ABSTRACT

Generative design systems have contributed in liberating the limits of design exploration, allowing designers to explore various design solutions. In this paper, we used one-dimensional cellular automata (CA) to generate an optimized solar screen in a south oriented classroom for efficient daylighting performance. We used Grasshopper for the modeling process, and Diva-for-Rhino, which interfaces with Radiance, to evaluate daylighting performance based on the IES approved method. CA rule number 210 was specifically employed to develop the necessary parameters for form generation where 847 different cases were examined. Results of this research demonstrated the potential of CA in achieving the intended visual aspects and daylighting requirements.

INTRODUCTION

A paradigm shift has occurred in design thinking where performance requirements control the decision making process. This shift has also offered the designer with the power of generative systems. In architecture, the use of generative systems can support design exploration in such a way that expands solution space for a multitude of formal iterations while satisfying and optimizing performance requirements. This approach is known as ‘Generative Performative Design’ where both form and performance requirements drive the generation process (Fasoulaki, 2008).

The concept of generative systems implies the use of codes and rules often merged with parametric modelling tools. Thus, they have the power to generate forms ranging from the simplest to the most complex through component-based software, where no need of programming or scripting experience is required (Milena & Ognen, 2010).

The increasing tendency to adopt generative systems in architectural design owes to a number of reasons: the automated non-monotonic methods for form generation; the exploration capabilities of large design spaces; the possibility of design optimization; high efficiency; reduction of labour and time and hence decreasing cost (Singh & Gu, 2012). Besides, generative models offer a high level of interaction and control over the digital representation and their operative part (Oxman, 2006). However, they lack the capability of meeting performance requirements without explicit integration with optimization and simulation techniques.

The need has therefore emerged in façade design for the ‘generative performative design’ approach, where performance acts as the driving engine behind the development of the generative technique. A few attempts have recently integrated the implementation of generative systems in a performance-based context. For instance, (Kotsopoulos, Casalegno, Carra, Graybil, & Hsiung, 2012) used shape grammars to generate electrochromic façade patterns on the southern façade of a house prototype while complying with visual and daylighting illuminance needs.

Other efforts, including (Zawidzki, 2010), (Zawidzki, 2009), and (Kim, 2013), integrated cellular automata (CA) to devise fenestration design strategies that comply with daylighting requirements. In these examples, daylighting as a performance criterion was the driving engine behind the formulation of shading systems for building facades, aided by the enhanced design exploration possibilities of CA; a well-known generative system that imparts a sense of visual quality and guides form generation (Wolfram, 2002).

None of the previous work however examined all possible parametric combinations in one exhaustive list, which are presumed to further extend the design explorations used to evaluate daylighting performance (Wagdy & Fathy, 2015). This was not common due to computational burden; however, we overcome it by using a parallel algorithm recently developed by the last author.

In this study, the goal was to achieve adequate daylighting illuminance levels in a south oriented classroom space using CA patterns. The generative flexibility of CA was capitalized on in order to set the resulting design alternatives free from monotonous and static prototypes, where geometrical forms are defined by fixed numerical values to produce and evaluate multiple alternatives. The rules and instructions that govern the geometric attributes and their relationships were based on two main aspects: daylighting adequacy and avoiding direct sunlight.

The paper aimed at capturing performative constraints to encode them by using CA parameters that comply with the IES approved method while controlling visual aspects.
METHODOLOGY
In this paper, both designers’ intentions and daylighting performance criteria govern the CA pattern generation. The form generation process complied with daylighting performance criteria using three main modules: a generative model, a simulation program, and an optimization algorithm. We used one-dimensional cellular automata to generate screen patterns for the façade of a classroom building, and then conducted a simulation to evaluate all possible generated forms through an exhaustive search method (Daintith & Wright, 2008; Wagdy & Fathy, 2015). Rhinoceros 3D modelling software and its graphical algorithm editor Grasshopper (Rutten, 2014) were used as a common platform for CA pattern generation and modelling daylighting simulation analysis, and optimization.

Screen Modelling
Rabbit plug-in for Grasshopper (Morphcode) was used to simulate the emergent behavior of cellular automata in the process of generating the screen patterns. We applied one-dimensional CA on a regular square grid. Each row represents a state of a time step forming an array of cells that show the history of generations, as shown in Figure 1. For each CA rule, a number of parameters were identified to explore their variations on daylighting performance. In this study, three parameters were varied, which are:
1. Cell depth; it ranges from (15 to 45) cm with a 5cm increment.
2. Black count; it ranges from (5 to 15) black cells, which indicates opacity that ranges from 20% to 60%.
3. Displacement value; which indicates the pattern shift in the X direction, as shown in Figure 3. The displacement ranges from (0 to 20) with an increment equal to 2 cell units, while cell size was fixed to 30 cm.

Rule Selection
According to (Zawidzki, 2009), eighteen one-dimensional CA rules were classified under the repetitive class, justifying their suitability for shading applications. In this set of rules, the opacity level of the whole CA array is proportional to that of the initial row condition. As shown in Figure 1, the initial black count, which was randomly set, controls the opacity of the whole array. All of the eighteen generated patterns shown in Figure 2 may have the same potential for diffusing daylight; however, we chose only one rule (210) to examine its efficiency on a south oriented façade in such a clear sky of Cairo.
Logic of CA Rule 210

Cellular automata was formed by an array of regular cells, where each has two possible states (0 or 1). In one-dimensional CA, the state of each cell depends on its previous state and its two adjacent cells in the previous time step. Hence, for the subsequent time step, the cell becomes ‘off’ or ‘on’ based on $2^3 = 8$ possible reference states, as shown in Figure 4. The total possible arrangement of the cell states relative to the eight references is $2^8 = 256$ cases or rules, ranging from rule 0 when all eight states are off, and rule 255 when all cell states are on. The naming logic of each rule returns to this arrangement. As shown in Figure 4, in rule 210, each ‘alive’ cell had a corresponding value that we added to form the rule name.

Daylighting Evaluation Criteria

Daylighting simulation analysis was conducted using Diva-for-Rhino; a plug-in for Rhino which acts as an interface for Radiance and Daysim for daylighting calculations (Solemma, 2014).

This study complied with the approved IES metrics mentioned in their report number LM-83-12 (IESNA, 2012). This method introduced two metrics, which are Spatial Daylight Autonomy ($sDA_{300/50\%}$) and Annual Sunlight Exposure ($ASE_{1000/250hr}$), giving absolute benchmark levels for the pass or fail criteria.

The first metric ($sDA_{300/50\%}$) gives an indication of daylighting adequacy inside the space, where a minimum illuminance of 300lux is meant to be reached at 50% of the occupied hours across at least 55% of the space area. The second metric ($ASE_{1000/250hr}$) indicates excessive sunlight exposure when receiving direct sunlight of 1000lux for more than 250 hours. This should not exceed 10% of the space area. For this study, optimal cases have to reach at least 75% $sDA$ and a maximum value of 3% $ASE$ to avoid possible visual discomfort due to sun penetration.

Classroom Configuration

The study was conducted on a generic south oriented classroom space located in the desert climate of Cairo, Egypt (30°6'N, 31°24'E, alt. 75m) with no external obstruction. The classroom configuration and parameters for the classroom space, window and screen are shown in Figure 5 and Table 1 respectively. Radiance parameters used for $sDA$ and $ASE$ calculations were set according to the IES as shown in Table 2.
RESULTS AND DISCUSSION

Examining all possible solutions and design alternatives of the façade screen allowed for investigating the impact of each variable on the required daylighting performance. Besides, it demonstrated clearly the effect of each variable on the other. By combining all possible values for each variable, seven values for depth lengths, and eleven values for black count and displacement, we evaluated in total 847 different cases.

A number of findings emerged from the simulation process. First, cell depth proved a large impact on daylighting performance. Both sDA and ASE decreased as the depth increased, as shown in Figure 4. However, it was required to decrease only ASE while increasing sDA. For large depths ranging from 35 to 45 cm, ASE succeeded to maintain its maximum threshold (3%); however, sDA did not exceed the minimum required value (75%). sDA exceeded 75% while maintaining the low ASE level only at a depth value of 35cm and by decreasing black count as illustrated in the adequate performance area. As for small depths ranging from 15cm to 25cm, sDA exceeded 75% at all black counts; on the other hand, ASE was too high reaching up to 46%. A compromise between the advantage of large depths in decreasing ASE and small depths in increasing sDA was found at a depth value of 30cm. We reached about 76% of the successful cases at this depth value. Since the cell size was fixed at 30cm, a correlation between cell size and cell depth was deduced, where the optimal results were realized mainly at depth ratio 1:1. Searching all possibilities, we found that sDA and ASE passed their benchmarks at both cell depth of 30cm and 35cm, as shown in Figure 6.

Table 1
Parameters of the classroom, window and screen

<table>
<thead>
<tr>
<th>SPACE PARAMETERS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Floor Level</td>
<td>1st floor (+365cm)</td>
</tr>
<tr>
<td>Room Area</td>
<td>48m²</td>
</tr>
<tr>
<td>Floor Height</td>
<td>320cm</td>
</tr>
<tr>
<td>INTERNAL SURFACES REFLECTANCE</td>
<td></td>
</tr>
<tr>
<td>Ceiling</td>
<td>80%</td>
</tr>
<tr>
<td>Walls</td>
<td>50%</td>
</tr>
<tr>
<td>Floor</td>
<td>20%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>WINDOW PARAMETERS</th>
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</thead>
<tbody>
<tr>
<td>Window to wall ratio (WWR)</td>
<td>70%</td>
</tr>
<tr>
<td>Sill</td>
<td>100cm</td>
</tr>
<tr>
<td>Window height</td>
<td>220cm</td>
</tr>
<tr>
<td>Window width</td>
<td>800cm</td>
</tr>
<tr>
<td>Glazing</td>
<td>Double Clear Pane (VT=80%)</td>
</tr>
<tr>
<td>Window Frame</td>
<td>Metal Diffuse</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>SCREEN PARAMETERS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Screen Reflectivity</td>
<td>35%</td>
</tr>
<tr>
<td>Cell Size</td>
<td>30cm</td>
</tr>
</tbody>
</table>

Table 2
Radiance parameters for sDA and ASE calculations

<table>
<thead>
<tr>
<th>EVALUATION METRICS</th>
<th>AMBIENT BOUNCES</th>
<th>AMBIENT DIVISIONS</th>
<th>DIRECT THRESHOLD</th>
</tr>
</thead>
<tbody>
<tr>
<td>sDA</td>
<td>6</td>
<td>1000</td>
<td>0</td>
</tr>
<tr>
<td>ASE</td>
<td>0</td>
<td>1000</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 1 sDA and ASE values for all depth lengths and black counts at displacement 2
Figure 2 The effect of black count on sDA at all depth lengths showing successful cases at displacement 2

Figure 3 The effect of black count on ASE at all depth lengths showing successful cases at displacement 2
Second, the black count, which denotes the opacity of the whole array, showed its remarkable effect on decreasing sDA at large depth values, where it suffered a sharp decrease at large depth values. On the other hand, it had a little effect on ASE, where it appeared constant at large depth values, as shown in Figure 7 and Figure 8. For instance, at depth length 35cm, sDA decreased from 91% at black count 5 to 26% at black count 15, while ASE decreased by only 1%. Conversely, at small depth values, increasing black count had a significant effect on decreasing ASE. However, it was not large enough to reach the required value.

In contrast, sDA slightly decreased and still maintained its large values. For instance, at depth length 15cm, ASE decreased from 44% to 35% while sDA decreased by only 2% to reach 98% at a black count of 15. The only case where black count had no considerable impact on both sDA and ASE was at depth value of 45cm, where sDA was too low; even at the lowest opacity where sDA reached only 26%. Besides, it had no impact on ASE at large depth values where ASE reached a bottom. In short, black counts ranging from 5 to 13 showed a success in reaching a balance between the required low ASE value and large sDA value at depth values 30cm and 35cm, as shown in Figure 7 and Figure 8. These values implied screen opacity ranging from 20% to 50%.

The last variable examined was pattern displacement. This variable showed no effect on daylighting performance, where 95 cases succeeded to pass the required criteria across all the eleven displacement values. Since they had a similar effect on daylighting performance, the previous analysis was concerned with explaining only one displacement value. In Table 3, we exemplify one optimal solution with 100% sDA and the lowest possible ASE to show the effect of screen configuration on daylighting distribution.

To sum up, searching all possible alternatives could sometimes be impractical due to computational capabilities; however, it provided the advantage of finding a large range of solutions that can be further refined using any other criteria or constrains. Besides, it indicates the implicit relationship between geometric attributes and the intended performance criteria. In this paper, we varied three parameters; screen depth, opacity, and displacement through a predefined set of ranges, and their correlation with daylighting performance was explicitly stated.

Both screen depth and opacity proved their significant effect on daylighting and their interrelation in reaching a trade-off between the two conflicting objectives: providing sufficient daylight and avoiding direct sunlight. Displacement value however showed its indifference on daylighting performance, so we can decide on its value according to visual intentions.

### CONCLUSION

The exhaustive search method in this case study contributed in reaching optimum daylighting performance, allowing for the examination of 847 cases formed by all parametric combinations. Owing to parallel computation, it became applicable to search the whole solution space. In addition, exhaustive search enriched the study with clear identification of the contributions of each variable and their interaction in enhancing daylighting performance. The depth ratio of 1:1 was the most successful in reaching a balance between avoiding direct sunlight and providing adequate daylight.

Cellular automata has proven its applicability in reaching a range of satisfactory results for static building facades. Having the results of CA rule 210 as a pilot study, more insights about the effective parameters and their range of values can be deduced. Thus, other CA rules can be explored effectively without the same computational demands. Yet, other generative systems need application within the same methodology to explore their effectiveness in satisfying designers’ intentions and required...
daylighting performance. Further work can apply other optimization methods such as genetic algorithms to benchmark their robustness in reaching optimal solutions for similar case studies. In addition, the achieved optimal solutions are merely the optimum from the perspective of daylight alone. Other domains such as energy loads, cost, and fabrication could influence the selection criteria. We intend to consider these aspects in future work.

REFERENCES


