DAYLIGHTING DRIVEN DESIGN: OPTIMIZING KALEIDOCYCLE FACADE FOR HOT ARID CLIMATE

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ABSTRACT
Facade design has significant impact on daylight. This paper presents a facade based on origami: kaleidocycle rings that can be morphed enhancing daylight performance in residential spaces, which complies with both LEED V4 and Daylight availability. Daylighting analysis was integrated using Grasshopper, Diva and Genetic optimization for a south-oriented living room facade in Cairo, Egypt, through two phases. First phase dealt with base cases of specific typology. Second phase was conducted using parametric optimization process. Results demonstrate that Kaleidocycle rings of 30 cm size and 64 rotation’s angle reached results that exceed LEED v4 requirements while passing Daylight availability standards.

INTRODUCTION
As the world gives increased focus on energy efficiency and occupant comfort, there is now an emerging need to include sustainability–related performance aspects within design, most notably energy and daylighting (Lagios et al., 2010). Façade openings play an important role in providing daylight, which is considered the best source of light that matches human visual response and required colour. Thus, they have a substantial positive impact on the occupants (Li & Tsang, 2008). More recently, New methodologies have been developed to use daylight simulation as a driven tool for design, which showed the benefits of parametric driven façade to reach maximum daylight quality.

In this research; daylighting will be the key performance criteria to design non-simplified double façades using parametric design and optimization tools for residential spaces. The paper presents initial findings of an ongoing research.

Daylighting in residential spaces
Daylight is an important element for residential spaces that can contribute to maintain the minimum illuminance level required to improve indoor environmental quality and user comfort. The benefits of a carefully planned daylighting concept range from an enhanced lighting quality for the inhabitants to a reduced artificial lighting consumption (Reinhart, 2001). Significant energy savings can be gained if the design process encompasses thoughtful daylighting strategies incorporated into the design process on the early design phases (Jason & El Sheikh, 2011).

Daylight Autonomy
Daylighting design is a key aspect of building rating systems such as Leadership in Energy and Environmental Design system (LEED). It uses metrics such as Daylight autonomy (DA), which is the percentage of annual work hours during which all or part of a building’s lighting needs can be met through daylighting alone (Reinhart et al., 2006).

Two metrics in LEED v4 are codified for evaluating daylight autonomy design, which allow a daylit space to be evaluated for a one year period using two different performance parameters: sufficiency of daylight Illuminance and the potential risk of excessive sunlight penetration (IES, 2012). These two metrics are: Spatial Daylight Autonomy (sDA) and Annual Sun Exposure (ASE) metrics, which forms together a clear picture of daylight performance that can help architects to make good design decisions. sDA describes how much of a space receives sufficient daylight, which is for residential spaces must achieve (sDA 300 lux / 50% of the annual occupied hours) for at least 55% of the floor area as shown in Table 1. sDA has no upper limit on luminance levels, therefore, ASE is used to describe how much of space receives too much direct sunlight, which can cause visual discomfort (glare) or increase the cooling loads. In LEED v4 ASE measures the percentage of floor area that receives at least 1000 lux for at least 250 occupied hours per year (C.Sterner, 2014), which must not exceed 10% of floor area (USGBC, 2013).

<table>
<thead>
<tr>
<th>sDA (for regularly occupied floor area)</th>
<th>Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>55%</td>
<td>2</td>
</tr>
<tr>
<td>75%</td>
<td>3</td>
</tr>
</tbody>
</table>
Hybrid Double Façade

Egypt’s climate is classified as hot desert arid climate according to Köppen’s climate classification system (Peel et al., 2007). It is characterized by high direct solar radiation and clear sky which demands special façade treatments to minimize heat gain while providing appropriate daylighting.

Double-skin façades are one of the building’s envelope solutions that can improve indoor climate while reducing the use of energy if designed properly (Poirazis, 2006). Traditional double façade types of buffer, twin face and extract-air, where the exterior layer is glazed, have been evolved for hot arid climate resulted in a hybrid approach which employs a shading screen as the exterior face coupled with a high performance curtain wall system as the interior layer of the façade (Boake, 2014). Energy savings are dependent on the specific configuration of the exterior shading screen. Screen patterns, tessellated layers, cellular units or origami crease patterns may present efficient solution to minimize heat gain while providing appropriate daylighting.

Origami-Based Design

Recently building skin explorations are carried out using inspired new ideas of the ancient art of origami. Origami offers a finite set of paper-folding techniques that can be cataloged and tested with parametric modeling software. Origami is based on the sequence, shape and relationship between surface and points which can be defined by rules (Figure 1). It can be viewed as a type of manual algorithm that can be translated to parametric models (Gao & Ramani).

![Figure 1: Origami forms based on geometrical rules and folding morphology.](image1)

Many origami planar explorations of the triangulated-based skins have been tested rather than volumetric 3d folding explorations. Lee & Leounis (2011) presented a surface manipulation tool that can transform the arrangement of folding planar surfaces, while Crawford (2010) studied a family of folding geometry to provide ventilation using parametric modeling. On the practical platform, the 25-story twin office towers in the United Arab Emirates feature a computer-monitored and sensor-controlled screen as shown in Figure 2, which responds dynamically to the sun, folding like origami to shade or expose the building.

![Figure 2: Al Bahar Towers in Abu Dhabi by Aedas, The folding shading system, opens and closes according to sun's position.](image2)

Gao & Ramani presented initial prototypical explorations for 3d folding as well as the associated transformative design concept called Kaleidogami. This method is used for developing spatial objects that can be flattened, folded and reconfigured. They developed the concept for a tetrahedral basic structural unit to enable new forms of 3D folding. By rearranging, combining and reconfiguring, one can obtain different configurations with tetrahedral basic structural unit or shape variation of folding representation, encompassing multi-primitive and reconfigurable foldable units (Figure 3).

![Figure 3: Tetrahedral basic structural unit exploration (Gao & Ramani).](image3)

Kaleidocycle Skin: Concept and Approach

Rotating rings of tetrahedrons called kaleidocycles are well known from recreational mathematics. Each tetrahedron in the cycle is linked to its predecessor and successor at opposite edges. The mobility criterion treats each tetrahedron as a rigid object (Fowler & Guest, 2005).

There is a lot of different kinds of kaleidocycles but the most rigid, stable yet interesting is the Hexagonal Kaleidocycle. Moloney experiments with pattern showed that increasing the number of edges beyond six proved counterproductive, as edge differentiation became harder. Moreover, the hexagon provided a relatively neutral orientation when a large number were combined in an offset (Moloney, 2011). A closed Hexagonal kaleidocycle is tested which is made up of six irregular tetrahedrons with three symmetry-distinct configurations (Fowler & Guest, 2005). These must be made so that: the hinge edges are orthogonal, and bases of isosceles triangles whose altitudes to the vertex angles are the same length as their bases.

The kaleidocycle skin is a mix of triangular and hexagon shapes that provide good edge detection and reasonable shading detection. The primary concept of the proposed skin, shown in Figure 4, is that when it rotates, the hole at the center periodically disappears (it closes up) to control different levels of daylight.
penetration using parametric modelling tool. The kaleidocycles are scripted to act as apertures, with a variable hole opening diameter, which will be optimized to improve daylighting performance.

Figure 4: Shows the Kaleidocycle rotation motions.

Parametric modelling potentials

Parametric tools in architecture have been gaining momentum over the past few years. The term refers to digitally modeling a series of design variants whose relationships to each other are defined through mathematical operations and different parameters. These relationships form a parametric space that could generate numerous of related but distinct forms (Schumacher, 2009). This new design approach provides architects with the possibility of making modifications on any parameters without the need to recreate the entire model (Wagdy, 2013), and offering a great potential for geometric design explorations. Using this approach provides architects with a high ability to optimize buildings with respect to various performance aspects. The impact of such a trend is yet to be seen on building forms and envelopes and their behavior with respect to different climate.

Grasshopper

In recent years, the design professions have begun experimenting with parametric design tools such as Grasshopper which was developed by David Rutten at Robert McNeel & Associates in 2007 as a parametric modelling plug-in for Rhinoceros 3D modeling software (McNeel, 2010). Grasshopper is a graphical algorithm editor that allows designers with no formal scripting experience to quickly generate parametric forms from the simple to the awe-inspiring (Day, 2009) as there are components within Grasshopper that allow custom scripts to be written in VB.NET or C# (Lagios et al., 2010).

Daylight simulation tools

Since green building rating systems such as the US Green Building Council’s (USGBC) LEED system encourage the use of simulations, designers are increasingly reporting that they are using daylight simulations within their designs (Gasiu & Reinhart, 2008).

There have been various plug-ins developed for Grasshopper that connect the Rhino geometry to simulation softwares. The Geco plug-in allows the digital model to be analyzed by Autodesk's Ecotect program (Frick & Grabner, 2011). Similarly, DIVA, which stands for Design Iterate Validate Adapt, for Rhinoceros 3D tools, and provides Grasshopper components to perform daylight analysis on an existing architectural model via integration with Radiance and DAYSIM (Reinhart et al., 2011).

Parametric simulations can give an idea of the variation in daylighting performance related to the variation of one or more parameters (Torres et al., 2007).

Genetic optimization algorithms

Optimization in building design is an interesting point of study because of the integrated nature of both environmental and energy performance. It is used to extensively search the design alternatives looking for high performance solutions in terms of specified goals. The simulation-based optimization can overcome the drawbacks of evaluative trial and error approach. In order to combine parametric modeling with an optimization technique to support design explorations and form finding, Genetic algorithms (GAs) have been considered. GAs can perform a series of simulations in a multi-dimensional search space, increasing the relevance of the cases simulated. They are used to find the configuration that best matches desired performance goals (Monks, Oh, & Dorsey, 2000; Turrin, Buelow, & Stouffs, 2011; Rakha & Nassar, 2011).

Genetic algorithms were shown to be effective in presenting new solutions to optimize light penetration and shading, taking into account many different aspects that influencing the performance of a façade (Zemella et al., 2011). The prediction of daylight levels by model-fitting was addressed by Coley and Crabb (Coley D, 1997) using genetic algorithms. Park et al. also (Park et al., 2003) maximised daylighting from a double-skin facade using non-linear programming. The principle was then developed into a real-time optimization program using genetic algorithms (Yoon et al., 2011).

The above literature review demonstrates that previous research did not present any case study which adopts the new LEED V4 daylighting simulation methodology, especially in hot climate conditions. Limited publications were concerned with the exploitation of window size and shading devises that control the solar penetration, and thus improvement of daylighting performance while diminishing the direct sunlight exposure could pave the way for their deploying better sustainable designs which can be appropriate LEEDV4 evaluation process.
OBJECTIVES

The main goal of this research was the enhancement of the daylighting of living room by employing a non-simplified shading technique formed by kaleidocycle rings. In order to achieve this goal, an objective was defined to identify ideal size/rotation of kaleidocycle rings by fulfilling both LEED V4 daylighting requirements and the Daylight Availability dynamic metric. Investigations focused on the use of parametric optimization approach to determine the “near-optimum” kaleidocycle configuration that suit living room space located in hot arid climate of Cairo, Egypt.

METHODOLOGY

The methodology implemented in this paper was divided into two successive stages. First stage focused on the analysis of daylighting performance for base cases with specific typology, while second phase is conducted using parametric optimization for different façade parameters to achieve the near optimum daylighting adequacy. The two phases used Diva-for-Rhino (a plug-in for Rhinoceros modelling software). DIVA uses RADIANCE and DAYSIM as its basic daylight simulation engines. Radiance and DAYSIM employ a reverse ray-tracing algorithm based on the physical behavior of light in a volumetric, three-dimensional model which should most accurately represent reality (Ward, 1994). RADIANCE/DAYSIM has been validated in many studies (Reinhart & Walkenhorst, 2001; Reinhart & Breton, 2009; Reinhart & Wienold, 2011). They represent accurately occupant comfort, behavior and the distribution of natural light in a space especially when compared to EnergyPlus (Ramos & Ghisi, 2010).

In this research, a sidelit space has been defined and constructed a base model on a hypothetical indoor residential space (living room) of 20 m² at the first floor, facing the south direction, which is located in Cairo, Egypt. Kaleidocycle rings will be applied to this south-oriented façade.

It should be noted that the reliability of the simulation results is dependent on a number of factors; the most notable of these is the modelling of the living room details and complex Kaleidocycle skin systems, as well as the geometrical and photometrical properties used. In order to improve the reliability of results, the suggested Kaleidocycle skin was modelled in full detail Figure 5. The properties of the living room, Kaleidocycle skin and the window were fully described in Table 2. Radiance renderings and visualizations of the tested solar screens were examined before simulation runs in order to ensure that the model geometry was correctly exported to the Radiance software.

Table 2: Parameters of the used living room.

<table>
<thead>
<tr>
<th>Indoor Space Parameters</th>
<th>Indoor Surfaces Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walls</td>
<td>Reflectance= 50%</td>
</tr>
<tr>
<td>Ceiling</td>
<td>Reflectance= 80%</td>
</tr>
<tr>
<td>Floor</td>
<td>Reflectance= 20%</td>
</tr>
<tr>
<td>Kaleidocycle</td>
<td>Reflectance= Metal diffuse</td>
</tr>
</tbody>
</table>

| Window Parameters       | VT= 80%                   |

Kaleidocycle Facade logic

Rhinoceros and Grasshopper have been chosen as a software platform to generate a parametric folding model focusing on solids’ motion, particularly, by which kaleidocycle transform from one configuration to another. The parametric model served as a mean for better understanding of the geometry of the rings.

Each Kaleidocycle ring motion is defined off the original geometry through a series of commands: rotate, move and mirror. Analyses of the movement of each ring in the system led to a discovery; it is possible to maintain the movement of the system by rotating along their axis of symmetry in order to open and close the skin. This allowed us to apply a closed cycle path of movement from end to end.

The parametric model starts with a hexagon, where each side of the hexagon represents the axis of symmetry for each tetrahedron. While simulating the movement of each ring the tetrahedrons must be kept connected edge-to-edge. The edges that are forming the tetrahedrons were generated from the vertex of the hexagon to be perpendicular / parallel to the hexagon plane. Each tetrahedron is drawn as surfaces joining the two opposite edges, rotating these edges from its mid points along an axe joining the midpoint with the center of the hexagon, while in the same time moving it towards or away from the center of the hexagon.

The concept of the proposed skin depends on the space created between the tetrahedrons as they rotate to open and close the Kaleidocycle rings. Different combinations of Kaleidocycle sizes and angle of
rotations led to different daylight performance. Those two variables are considered the main parameters of the design which were controlled with numeric sliders. Figure 6 shows various Kaleidocycle size configurations ranging from 20cm to 65cm for each unit with a step size of 5 cm, while Kaleidocycles with different rotation angels ranging from 0 to 90 degrees with a step size of 10 degrees are illustrated in Figure 7.

**Figure 6: shows the Kaleidocycle size configuration ranging from 20cm to 65cm (step size= 5 cm).**

**Figure 7 shows the Kaleidocycle rotation angels ranging from 0 to 90 degrees (step size= 10 degrees).**

**Simulation logic**

The simulation process that was conducted on this research can be considered as one of first application of LEED v4 daylighting methodology; the available graphical interface tools such as DIVA or Ladybug do not provide a straightforward procedure which can be used to evaluate the second criterion of Annual Sunlight Exposure (ASE), therefore the methodology which is presented in this research is original and follows precisely the Approved Method IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE) described in Illuminating Engineering Society report number LM-83-12.

The simulation process conducted in this paper complied with both LEED V4 daylighting requirements and Daylight availability (DA). LEEDv4 concentrates on (sDA) and (ASE) which were described before in the literature review. Three Daylight Availability evaluation levels were used: “daylit”, “partially daylit” and “over lit” areas. The “daylit” areas are those that received sufficient daylight at least half of the year-round occupied time. The “partially daylit” areas are those that did not receive sufficient daylight at least half of the year-round occupied time. The “over lit” areas are those areas that received an oversupply of daylight, where 10 times the target Illuminance was reached for at least 5% of the year-round occupied time (Reinhart & Wienold, 2011). This section is focusing on the recreation methodology that was used on this research.

**Spatial Daylight Autonomy (sDA)**

The simulation parameters was set to measure daylight Illuminance sufficiency for the living room, DIVA parameters were set to calculate the percentage of analysis points that exceeds a specified Illuminance level (300 lux) for at least 50% of the total occupied hours from 8am-6pm over the year (IES, 2012), while the percentage of sDA should be at least 55% or 75% to achieve 2 to 3 LEED points. However, the authors used an optimization approach to maximize the percentage of sDA more than 75%. For sDA and Daylight availability metric Radiance parameters were set as shown in Table 3.

**Table 3: The Radiance parameters set for sDA and Daylight Availability metric.**

<table>
<thead>
<tr>
<th>Ambient bounces</th>
<th>Ambient Divisions</th>
<th>Direct threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>1000</td>
<td>0</td>
</tr>
</tbody>
</table>

**Annual Sunlight Exposure (ASE)**

Annual Sunlight Exposure (ASE) is the second metric used by LEED, which searches for any potential source of visual discomfort, particularly the presence of direct sunlight. This metric calculates the percentage of the analysis points that exceeds a specified Illuminance level, 1000 lux, for at least 250 hours of the occupied hours without any contribution from the sky (IES, 2012). Grasshopper was used to collect and filter the Illuminance values of each analysis point over 3650 hours, and present the final ASE percentage along with the total number of hours for each analysis points which is exposed to direct sunlight. Grasshopper facilitates the process for all analysis points in order to make it feasible for optimization. Table 4 shows the Radiance parameters that were used to calculate the ASE.

**Table 4: The Radiance parameters set for the ASE.**

<table>
<thead>
<tr>
<th>Ambient Bounces</th>
<th>Ambient Divisions</th>
<th>Direct threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1000</td>
<td>0</td>
</tr>
</tbody>
</table>

**PHASE ONE: BASE CASE SIMULATION**

First simulation phase dealt with base cases for Kaleidocycle rings of 20 cm size but with different rotation angles ranging from 30 to 90 degrees with a step of 15 degrees as a part of Daylight Availability (DA) simulation as shown in Figure 8.
Figure 8: Shows the Daylight Availability (DA) Performance of the Base case

The results showed good potentials for the Kaleidocycle rings in enhancing daylighting performance that could be optimized to comply with LEED V4 daylighting requirements as well as Daylight availability (DA) standards.

PHASE TWO: PARAMETRIC OPTIMIZATION

This stage aims to optimize the Kaleidocycle configurations by conducting a parametric optimization process.

Optimization Parameters

All model parameters were fixed except two variables which are used for the optimization as show in Table 5.

<table>
<thead>
<tr>
<th>Optimization Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opening Size</td>
</tr>
<tr>
<td>20 cm to 65 cm (step 1 cm)</td>
</tr>
<tr>
<td>Rotation Angle</td>
</tr>
<tr>
<td>0° to 90° (step 1°)</td>
</tr>
</tbody>
</table>

Optimization results

The optimization stopped after 73 generations, the best results of each generation is presented in the graphs Figure 9, while each generation contained 30 trials. The graphs show that the daylighting performance results are gradually enhanced till the optimized ones. The optimization objective was set to maximize the daylit area and to minimize the over lit and ASE areas. The last generation of the optimization process reached the optimum solution which eventually gives a better performance than the one required by LEED v4. The optimum solution in shows the Kaleidocycle size became small to have Figure 10 more openings with large angle which allows for better daylighting distribution. On other hand, the daylighting performance of this solution can easily get 3 LEED points because sDA = 100% which is more than the required 75%, and the ASE is equal to 5% which is less two times than the required (10%). Furthermore the daylight availability metric shows a comparable performance, even with 6 bounces the Illuminance levels did not exceed 3000 lux at any point except the same three points which were declared by ASE metric. A comparison evaluation was made to verify the reliability of the optimization results, the comparison results are illustrated in Table 5. All configurations was tested at 70% WWR which represent the same ratio of the optimized solution.

Table 5: Shows the Daylight Availability (DA) Performance of the comparing cases.

<table>
<thead>
<tr>
<th>Case</th>
<th>Partially Lit</th>
<th>Day lit</th>
<th>Over lit</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0</td>
<td>55</td>
<td>45</td>
</tr>
<tr>
<td>B</td>
<td>0</td>
<td>60</td>
<td>40</td>
</tr>
<tr>
<td>C</td>
<td>50</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>D</td>
<td>0</td>
<td>75</td>
<td>25</td>
</tr>
<tr>
<td>E</td>
<td>0</td>
<td>90</td>
<td>5</td>
</tr>
</tbody>
</table>

A: Simple window without shading.  
B: Simple window with electrochromic 60% VT.  
C: Simple window with electrochromic 30% VT.  
D: Double Façade with Kaleidocycle rings, Size =20 cm, Angle=75 degrees.  
E: Optimized Double Façade with Kaleidocycle rings, Size =30 cm, Angle=64 degrees.

CONCLUSION

This paper presents a hybrid double façade design driven by daylight performance through incorporating daylighting simulation tools and genetic optimization with a parametric facade model of an origami-based; kaleidocycle rings. The simulations were conducted for a south oriented façade of a standard living room for hot arid climate of Cairo, Egypt. Several Kaleidocycle parameters were modelled but all of them were fixed except two variables; opening sizes and rotation angles which were used for the optimization process. A two stage methodology was adopted, while the first phase showed potentials in enhancing daylighting performance by changing façade typology, the second phase proved that Kaleidocycle rings of 30 cm size and 64 rotation’s angle reached better daylighting distribution that exceed LEED v4 requirements and passing Daylight Availability standards (Figure 10). The paper demonstrate that integrating daylighting simulation tools and genetic algorithm to drive parametric façade typology contribute in reaching better daylighting performance. In the future, this study will be extended to consider thermal loads in façade design.
BIBLIOGRAPHY


