A Generative Parametric Technique For kinetic cellular façade to optimize Daylight Performance

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At present the kinetics is basic, but there is no doubt that research into the field of responsive building facades will continue, to find more sophisticated design and technical solutions. This research explores the possibilities of kinetic composition afforded by Origami different techniques using squared module. Origami and paper pleating techniques are one of the conceptual design approaches from which Kinetics can be developed. The paper examines the possibilities of different arrangements of folded modules to create environmental efficient kinetic morphed skins. The paper aims to achieve different Kinetic origami-based shading screens categorized by series of parameters to provide appropriate daylighting. The main tested parameters are the form of Origami folds, the module size and motion scenarios. Ten origami cases where explored first using conceptual folded paper maquette modules, then parametrically modelled and simulated at four times of the year, 21st of March, June, September and December, taken every hour of the working day.

Keywords: Kinetic cellular façade, Origami, Parametric modelling, Parametric simulations, Daylighting performance.

INTRODUCTION
Origami and paper pleating techniques are one of the conceptual design approaches from which Kinetics can be developed (Adrover 2015). Applications of kinetic origami and folding concepts can be used repetitively in modular large-scale facades. Therefore, the folding technique concept is not originally intelligent, but it represents the ability of controlling the structure by moving part or all of it. Accordingly, some origami and paper pleating techniques could be demonstrated into kinetic cellular facade. Origami screen, which act as Kinetic solar screens, present efficient solution that can be used externally to minimize heat gain while providing appropriate daylighting (Mahmoud and ElGhazi 2016). Origami transformation was analysed in terms of skin components, defined as the transformation of arrangement and geometry of individual kinetic parts and the mo-
tion of control means between them. Origami offers a finite set of paper-folding techniques that can be cataloged and tested with parametric modeling software. For this work, Rhinoceros and Grasshopper have been chosen as a software platform to generate a parametric folding tool focusing on single surface folding, particularly where surfaces can transform from one configuration to another while retaining their planarity (Dave and Brian 2011).

The paper focuses on optimizing the divisions and number of folds and its movements. The study is a way to achieve different deployable façade shading systems categorized by a series of parameters that describe the strengths and weaknesses of each tessellation. Through the kinetic behaviour of Origami geometries the research compares simple folding diagrams with the purpose to understand the potential of kinetic patterns’ morphology for application in adaptive facades. The possibilities of using a responsive folding technique to develop a kinetic surface that can change its configuration are here examined through the variation of parameters that influence kinematics’ form. Surface manipulation tool that can transform the arrangement of folding planar surfaces, studied a family of Squared cell folding geometries to provide daylighting using parametric modelling. These early kinetic design explorations introduce the fourth dimension of Time as a key element of the process of transformation.

**BACKGROUND ON ORIGAMI**

Many origami explorations of building skins have been tested in previous research, (Lee and 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 modelling. The research team (Elghazi et al. 2014) (Elghazi et al. 2015), selected a 3D kaleidocycle origami module to design an environmentally responsive kinetic screen. Origami Screens act as Kinetic solar screens which have a great environmental performance energy efficiency (Moloney 2011) (Mahmoud and Elghazi 2016). Origami screens present efficient solution that can be used externally to minimize heat gain while providing appropriate daylighting (Elghazi et al. 2015). Some projects apply the Origami folded façade concept as static treatment to screen the glazing, while others merged it with intelligent kinetic systems. For example, a static folded aluminium façade shelters a biomedical research facility at a hospital of Navarra, Spain. The building's key architectural feature is the exterior louvers constructed of 3mm-thick perforated aluminum panels arranged in a tessellated origami pattern. Integrating kinetic systems, the 25-story twin office towers in the United Arab Emirates merges the origami façade concept with the intelligent sensor-controlled screen that responds dynamically to the sun, folding to shade or expose the building as shown in Figure 2. Another example was recently completed Q1 headquarters building in Essen Germany is shaded by 3,150 kinetic "feathers" that open and close based on user input and sensor data as shown in Figure 3. Similarly, The Syddansk Universitet communications and design building in Denmark features a climate-responsive kinetic façade using similar configuration as shown in Figure 4.

![Figure 1](image1.png) A selection of folded Miura geometries.

![Figure 2](image2.png) Al Bahar Towers, The folding shading system, opens and closes according to sun’s position.
PARAMETRIC MODELING

Parametric design refers to a practice of digitally modeling a series of design variants whose relationships to each other are defined through one or several mathematical relationships (parameters). Parametric models can automatically adjust geometric models in response to dynamic real-time data (Davis et al. 2011), to produce a flexible forms that can be animated (Leach 2009). It is considered an essential tool during this research due to the complexity of the folding operations which was made to design a flexible form that when collapsed would be able to open diaphragm enabling daylight to enter the space and when expanded would form a planar flat surface. Initially, the parametric model began with a square. The folds were composed by finding relations and connections between the vertices, mid points of edges of the square to its center point. The relations of lines and points changes in order to open and close the diaphragm. The main parameters of each Origami unit form were the motion of the folds. Different combinations of rotations and translations led to different characteristics of the diaphragm. The parametric model allowed for an evolving understanding of the how each fold influenced the properties of the diaphragm. When the geometry was digitally unfolded and examined over the range of positions, from being fully closed to fully open, it served as a means for better understanding the geometry of the diaphragm. It could also be used to unfold the diaphragm into a single form for the further fabrication process.

DIVIDING A SQUARE

However, with origami, it is surprisingly easy to achieve different divisions of a squared module. One of the ways of using geometric shapes is by splitting a shape up into simpler shapes or splitting it in a systematic way to make new shapes. At first, Simple divisions or less complex pattern can be used to actually divide the square horizontally or vertically, creating a grid.

Every step adds as many lines, cease or tessellation as possible which do not depend on each other but previously existing lines. This means that you can create different 3D configuration from the same grid divisions. Pattern sequences are used to split the square into number of triangular parts. It is accomplished by connecting lines between intersections, corners of the square, or from the center of each side to the two corners of the opposite side as shown in Figure 5.

METHODOLOGY

To integrate all characteristics of architectural design, a comprehensive methodology is required to consider the aesthetic qualities of the façade and the performance behavior of the skin. This paper explores origami-based Kinetic façades design to control daylight uniformity through three phases. The first phase explores kinetic behaviour of origami geometries through paper maquettes to compare different simple folding configurations to understand the movement at global scale. The second phase use Parametric modelling tools to model different kinetic
origami modules through the variation of parameters that influence kinematics' form. The third phase compare kinetic origami cellular façades' configurations using parametric simulation in optimizing Daylight Performance.

**The First Phase**

Paper modeling of transformable surfaces is helpful to be able to visualize surface movement. Concepts of folded modules are explored through paper maquettes, although they may not be worked up into fully resolved structures. Paper-folding is a technique of alternating mountain and valley folds in an arrangement that allows movement in a folded model as shown in Figure 6.

**The Second Phase**

The Second phase exploration of the folding geometries was executed in the Rhinoceros CAD environment. Rhinoceros (Rhino) is a stand-alone, commercial NURBS-based 3-d modelling tool. The parametric modelling script constructed the tested geometry by firstly; building the office room and dividing the southern façade into modular units and secondly; modelling the origami unit modules to be located on it.

Origami derives from the Japanese words on ('folding') and kami ('paper'). It is originally the ancient Japanese art of transforming a flat sheet of paper into a sculpture or shape (Adrover 2015). Two-dimensional object is transformed into a three-dimensional one by only a series of folds. These folds convert the paper object into a new entity with surprising strength and kinetic properties. Paper gluing or cutting, or assemblages of paper cuts, are not defined as origami but are also explored as 'paper pleats' (Adrover 2015). Starting with a piece of paper and just by folding, ending up with diverse range of forms and patterns has attracted many people and resulted in hundreds of books and internet sites, origami courses as shown in Figure 1 (Sorguç et al. 2009). In the 1960s, the geometrist, artist and computer scientist Ron Resch conducted relevant studies of deployable origami structures not just in small conceptual models, but also in surprisingly large-scale ones. Today, applications of deployable origami and paper fold concepts range from aerospace applications to maps, textiles, kinetic art and sculpture.

**The Office Space.** In order to understand all the possibilities and limitations of creating a performative building skin, a side-lit south-facing office space in Cairo, Egypt has been selected as a case study. In office-type environments, where occupants typically cannot freely adjust their position and have rather...
stringent visual comfort requirements, the building skin has to provide glare control using either clever façade orientations and design or automated shades (Reinhart 2014). The office could be considered as one of many identical rooms stacked together to form a facade (Reinhart 2014). It was modeled using grasshopper, with spatial dimensions of 4m (width), 8m (depth) and 3m (height) as shown in Figure 7. The measured space is 8 m deep to give the opportunity to clearly test the screen efficiency. The Origami screen was allocated as a mediate interface in front of the glazing layer in the southern facade.

The Second phase exploration of the folding geometries was executed in the Rhinoceros CAD environment. Parametric models connect points in a desired order and adjust the arrangement of folding planar surfaces, to generate base lines of Origami pattern using Grasshopper (McNeel 2010).

**Screen logic.** Although the geometry of the skin is important as it impacts the overall performance of the building, due to the overall paper objective, a simple squared module geometry was chosen as a case study. The overall design of the skin is composed of Origami modular folded in different directions, that acts as apertures. The horizontal and vertical rotation and translation of the units creates the depth of the skin; the simplest forms of folding behave similar to fins. Since the module is defined by adjustable base lines, changing the numerical values associated with each line can result in different shape proportions. The squared folded module could be repeated as many times as desired. In fact, the generated module is used as input for the rectangular grid component. This action allows a repetition onto the grid by module geometry, cells dimensions and number of cells along the X and Y-axes inputs. Basically, the pattern is originated by the main module, digitally defined by a series of points connected by lines. It’s defined off the original geometry through a series of commands: move, mirror, and rotate. The simulation of the digital folding of the model is decidedly more complex to define since the kinetic movement of repeated folds must have their own axis and center of gravity as well as be located on the grid with arrangements to formulate the entire surface.

On the whole, Ten tested cases of folds are tested as in Figure 11. There are mainly two set of variables on which the script is based upon. First of all, The motion variable of each folded module ranging from totally closed to totally opened as shown in Figure 11, only Six intermediate steps were tested as shown in figure Figure 8. The second variable is the size of the folded module. Three module sizes were tested to divide a façade with dimensions 4m (width) x 3m (height) which are; (2x1.5 m), (1x1m) and (0.5x0.5 m) as shown in Figure 9.

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**Figure 7**
Spatial dimensions of the office space.

**Figure 8**
The Six intermediate motion tested steps.

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SHAPE, FORM AND GEOMETRY | Applications - Volume 2 - eCAADe 34 | 403
The primary concept of the tested foldings of kinetic origami skin, shown in Figure 10, is that when it moves, either the corners of the square or the center open to control different levels of daylight penetration using parametric modelling tool.

**The Third Phase**

The Daylighting Simulations will be integrated using Grasshopper and Diva. The DIVA plugin was used to perform the daylight analysis via integration with Radiance and DAYSIM. Experimentation was conducted using point in time simulations for year-round performance, therefore, Iterative runs will be performed for each configuration system, each run was planned to be performed for four times of the year, March 21, June 21, September and December 21, taken every hour of the working day from 8:00 am to 6:00 pm.

Daylighting evaluation is analyzed using two codified metrics in LEED v4 to evaluate daylight autonomy design. These two metrics are: Spatial Daylight Autonomy (sDA) and Annual Sun Exposure (ASE) metrics, which forms together a clear picture of daylight performance. sDA describes how much of a space receives sufficient daylight, which should achieve (sDA 300 lux / 50% of the annual occupied hours) for at least 55% of the floor area. sDA has no upper limit on luminance levels, therefore, ASE is used to describe how much of space receives too much direct sunlight. It measures the percentage of floor area that receives at least 1000 lux for at least 250 occupied hours per year, which must not exceed 10% of floor area (USGBC 2013).

These two metrics were set to evaluate static buildings performance, which need to be modified to adapt the dynamic buildings changeability. For the dynamic system evaluation, some hourly performance evaluations of the working hours must be established to trace the daily, monthly and annually façade response for climate changes, therefore HsDA (Hourly spatial Daylight Autonomy) is used. HsDA must exceeds 300 lux for at least 55% of the floor area, where the Hourly Sun Exposure (HSE) is measured instead of the Annual Sun Exposure (ASE). HSE measures the percentage of floor area that receives at least 1000 lux per hour and shouldn’t exceed 10% of floor area (Elghazi et al. 2015).

**Daylighting Performance Simulation.** As previously mentioned, DIVA-Grasshopper is employed to measure Daylight Autonomy (HsDA and HSE). The geometry of the skin was connected to the DIVA plug-in. Each modeled surface was assigned a specific material such as walls (50% reflectance), glazing (80% visual transmittance), ceiling (80% reflectance), floor (20% reflectance) and exterior surface material (30% reflectance). A set of sensors or nodes was located above finish floor at (0.7m) high as shown in Figure 12 to calculate (HsDA and ASE).
Figure 11
Parametric Variation of the folding module:
The module was reconstructed in Grasshopper for a parametric alteration of motion. The rotation of folds was parametrically adjusted from 0 to 85 degrees (10 cases 10 steps).
The parametric model provides a constant feedback on the explorations of the proposed scenarios of Origami patterns to be animated for daylighting simulation. The main tested parameters are the form of Origami folds, the module size and motion scenarios. The simulation includes 10 explored origami screens with variations of 3 module sizes and 6 motion steps resulting in (180) cases tested on two simulation stages. First measuring illuminance at four times of the year, March 21, June 21, September and December 21, taken every hour of the working day from 8:00 am to 6:00 pm (7200 runs) to be able to compare different configurations.

RESULTS
The process of parametric simulation for the Ten tested cases took about seven days to be completed and written in spreadsheets using SpeedSim-for-DIVA plugin along with grasshopper (Wagdy 2015). The daylighting performance results is represented in terms of SDA and ASE for different Origami modules. The best possible solutions were found by reaching the balance point between SDA and ASE. It aims to maximize the sDA value while minimizing the effect of ASE to get rid of direct sun exposure.

It was found that the large Origami module (1.5x2m), resulted in a relatively high percent of HSE and over-lit portion of space while the small modules (0.5 x 0.5 m) results in a partially day-lit space. The intermediate sized modules (1m x 1m) could relatively get rid of direct sun exposure while maintain appropriate Day-lit percentage as shown in Figure 13. In addition, this size of apertures maintains a minimum level of contact with outside.

All the kinetic folded tested cases resulted in acceptable daylighting performance. Acceptable daylight performance was mostly achieved at fully opened cases and partially opened in winter time. Unacceptable HsDA results always appears in December at 4:00 & 5:00 pm.
Figure 14
The best Four configurations of 1 x1 1m size modules which reach appropriate Daylighting.
The simplest form of folding the square horizontally creates an overhang that protects the interior space from direct radiation, as well as creating a small scale light shelf that re-directs daylight into the space beyond, resulting in a good HSDA percent for the deep office space. Some kinetic complex Origami configurations, provided an appropriate daylighting ranging between 75% and 90% daylit area. As shown in Figure 14, Results of “A”, the traditional horizontal kinetic screen, achieved HsDA (higher than 300 lux) for 75% of the floor area for 67.5% of the tested hours and 90% of the floor area for 25% of the tested hours. On the other hand, The HsDA results of "B" and "D" are slightly lower than "A", they achieved HsDA for 75% of the floor area for 60% of the tested hours while results of "C" achieved HsDA for 75% of the floor area for only 50% of the tested hours. The HSE results of "D", that receives more than 1000 lux, achieved 10% of the floor area for only 7.5% the tested hours. Accordingly, "D" is considered the lowest HSE and therefor the most energy efficient. Finally, the horizontal kinetic screen "A" achieved very high HSDA while The star-like kinetic screen "D" get rid of HSE high values. On the whole, the graphs show how kinetic motion variation of origami module could positively affect daylighting performance moving from one position to another through day and year as shown in Figure 14. This enriches the aesthetic qualities and façades articulation of the façade while enhancing the daylighting performance behavior of the skin.

CONCLUSION
Kinetic Origami cellular façade can be used as efficient solution which responds dynamically to the sun, folding to shade or expose the building; resulting in minimized heat gain while providing appropriate daylighting. Folding surfaces, particularly complex crease configurations, can be modeled and tested in variation using these algorithms. This makes it possible to design and test folding pattern configurations by creating a flat tessellation pattern. It is recommended to test daylighting performance in the different orientations to reach better understand-