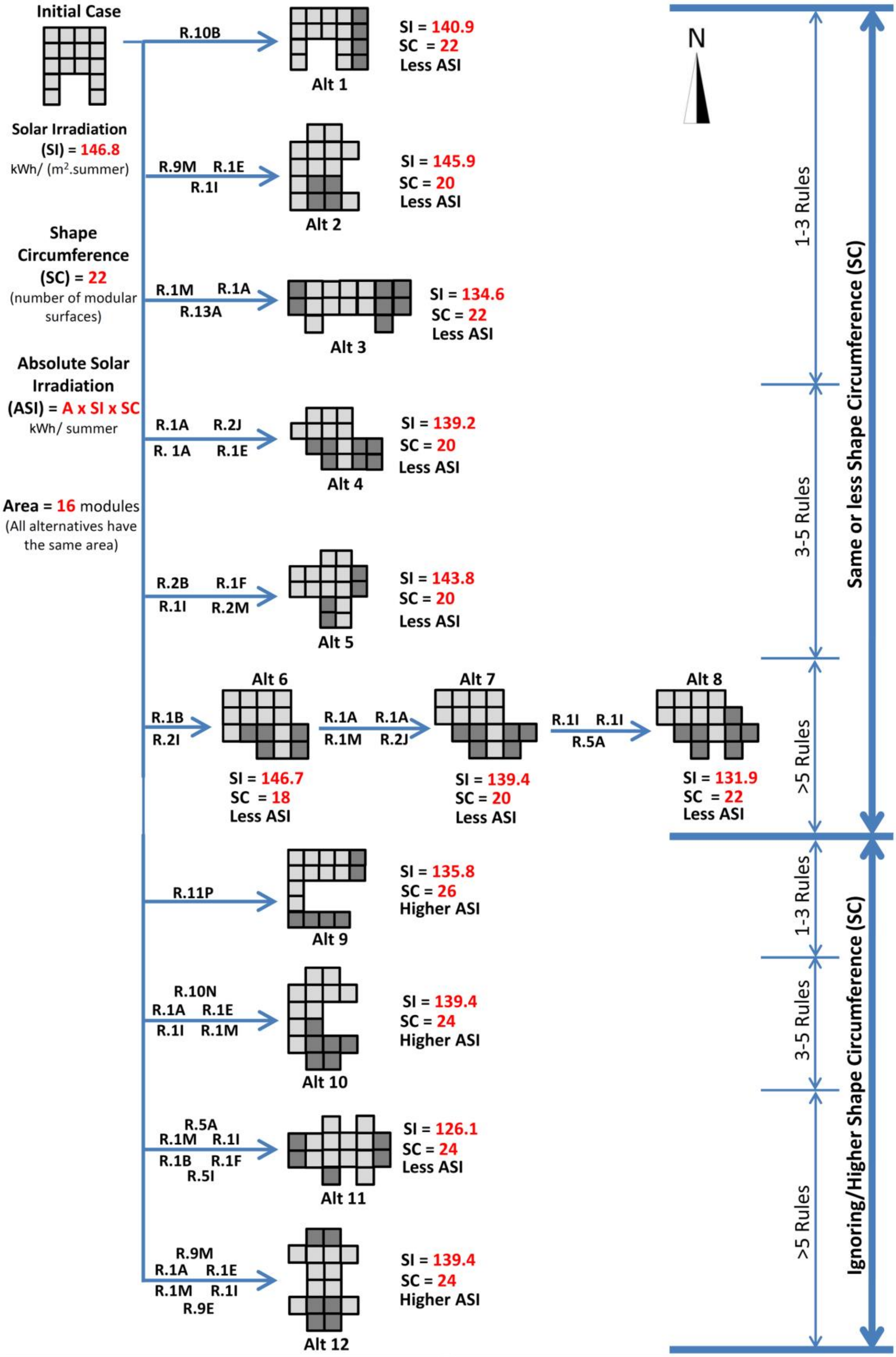
Fig 5. Examples of calculating SI on BLS cases using the developed SG rules: a) steps of calculation processes; b) example/cases that cannot be performed in the calculation processes.

3.5. *The Outputs:*

Self-shaded alternatives can be accordingly generated and tested, either with less SI than the initial case or less ASI also as well. Detailed applications are detailed below.

IV. APPLICATIONS OF THE PROPOSED APPROACH

Figure 6 presents an application of the proposed approach using an initial BLS to generate 12 better self-shaded alternatives with the same SA and different limitations. Specifically, many better self-shaded alternatives can be generated with the same or less SC; this confirms not only decreasing SI but also ASI as detailed before. If higher SC is allowed, ASI may be increased in majority of alternatives accordingly, while SI may be also decreased in some alternatives. However, level of modifications applied can be also controlled using the number of rules applied, and generated alternatives can be also re-optimized towards better ones. For example, alternative 1 (Alt 1) is similar to the initial case; the initial BLS can be optimized only using ratios or orientations not rules, while Alt 4 to Alt 8 are totally re-shaped far from the initial case due to applying 4 rules or more, however, Alt 8 represents the lowest SI (131.9 kWh/ (m^2. summer)) with the same SC. With allowing higher SC, Alt 11 achieves the lowest SI through the application as well as less ASI; this confirms that higher SC do not always means higher ASI.



☐ A shape module (assumed to be 8m*8m for example)

■ The modified modules after applying the rules

R.*xy*: *xy* denotes the rule code

SI: Solar Irradiation (kWh/(m².summer))

SC: Shape Circumference (Number of modular units)

ASI: Absolute Solar Irradiation (kWh/summer)

Alt i: Alternative Number (i)

Notes:

- All shown alternatives have the same area (16 modules) and their SI have been reduced.
- Alternatives with equal or less SC than the starting shape (=<22) represent reduced ASI accordingly, while some alternatives with higher SC cause higher ASI.
- The illustrated values have been simulated using Autodesk Revit using Cairo weather data relevant to the denoted location (Cairo).

Fig 6. Different examples of applying the developed SG rules towards better self-shading with controlling other variables.

V. VALIDATION

To check the effect of the added self-shading on alternatives' surfaces and validate their optimization, the 12 alternatives presented in the previous application in addition to the initial case have been tested again from the perspective of energy consumption, since many studies indicated the clear effect of self-shading on reducing energy consumption such as [2; 3; 12; 42; 43] and many others. The simulation has been conducted using eQuest [44] for high-rise office buildings (15 stories) in the same location. The results present that all self-shaded alternatives have also less annual and summer energy consumption compared with the initial case as shown in Figure 7, and the best reduction in annual and summer energy consumption in this set of alternatives could reached around 92% in Alt 11, which is also the best generated self-shaded alternative.

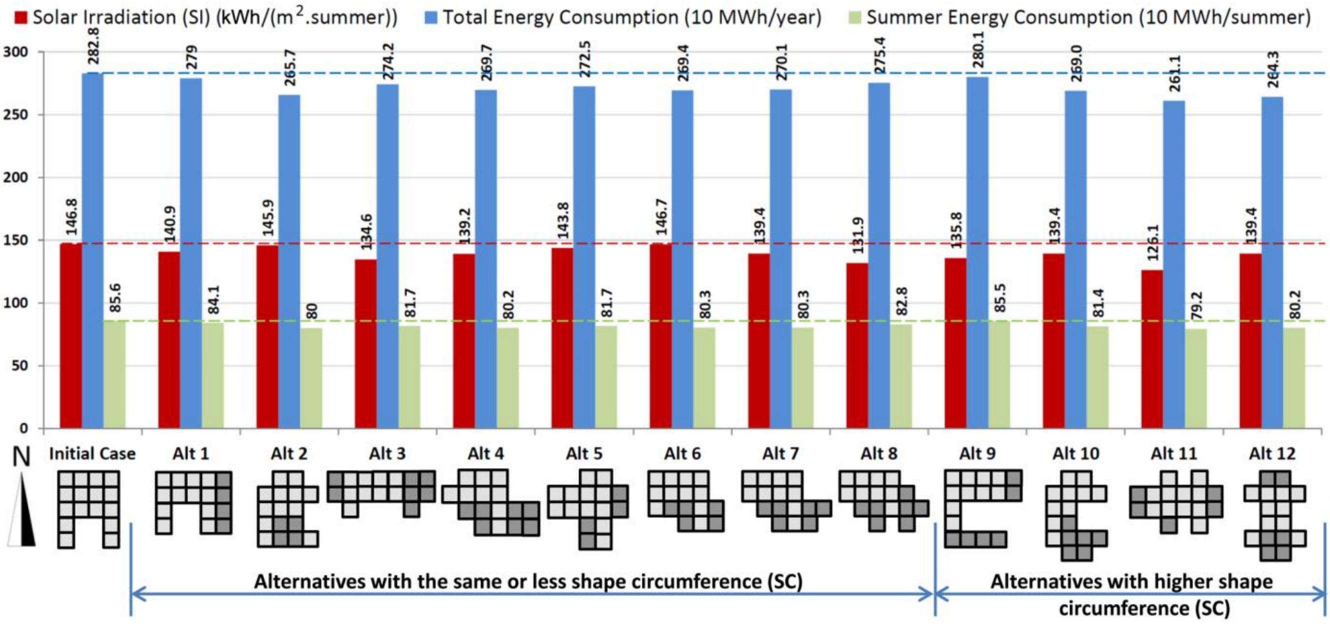


Fig 7. Analyses of the initial case and the generated 12 alternatives

However, it is important to compare this approach with the manual expectation of self-shading to demonstrate its usefulness and how far is needed; this manual expectation can be studied via the selections of designers to self-shaded alternatives in different levels. This is not confirming the results while it validates the approach usefulness. Accordingly, a questionnaire has been prepared for that to ask 30 designers to select self-shaded alternatives provided in 9 questions (MCQs). As shown in Figure 8, the questions have been designed to cover different treatments and ordered ascending based on their difficulty using the number of choices. The significance between higher and lower SI values is considered to be varied from 28% to 5%. However, it was requested from questionnaire takers to choose the best and worst alternatives from self-shading perspective; the alternatives provided in each single question have the same SA and SC, so designers are asked about self-shading (either SI and ASI since they are directly proportional) without integrating other variables. Hence, 30 architectural designers\academic members with different experience levels but minimum knowledge of environmental control basics and the location climate completed the survey; their classifications has equivalent distribution as shown in Figure 9. By analyzing the survey results as shown in Figure 10, 38% is the percentage average of choosing right selections in the whole survey, which means that the ability of expecting the best self-shaded BLSs cannot exceed some limits / integrated details. Furthermore, the effect of treatments' orientation is not easily expected as shown in question 1 and 8; the right selections represent 43% in question 1 (2 choices), while they represent 40% and 30% in choosing best and worst BLs in question 8 via 4 choices), respectively. The effect of cavities' ratios and numbers are easily expected, as shown in question 2 and 3 that represents 97% and 80% right selections, respectively, the worst alternative in question 6 achieved high right selections also (63%). By analyzing selections in question 4, 5 and 6, it is obvious that selections were mainly based on facing or cavities on west and south orientations only and this expectation is not right in all cases, for example, best alternatives in question 4 and 5 ((a) and (b) respectively) were rightly selected by few designers, also 85% of the selections in question 5 went to choice (c) as a best alternative although it is the worst one in the question. Since question 9 is the hardest one (highest number of choices and lowest significance between alternatives), around two thirds of the selections went to a wrong best and worst alternative.

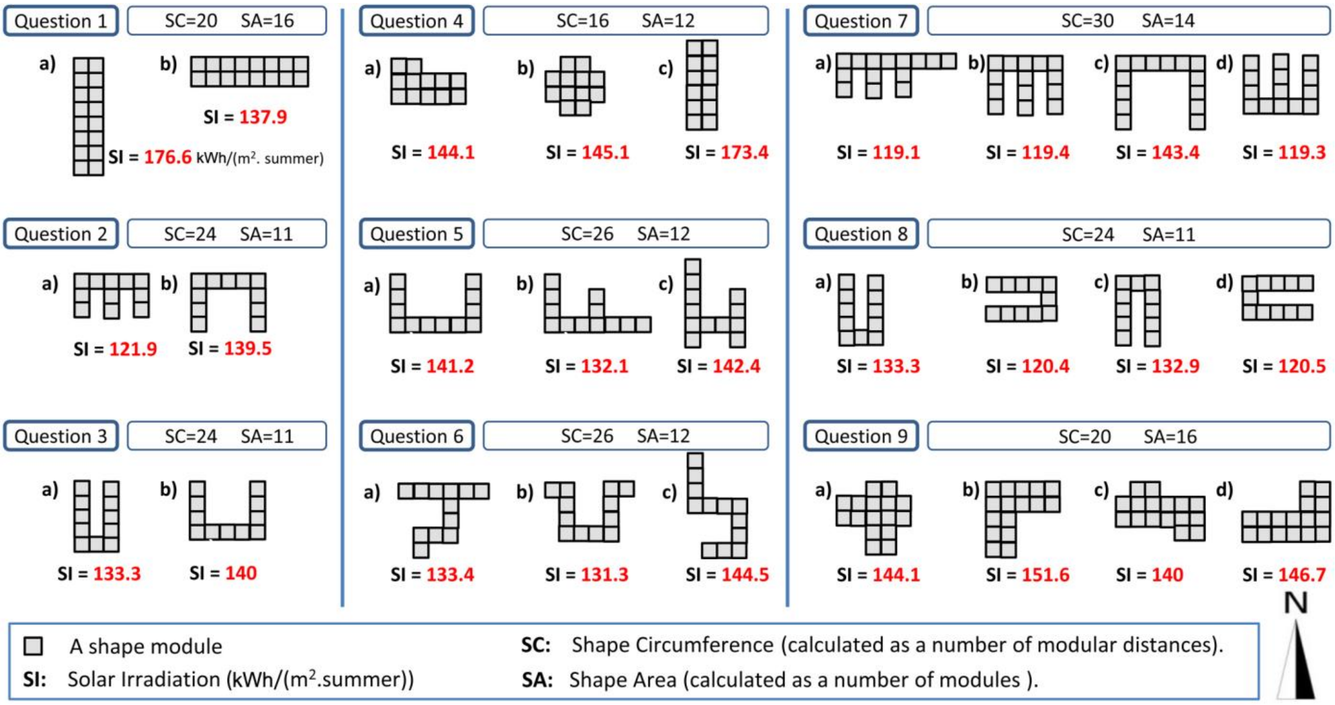


Fig 8. The questions and alternatives used in structuring the survey

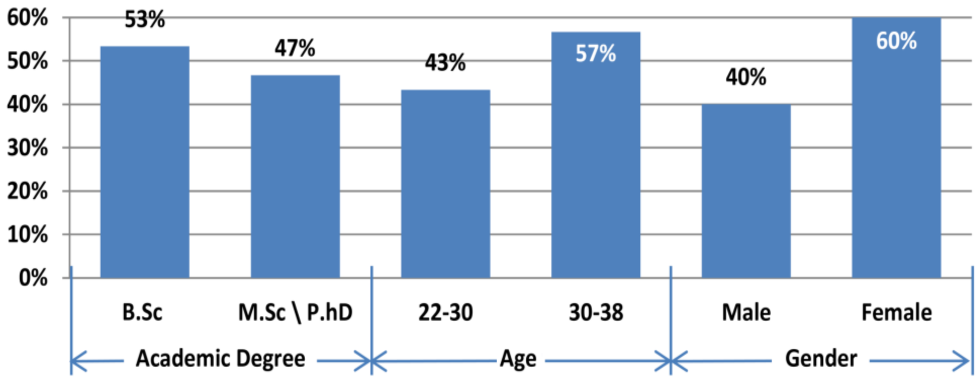


Fig 9. The specifications of questionnaire takers

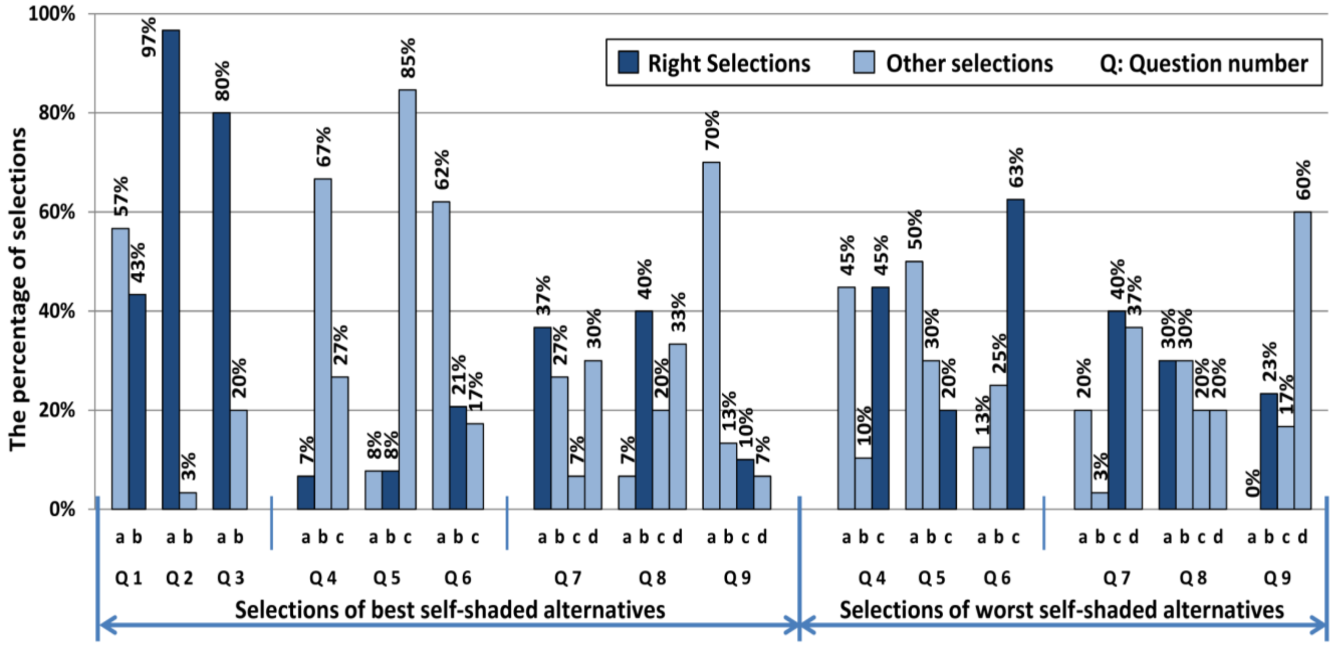


Fig 10. The designers' selections in the conducted survey

VI. DISCUSSION

The main contribution of the presented approach are: a) achieving alternatives with better self-shading facades with considering SA and SC as required without using shading devices at all - which may be a followed/an additional step if needed; b) automating the optimization of BLSs using SG theory that can be easily extended to a computational tool; c) using the simulation results of these treatments directly in design cases; d) using the simulation results to calculate easily SI average of any cubic layout using the values of its particular components without needing to simulate the case individually; and e) selecting optimal treatments and their ratios in each orientation through 320 different treatments to be utilized by designers. As limitations, the proposed approach is not suitable for: a) optimizing all cubic layout; cavities and protrusions may not be suitable to be applied on BLSs with narrow widths for instance; b) curved or free BLSs; while it may be extended easily to include other cubic varieties; c) detailed BLSs in specific cases; d) different climate zone; the results may be affected and best treatments may be changed accordingly; e) low building heights; then building height will be more sensitive, not fixed as studied, since SI in cavities can then be gained from the building roof, accordingly self-shading may be prevented; f) studying buildings with surrounded/affecting neighbours and/or in a specific context; although neighbours and urban contexts will provide extra self-shading, this will affect the selection of best treatments to that case specifically; and g) judging the performance before the processes especially if the same SA and SC are required within the optimization; many treatments then have to be extracted or applied (not only the best ones) then tested after the optimization, while direct modifications can be predicted earlier.

Based on the simulation treatments, all corner indentations (R.1, R.2, R.3 and R4) can decrease both SI and ASI in different orientations, although the optimization is not sensitive since all of them are simple modifications to the building corners. Furthermore, these corner indentations should be used for optimizing ASI since no difference in SC are applied with allowing direct self-shading in 2 facades (top 15 rules reducing ASI are in groups R.1, R.2 and R.3). To reduce SI regardless ASI, narrow cavities (groups R.7 and R.8) are recommended; this is reasonable since more self-shaded in two sides are added instead of a direct orthogonal orientation. On the other hand, the majority of other indentations (R.5 to R20) decrease SI and/or increase ASI with different percentages; these rules can still be utilized in the generation process by: a) replacing them from initial BLS with any other better rules; b) applying them beside other better rules to get alternatives with lower SI and/or ASI in total; c) applying them to decrease SI only with an acceptable increase in ASI caused by the increase of SC; the increase of SC is already recommended architecturally from many perspectives such as approaching the external view, daylighting, ventilation and others.

The 12 generated self-shaded alternatives through the conducted application matched also an energy consumption optimization annually and in summer months; which confirm the BLS optimization due to the relation between both self-shading and energy consumption as referred via other studies. With comparing that with the designers' selections to better self-shaded BLS, the survey results present that: a) the proposed approach is useful and needed to conduct right selections among alternatives due to the number of right selections, which means that the ability of expecting the best self-shaded within the surveyed sample cannot expect some details of best self-shaded BLSs. For example, some treatments are easy to be expected manually such as the effect of cavities' ratios and numbers, while the effect of treatments' orientation is not easily expected; and b) the majority of designers' selections went to facing or cavities on west and south orientations, which is reasonable, while it was not always the right selection in different cases.

VII. CONCLUSION

This paper introduces a novel optimization approach for reforming high-rise BLSs towards better self-shading computationally, along with the determination of different treatments to be applied using SG theory. High-rise buildings in Egypt, as a hot climate zone, are used to demonstrate the proposed approach and test its applications. The paper started with introducing how alternatives can be optimized especially through SG theory, and then an application on an initial case has been conducted. The approach framework starts with an initial BLS, as an input, to be optimized towards self-shaded alternatives. Accordingly, a pool of 320 SG rules has been developed and simulated via Autodesk Revit to be used; these rules include cubic treatments with different ratios, orientations, level of modification, and accordingly different BLSs are developed or created with applying suitable rules selected for the case. The main variables that can be controlled in the generation process of alternatives are SI (kWh/ (m^2. summer)), SC, ASI accordingly, SA and number of modifications; SI has been used to measure self-shading on building surface. Based on the inputs, rules can be ranked based on their effect on SI and ASI on that case and accordingly to generate a number of alternatives. SI of initial BLS and its alternatives can be simulated computationally with any suitable simulation tools or calculated partially using the simulated treatments.

The proposed approach has been demonstrated via an application using a high-rise BLS in Cairo, Egypt, and accordingly 12 better self-shaded alternatives have been generated; all these alternatives have the same SA of the initial case and some of them have the same or less SC, however, all alternatives have been optimized. If higher SC is allowed, SI is also decreased while ASI may be decreased only in some alternatives. The initial case and its 12 alternatives have been also tested using eQuest (DOE 2) to check the effect of the added self-shading on their surfaces; all self-shaded alternatives in the application have also less energy consumption compared with initial case that has the same area, and the lowest alternative achieved 92% of the annual and summer energy consumption of the initial case. Also, the proposed approach has been compared with the manual expectation of self-shading to demonstrate its usefulness and how far is needed; this has been conducted via a questionnaire that asks 30 designers to select best and worst self-shaded alternatives provided in 9 questions (MCQs). The average of choosing right selections only equals 38%, so according to the survey, the approach is useful for many designers since the ability of expecting the best self-shaded within the surveyed sample is limited if different treatments are integrated, also the effect of cavities' ratios and numbers can be easily expected, while the effect of treatments' orientation is not.

This approach can help designers in achieving automated and/or selecting self-shaded BLSs that suits their design cases without needing to test single trials; all generated alternatives are applicable so designers can select directly among them. Also, the approach presents other contributions such as using the simulation results of these treatments directly in design cases or to calculate easily SI average of cases. The proposed approach is not suitable for optimizing few detailed cubic cases, curved or free BLSs, different climate zone, low building heights or studying a building with affecting neighbours. The developed computational framework can be easily extended to be a computational tool with a friendly Graphical User Interface (GUI), and it may include a 3D environment (e.g., via a SketchUp interface) with more intelligent and interactive features. Furthermore, the proposed approach can be extended to include other varieties, options and building envelope features, such as more available modifications (e.g., facade tilting), treatments (e.g., twisting, revolving, etc,) and criteria to be optimized (e.g., thermal comfort, daylighting); this will generate accordingly different sets of alternatives in shapes and performances. Moreover, the optimization limitations can be exceeded towards wider scopes; such as considering surrounding buildings and site inputs rather than free buildings as studied; this will lead to the development of a new urban, built environment and architectural design processes for self-shaded alternatives, and more architectural creativity should be included then.

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Title Arabic:

تحسين أشكال المبانى نحو أنسب تظليل ذاتي: منهجية حاسوبية

Arabic Abstract:

تحظى المباني المظللة ذاتيًا باهتمام كبير خاصة في المباني المرتفعة بالمناطق المناخية الحارة. يقدم هذا البحث إطار جديد لتحسين أشكال المباني المرتفعة نحو انتاج بدائل أكثر إظلالاً ذاتيًا من الشكل المراد تحسينه، بالإضافة إلى تحديد المعالجات المختلفة لتحسين أى شكل معطى وذلك باستخدام "نظرية قواعد الأشكال"، وتمت المحاكاة لأداء البدائل باستخدام برنامج (Autodesk Revit). تشمل المتغيرات التي تم أخذها في الاعتبار أثناء عملية انتاج البدائل: معالجات مختلفة ونسبها وتوجيهاتها المتعددة، وكذلك التحكم في مساحة الشكل ومحيطه عندما يلزم. تم استخدام نماذج مختلفة من المباني المرتفعة في مصر لإظهار المنهج المقترح والتحقق من تطبيقاته. تظهر نتائج الدراسة - ومن خلال عدة تطبيقات – إمكانية المنهج المقترح من انتاج بدائل أفضل إظلالاً بشكل ذاتي من المبنى المعطى المراد تحسينه مع التحكم في المتغيرات سالفة الذكر إن لزم. تم اختبار هذا التحسين أيضًا من منظور استهلاك الطاقة على ١٢ بديل، وكذلك تم التحقق من عائد المنهج المقترح من خلال مردود مصممين معماريين. يمكن أن يساعد المنهج المقترح المصممى المعماريين في تحقيق أفضل إظلال ذاتي للمباني قيد التصميم والتي لا يمكن انتاج بدائل لها مباشرة عبر عمليات المحاكاة الفردية.