DYNAMIC SHADING DEVICES

Exploring origami architecture in the digital design medium to 'optimise' daylighting performance.

T. VUGREK,
University of New South Wales, Sydney, Australia
tim.vugrek.999@gmail.com

Abstract. Responsive facades are an expanding research field that incorporates new kinetic possibilities of materials and/or elements that can benefit many areas in the built environment such as controlling complex daylighting or temperature conditions unachievable by current conventional blinds. Current commercially available blinds for office environments are typically linear/planar shading systems which translate either horizontally or vertically in movement and have a limited degree of control over daylighting. Therefore, this research carries its inspiration from architectural origami explorations and highlights its design potential to transform 'two-dimensional' planar elements into 'three-dimensional' dynamic forms, allowing for greater functionality and performance of kinetic elements through simple folding techniques. In the 21st century, digital tools such as Rhino and Grasshopper are becoming increasingly important in the design process where parametric modelling provides great strengths in the ability to create fully modifiable and adaptable digital models that can simultaneously provide accurate simulations that positively contribute to the final design. It is hypothesised that a digital design approach will open new design possibilities, such as being able to accurately model, dynamically test and control movable elements of an origami inspired shading system and explore this in response to real world environmental conditions. It is hoped that the implications of this research will contribute to fields of architecture and engineering through highlighting the value of parametric design in exploring optimal design goals for an internal office façade, whilst simultaneously creating realistic visualisations and simulations that have a high degree of accuracy.

Keywords. Kinetic facade, shading system, origami, parametric modelling, shading performance.

1. Introduction: (Research context and motivations)

Kinetic shading systems in architecture are primarily mechanical devices that adjust or adapt to filter light and create optimal conditions for a given space. The motion that the system creates also has the potential to enhance aesthetic architectural experiences (Mahmoud, A. H. A., & Elghazi, Y., 2016) whilst allowing specific lighting scenarios to be precisely controlled. There are many components to how a kinetic shading system works. Overall, most shading screens explore different configurations of elements and how they are controlled. This may be through a manual actuation of a mechanism, or an automated movement using motors or linear actuators to drive a specific motion in the system.

Conventional blinds for office environments, including those that are commercially available, are typically linear/planar shading systems which translate horizontally or vertically and have limited degree of control over daylighting. Some of these blinds include venetian blinds which include slats that are operated by a pulley system, or roller blinds which work by wrapping fabric around a rotating tube. Whilst these designs are adequate for most conditions, there is an opportunity to investigate new solutions that are more dynamic in movement and optimal for altering the performance of a façade in terms of direct sunlight and solar gains.

Usually the success of performance comes down to not only the technology diving the design but also the "effective design process related to it" (Sharaidin, Kamil, 2014, p. 6). Therefore, in the 21st century where digital tools for parametric modelling as well as simulation are available, the process used to carry out a specific design can enable effective and efficient outcomes in exploring and optimising various configurations of variable elements.

Few window blinds apart from a Concertina type blind and Roman blinds, which are commercially available, explore how origami-like folding mechanisms work as part of an overall shading system. Therefore, there is the potential to further investigate and abstract the mechanical advantage of an origami inspired design for a shading device in order to create better and potentially more sustainable office lighting conditions.

2. Research Aims

The research can be summarised by the following 3 aims:

- Developing upon current conventional blinds to propose more 'optimal' and sustainable solutions for window façade shading.
- Increase shading performance through a responsive and modular system, where individually controlled elements can be programmed to potentially adapt to internal and external environmental conditions.
- Achieving complexity through simplicity in design by using simple folding techniques that contribute towards efficiency in manufacture, durability and cost effectiveness.

3. Research Question(s)

Based on the issues outlined in the introduction and the derived aims, the question the research this project investigates is:

* How can computational design tools be applied to optimise the design of an internal kinetic shading system for office environments? *

4. Methodology

Action research (AR) is a valuable research methodology that has been utilised within the fields of science and technology since the mid-twentieth century (Baskerville, 1999, p. 2). Because it is so grounded in practical action, it produces research results that are very reliable. (Azhar, Ahmad, & Sein, 2010, p. 88) The design of this methodology starts with an understanding of the problem and creating plans and strategies to solve it. The next stage is where the specific methods for the project are carried out which fulfils the 'action' part of the research. This stage is followed by observation which may include observing data or assessing the value of a design qualitatively or quantitatively. The final stage includes reflecting on the observations and linking the findings back to the problem and deciding whether it is a solution. The whole purpose of the AR design is to be cyclical in that this process can repeat if needed until an outcome or understanding is achieved and can therefore further inform a specific discipline of research.

In relation to designing a kinetic system, an action research methodology is very much applicable as in order to reach a specific goal, there are various

digital and/or analogue strategies that are to be carried out and simultaneously assessed. In answering the question of "how computational design tools can be applied…" to design a dynamic shading system, a cyclical action research methodology can be applied starting with a design problem which is identified. This problem is how the design of the shading device can achieve its overall goals, such as shading efficiency and functional/mechanical proficiency, through various computational design methods/tools.

What is unique about this projects design process is that there are many layers of experimentation and testing including parametric modelling of the shading screen, digital daylighting simulation and analogue experimentation, which means various AR cycles will not be linear (one cycle after another). For example, certain digital design considerations related to material exploration may inform a more appropriate analogue approach or certain analogue testing may pose limitations that only can be achieved digitally. Therefore, each design cycle runs parallel to each other where different design approaches constantly inform one another in order to come to better understandings of what the most appropriate method is. This process is also a method of observation and assessment in that each stage of the design process informs the designer what the most effective solution is (digital or analogue) and therefore one may determine how to best carry out the design of the kinetic system. Every step in this cycle is always linked back to either new or previous research whilst additionally creating new findings that may benefit future computational designers undertaking a similar project.

5. Background Research/Literature review

The Japanese word origami (ORI and KAMI) translates to the "art of folding paper" (Capone, Mara., et al., 2019, p. 716). The value of origami in contemporary architecture is its potential of transforming planar surfaces. It is through the 'fold', which is one of the most basic design techniques, that the reconfiguration of 2D elements can visually create more complex 3D configurations and depth. These folds are essentially hinges created in the material itself which means no additional elements are needed to fold the origami module. With parametric tools, "changing the designer way of thinking" (Capone, Mara., et al., 2019, p. 716), variable configurations may be tested and explored through the adjustment of parameters in a digital environment, ultimately contributing towards optimising how effectively origami can improve kinetic shading systems.

When looking at pre-conducted research concerning kinetic shading systems, there have been numerous design approaches used to conduct the whole process, with at least some stage utilising digital tools. The paper by Nancy Yen-wen Cheng on 'Shading with Folded Surfaces' looks at how different design tools informed each stage of the project. It discusses how digital parametric modelling is very beneficial for experimenting with different folds through simulation, however, physical testing for the daylighting was carried out due to materials adding constraints to the folding of the shading screen. In this paper it highlights the potential constraints for computational strategies because of material and joining techniques and emphasises how a hybrid design approach is more appropriate for this specific project.

Research by Youmna Saad Elghazi and Ayman Hassaan Mahmoud on Origami Explorations, also explores a similar project involving a dynamic shading screen whereby more emphasis on parametric modelling and simulation was undertaken during the design process. This project analysed primarily variants of a squared module and explored how different arrangements, tessellations and opening positions create environmentally efficient skins. (Mahmoud, A. H. A., & Elghazi, Y., 2016, p. 399) The results of the digital testing demonstrated efficient solutions however the limitation of this research was that no physical prototype was made to prove how the individual elements in the system can work mechanically.

When considering industry level projects, there have been various façade designs that capture new kinetic possibilities of elements in relation to a dynamic and adaptable movement in the façade system. One example includes Abu Dhabi's Al Bahar Towers, completed in 2012, which is an external responsive façade inspired from a traditional Islamic lattice pattern. It is designed to reduce solar gains by more than 50 percent contributing to environmental sustainability and adds more control over natural daylight, reducing the need for artificial light. One of the limitations of this system was its degree of complexity, which was reduced through simple geometric choices, however with numerous mechanical hinges being exposed to external environmental conditions, such a system would be inefficient to maintain in the long term.

The Institute of Building Structures and Structural Design (ITKE) designed a kinetic façade system called FlectoFold, that was displayed in 2017-2018 that highlighted modular elements with pneumatically actuated material folds, opening "…the possibilities of active and autonomous modes of control and operation." (Institute Of Building Structures And Structural Design, 2019). Some of these possibilities include the ability to program and

control individual elements without the need for uniquely designed mechanisms to create an adaptive and dynamic system that has heightened capabilities in relation to controlling façade related/generated lighting conditions.

Based on this research, one can clarify that origami inspired shading devices in many cases offers improved performance over conventional linear systems. Computational simulation was also quite effective in the design process including simulation for the daylight as well as for animating the folds. However, most examples indicated that physical prototyping and testing was necessary for fully understanding how these systems could be implemented to either a large or small scale, working with proper forces and material.

Additionally, there are variables yet to be accounted for in relation to testing configurations of an origami inspired shading screen particularly in relation to an internal office facade. For example, the individual shading modules may have to be smaller to fit a smaller sized window and this may affect performance in terms of lighting control.

Based on the material gathered, it was also hypothesised that physical prototyping would inevitably be a requirement in order to fully determine if the design process of origami-inspired shading systems is possible to be undertaken exclusively in a digital environment. Therefore, when conducting the research project, it was aimed to explore similar computational strategies and methods, illustrated by previous research, and taking a fresh approach to highlight new potential findings in relation to the digital and physical performance of an origami inspired shading screen.

6. Case Study

Assessment and experimentation of various folding motifs from research and digital simulations

Based on existing research on origami folding, the first stage of the case study involved identifying the behaviour of a series of origami folds and how these could be modelled in a digital/virtual environment. These folds were primarily based on a square 'motif', which is a module based on various configurations of diagonal, vertical and horizontal creases that highlight the importance of symmetry based on translation, reflection and rotation. These types of folds were adopted because of their geometries

ability to be tessellated effectively in a square or rectangular window façade. Translation symmetry is highlighted when each module of the pattern is the same when placed side by side. Reflection symmetry is when the module is repeated in one direction however as a mirrored image. These folds have a common crease that aligns with one another and can create greater complexity than translation configurations. Rotational symmetry is created when the creases repeat around a common point.

Based on identifying visual examples of these folds, an appropriate folding module was determined. The type of symmetry was a translated motif because of its consistency with other modules (see figure 1). The choice was informed based on future fabrication viability, having 6 parts per module with 2 different sized elements. This decision was also adhering to one of the project goals of achieving complexity through geometric relationships whilst maintaining a simple module design.
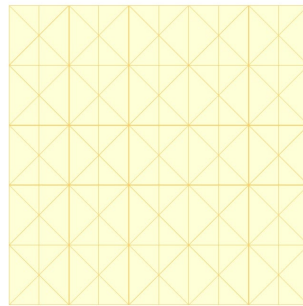
Figure 1. Chosen motif geometry tessellated as a 5x5 grid

**Developing a variable parametric model**

The next stage involved starting the digital design process where a parametric model was developed in Rhino/Grasshopper 3D incorporating the chosen motif. This process started with constructing the squared module utilising grasshopper geometry and creating the internal lines that were separated into two different groups that would make up the valley and mountain folds. The 2D module geometry was then applied to an array of points to then create an entire surface from the modules being tessellated together. Once the 2D geometry was generated including separated mesh faces, the Grasshopper physics plugin Kangaroo was utilised to create

appropriate hinges with an angle range from 0 to 180 degrees for valleys and 0 to -180 degrees for mountains. These hinges also received other appropriate geometry such as points to define the start and end of the fold. These hinges acted as goal objects for the kangaroo solver (rules/geometry for the kangaroo solver to process) which also received additional goal objects such as line lengths to stabilise geometry and anchor points to prevent general displacement of the mesh faces.

Once the grasshopper script was developed, I was able to refer to my project goals and visualise what type of dynamic movement could be achieved. The primary advantage of the parametric model was the complete control over the geometric relationships between elements of the shading screen including the module sizes, screen size and folding strength. What was unknown to me at this stage however was how to determine what the appropriate module size needed was. For example, if fitted in a window façade, one may need to determine whether larger or smaller elements will not only fit the desired space but also provide enough control over the daylight.

Extracting necessary data from the parametric model

To answer the first question, additional data was required to be extracted from the simulation model. When observing the new forms created through adjusting the folding factor in kangaroo, the amplitude of the geometry dynamically changes in both positive and negative 'z' directions. Therefore, it was necessary to extract this data from the digital model for one to determine what the max module size can be if being fitted in a window façade cavity space. This was achieved by creating a straight line between the apex of the module and a point created from its lower limit and measuring that distance. This new data could then be displayed and updated simultaneously to parameter adjustment enabling the digital model to provide constant feedback allowing one to easily determine the largest possible module size.
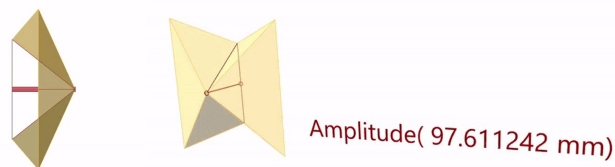
*Figure 2. Displaying the amplitude value in real time to the kangaroo simulation*

Performing a series of daylighting simulations

Addressing the question of daylighting performance required the utilisation of the Grasshopper plugin Ladybug (which includes components for sunlight hours analysis). The goal was to set up a series of tests that could prove the overall shading benefits of the system. Based on the research by Youmna Saad Elghazi and Ayman Hassaan Mahmoud, it was already evident that this type of origami system offered more daylighting control over a conventional linear blind, therefore my aim was to take some of these tests a step further to explore any further shading potential for the new origami shading screen. The test that was carried out was a sunlight hours analysis based on location data in Sydney CBD. The time period tested was June 21st 9am-3pm. The month and date were left as a default setting as this information was not critical for the test, however the time was important as it highlighted typical office hours when the shading system would be relevant.

The first test carried out was to observe the difference in orientation (North vs West) with a screen made up of 10x10 200mm modules (2m² screen size). Three different opening states were also simultaneously tested. Results were gained by observing the colour gradient generated by Ladybug and making comparisons between orientation and opening positions. The results proved to be quite successful as both orientations displayed the same gradient and legend.

Figure 3. Daylighting Test 1 highlighting performance difference of façade orientation
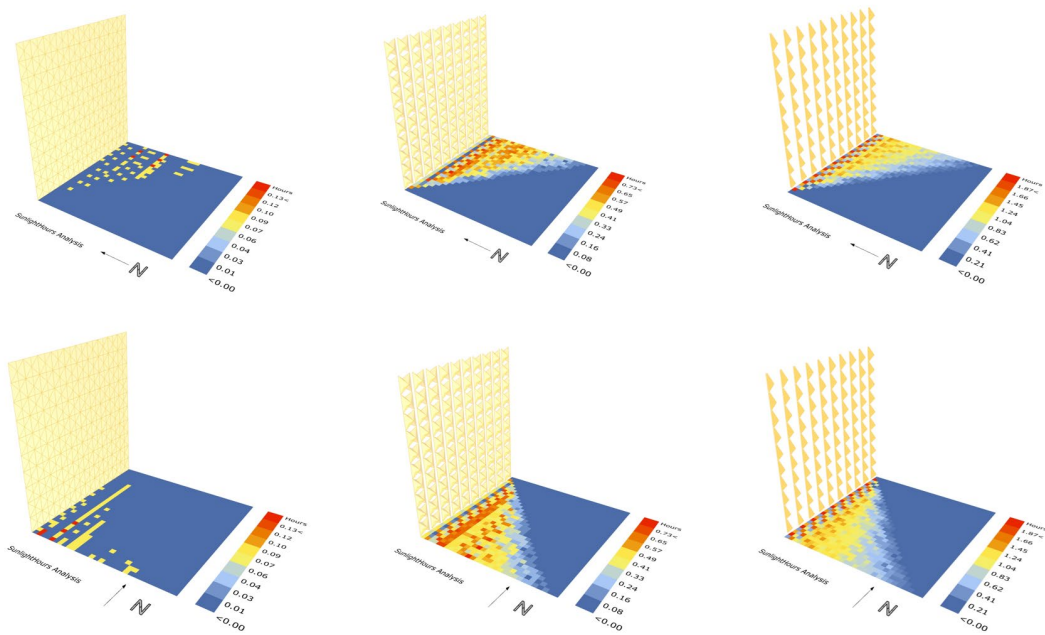
The second test carried out was to compare the shading results of different module sizes. This was also to answer an earlier question of which module size would be most appropriate for the shading system. The tested sizes were 200mm^2 vs 500mm^2 modules and this was undertaken in a single North facing orientation with the same screen size and opening positions. When observing the gradient results, it was evident that the system with the smaller modules had more daylighting control than the one with larger modules. This was mostly due to the number of openings available in the system, with more smaller openings highlighting a smoother gradient than the system with larger openings highlighting a gradient with more divisions in the sunlight areas.
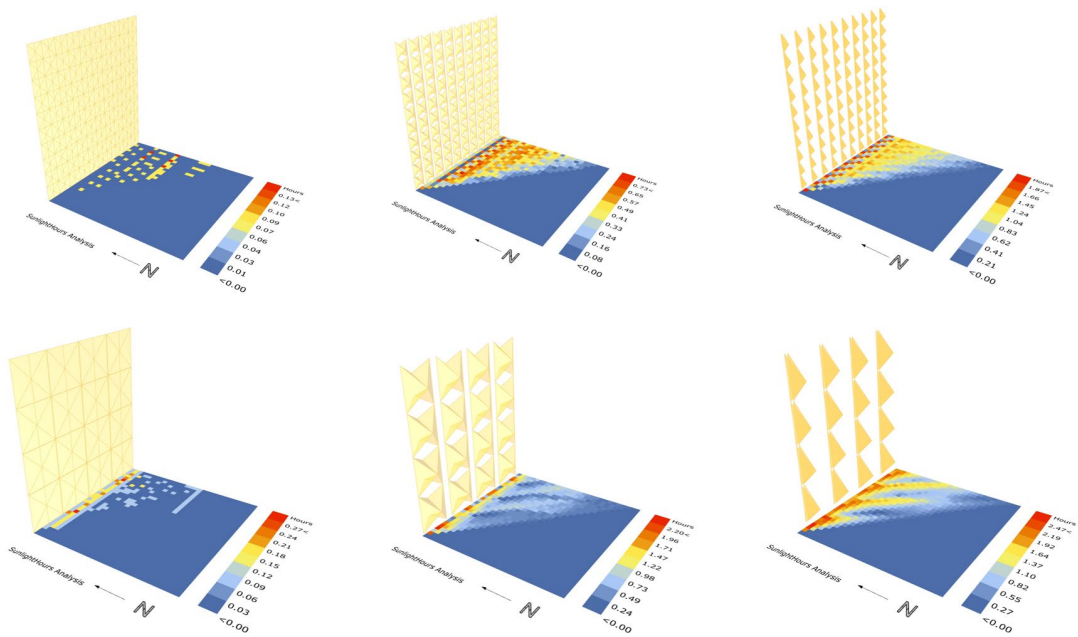

Figure 4. Daylighting Test 2 highlighting performance difference of module size

The final test conducted was to explore the potential of a dynamic system. The first step was to modify the original script to include an attractor point representing the suns path or a person near the shading screen. This point would be where the shading modules would be closed and moving away from the point the modules gradually open. This allows the system to become more adaptive and be open or closed in specific areas where it is most appropriate to create shade. The test was carried out with the same

criteria as test 1, however I compared a single dynamic open/close scenario to a single global opening position (0.5 folding factor). The test resulted with the dynamic scenario creating more shade near the attractor point and allowing sunlight elsewhere, compared to same sunlight levels covering the test area.
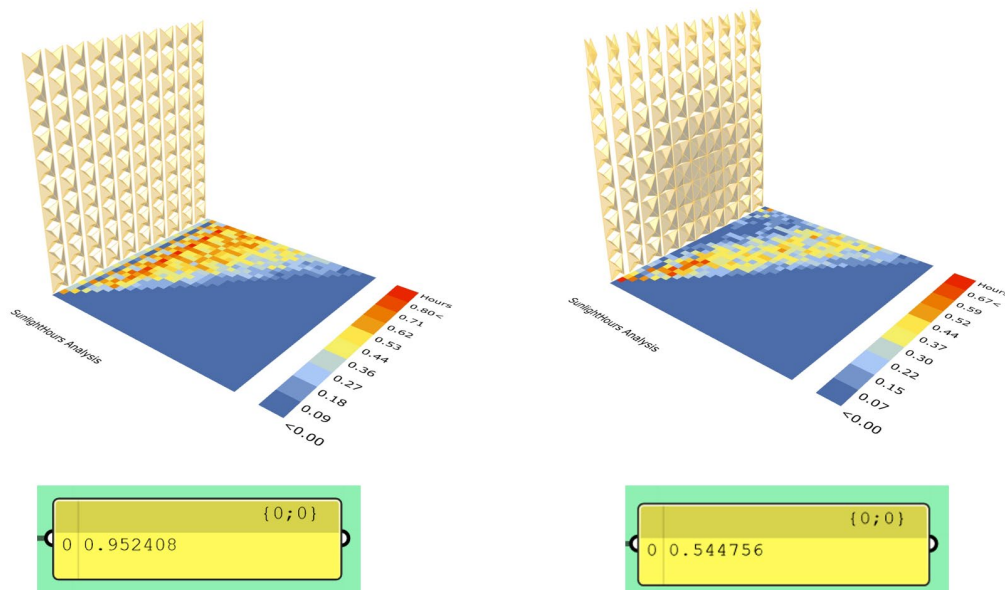
Figure 5. Daylighting Test 3 highlighting the performance of a global vs dynamic system with total sunlight hours displayed

Constructing a first iteration physical prototype

The final stage of my project included fabricating and constructing a single iteration of a physical prototype to illustrate how well the geometry in a digital environment would translate to a physical environment and accurately the geometry would respond. The prototype was constructed using laser cut (3mm) plywood panels attached to a fabric underlayer. The panels were to act as the rigid faces while the fabric underlayer would act as a folded material hinge. What was observed was that whilst the geometry translated quite well in terms of the folds, there was a lot of unexpected behaviour when regarding additional forces being applied, with the fabric underlayer causing a lot of free movement. It was this behaviour that concluded my research as a limitation was highlighted in that the physical behaviour was incongruent to the digital behaviour. This pointed me back towards my initial research to assess the possibilities of how the prototype could be actuated in terms of potential mechanical/pneumatic movement.

7. Discussion (evaluation and significance)

Throughout this research project there were various key outcomes illustrated that positively addressed the overall research question of the value of a computational approach to design. The first outcome was highlighted through the capabilities of having a parametric model for the shading screen. This included having a fully adaptable digital model for any façade space and having the ability to extract necessary information from the new forms generated and displaying them in real time simultaneously to any parameter adjustment. This allows one to know the geometric limitations of the origami modules within a façade and make parameter adjustments accordingly. Performing digital daylighting simulations also depicted positive results in terms of how the geometry of the shading system would perform under realistic conditions. What was discovered is that the geometry reacted well under different orientations due to its symmetrical nature however it was different module sizes that mattered when it came to effective daylighting control, with ideally smaller modules being more beneficial.

Utilising additional computational design techniques such as an attractor within the system also highlighted enormous potential of a fully dynamic shading system that can intelligently adapt to specific daylighting scenarios or conditions based on a person's position in reference to the shading screen. The potential here is the ability to shade specific areas maintaining an optimal balance between light and shade. The digital model highlights the

possibility for this system to be further developed, however when taking material and mechanical functionality into consideration, this is where the limitations of digital tools are highlighted. Whilst the translation of virtual geometry to physical manufacture is possible (as highlighted by the initial prototype), it is additional material properties and behaviour that dictates how the movement of the folding is realised. This would further inform what potential drivers are needed to actuate the system whether it may be mechanical, pneumatic or manual. It is these considerations that highlighted the current limitation of a computational design approach and therefore this directed further research in this area to further develop this system physically.

When looking back at pre-conducted research, it was evident with projects such as the Al Bahar towers that a fully dynamic system could be achieved, however when considering a mechanical approach where numerous actuators are required, this becomes a very complex and costly design that is also difficult to maintain because of its multitude of moving parts.

One project that illustrates great research potential to address this question is FlectoFold by ITKE, exploring how individually addressable elements can be actuated by utilising pneumatic elastic hinges. The potential here is that material hinges can be actuated using pneumatics opposed to individual motors, addressing the issue of complexity. The challenge, however, would be how to apply this technology on a smaller scale more appropriate for a window façade in an office space, where the mechanics/pneumatics become more intricate and more difficult to conceal. Additionally, a dynamic system would also require a subframe to support each of the folding elements, and this could be a potential issue for a window façade where the view could be partially obstructed.

Therefore, based on current solutions, a dynamic system may not be the most appropriate design choice for an internal office window, however, there is still further design potential for this system to be implemented in the future. Nevertheless, the utilisation of origami modules within a shading system for an office environment can still be implemented with performance benefits, however, a potentially more simplistic global or partially dynamic opening arrangement would need to be considered.

8. Conclusion

In developing a dynamic shading system, computational design tools incorporating parametric modelling and simulation have proven to be incredibly valuable to the design process. This method allows one to create adaptable screens for any façade space through parameter adjustment in Grasshopper and assess its shading performance simultaneously utilising digital daylighting analysis tools such as Ladybug. Both daylighting and digital folding simulations demonstrate a heightened potential for origami inspired shading modules in that a simplistic, yet dynamic movement can be achieved and visualised whilst providing improved shading performance in comparison to linear blinds.

The critical question however, is when considering material complexity and mechanical functionality, how can a dynamic 'attractor' based system with individually addressable elements be developed whilst maintaining a simplistic and robust design? This is a question that poses a future direction of research encompassing material science and mechanics which are vitally important in understanding how this project could be physically constructed and if its movement could behave according to its digitally ideal environment.

Therefore, it is recommended that additional research and physical prototyping would be required to carry out the next step in this research project. Nevertheless, a computational design methodology as well as digital tools have provided an important foundation in understanding and designing an origami inspired shading system and I believe the implication of this design approach can be applied to any façade design proposed by the architectural and engineering industry.

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