Kinetic Facades:

Towards design for Environmental Performance

An exegesis submitted in fulfilment of the requirements for the degree of
Doctor of Philosophy

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Statement of Declaration

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program; any editorial work, paid or unpaid, carried out by a third party is acknowledged; and, ethics procedures and guidelines have been followed.

Signed

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Kamil Sharaidin
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Abstract

Over the past few decades, kinetic facades have emerged as alternative building envelopes, designed to meet the increasing of varying and complex demands related to user comfort, energy consumption and cost efficiency. This concept has been described in a number of ways, ranging from the usage of innovative components to highly complex designs and advance technological application.

In this research, kinetic facades are defined as the ability to response and adapt to the changes of the environmental conditions. The strategies mainly focus on the functions and performances of kinetic facades in the context of indoor daylight quality and thermal heat performance. These are achieved by examining the role of kinetic elements on the building facades to form effective kinetic configurations in response to environmental changes. Identifying and evaluating the performance of kinetic designs on the building facades at the early design phase will assist designers to understand design issues and strategies in constructing the kinetic facades. Although the existing design implementation of kinetic facades were intended to enhance the building performance, the inclusion of daylight and thermal radiation, a fair number of them struggle to achieve the optimum performance after the facades were installed and being operated.

Designing and evaluating responsive kinetic facades are complex tasks as they involve interactive kinetic elements within three-dimensional dynamic physical elements or components that constantly change. Therefore, this research presents a methodology, alternative tools, and design evaluation techniques, which define a performance-based design, an approach to analyse the design and simulate responsiveness of kinetic facades during the early design phase. This demonstrates how the process of designing and developing kinetic facades can be effectively tested and evaluated to understand the challenges and problems before the actual facades are constructed and installed in the buildings. As designing static facades totally contrasts from designing dynamic components that involved various state changes, this research proposed alternative platforms for designers to design and evaluate the kinetic facades, which respond to the environmental condition. One major contribution of this research is a dual methodology for designing and evaluating kinetic facades, using analogue and digital simulation tools. Rapid prototyping and physical testing were used at the early design stages with the aid of digital tools for verification of the architectural kinetics whilst more detailed physical experimental tests were performed on a one-to-one scale installation on site. These evaluations are aimed to achieve an optimum automated facade configuration, which specifically enable design exploration of semi autonomous or fully autonomous configurations of a kinetic facade system.

The process of evaluating the performance of kinetic design via digital simulations and physical testings allows designers to overcome the limitations of the existing analytical and digital simulation tools. This investigation demonstrates the design approach and techniques to conduct an evaluation on kinetic design through physical prototyping and testing, which complement the findings gain from existing digital simulation tools. Ultimately, this research is intended to provide insights and alternative platform for designers to improve, validate and make informed decisions during the early design development while offering unprecedented ways of exploring design options and strategies in realising the kinetic facades towards environmental performance.

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Terms and Keywords

Responsive Facades

Facades with the ability to respond to their environment by either typological change of material properties alter the overall form or local alteration by regulating their energy consumption to reflect the environmental condition that surrounds it.

Kinetic Facades

Kinetic Facades describe the actual movement or motions through geometric transformation in space that affect the changing state or material properties or physical structure of the building facades without compromising the overall structural integrity. Applications of kinetic facades are to enhance the aesthetic qualities, respond to changing of environmental conditions and perform functions that would be impossible for the static facades.

Kinetic Pattern and composition

Relative movement of individual kinetic parts in time and space, which as formed by multiple singular kinetic event clusters, or propagate across facades over time.

Kinetic Configuration

A programed of movement assign to the multiple kinetic singular to react and form specific behaviour.

Kinetic Response

Kinetic Response described as reaction cause by the motion. In this exegesis the Kinetic response refers to the movement generated from changes of daylight and thermal heat condition.

Motions

Motions referred in this exegesis are related to the movement generated by the changing state of the building facade.

Multi-performance Criteria

Multi-performance criteria are process of weighing multiple criteria based on different variables negotiated for the best suitable design. The process can be based on analogue or digital-driven which might not lead to optimisation rather inform decision-making process effectively. In this exegesis, I referred the multi-performance criteria in the context of digital simulation and form finding process.

Digital Design tools

Arduino

Arduino is an open-sources electronic platform based on easy-to-used software. It is created for designers to explore the interactive project related. It senses the environment by receiving inputs and sending output such as from sensors or actuators, and affects its surroundings by modulating lights, motors and other actuators. *Arduino* can be programmed by writing code in the *Arduino* programming and processing language.

Raspberry Pi

Raspberry Pi is an affordable, tiny credit card size computer that can be plug into a computer monitor or television. It is a little device that enables people of all ages to explore computing and learn how to program in language like Scratch and Python. It also has similar function as a desktop computer for activities such as browsing the Internet and playing video to making word-processing, playing game and spreadsheets.

Firefly

Andy Payne and Jason Kelly Johnson develop *firefly* in 2010. The software tool enables the connection and interaction between analogue and digital devices. It provides a direct connection between *Arduino* microcontroller and the algorithm software, Grasshopper in Rhinoceros environment.

Grasshopper

Grasshopper is a visual programming language developed by David Rutten at Robert McNeel & Associates. It operated within Rhinocerous 3D modeller, which offers the visual algorithms and parametric modelling. The program is capable of creating custom designed programs that can extend the functionality. Various type of analysis ranges from sound, structural, design optimisation and controlling Arduino are just a few tasks that can be operated within the Grasshopper software.

Rhinoceros 3d

Commercial 3D computer graphic and computer-aided design application developed by Robert McNeel & Associates. It is based on NURBS mathematical modeling, which focuses on generating mathematically precise representation of curve and freeform surfaces within computer graphics as different to polygon mesh-based application.

Autodesk Ecotect Analysis

Its environmental analysis software, which, allows designers to conduct simulation to evaluate building performance. The software combines analysis functions with an interactive display that present analytical environmental result ranges from thermal heat, lighting condition and humidity that reflect within the building context. *Ecotect* is dissimilar from other analysis software tools as it is targeting to be used in earliest stages of design, a phases when simple decision can be leveraged to affect the final outcome.

Climate Consultant5.5

Climate Consultant is an application that provides comprehensive and reliable data about local climate. The data are translated into charts, graph and other graphic display that can be easily understood and used by designers.

TouchOSC

TouchOSC is software that served as a platform to develop control interface for mobile devices. The software capable of receiving the signal or messages over a wireless network and enables the mobiles devices to act as a remote controls

Galapagos

Galapagos is an evolutionary solver for *Rhinoceros*, *Grasshooper*. It is applications that apply evolutionary logic are either aimed at solving specific problems, or it is a generic library, which allow other programmers to interact with. This software also allows non-programmers to create generic platform to be used on wide variety of problems.

Physical Design tools and Technology

Servomotor

A servomotor is a rotary actuator that permits precise control of angular position, velocity and acceleration. It consists of a suitable motor couple to sensors for position feedback. It is often used in closed-loop control systems such as robotics, CNC machinery or automated manufacturing.

RGB LED

RGB LED is a two-lead semiconductor light source. The colour of the led is determined by the energy band gap that has been assigned to the semiconductor. RGB LED used in this research mainly as indicator for the temperature, which represent the thermal heat condition from Blue (Cold) to Red (Warm).

Photo-resistor (Light sensors)

Photo-resistor or light-dependent resistor (LDR) or also know as photocell is a light controlled variable resistor. The resistance of the photo-resistor decreases with increasing incident light condition or in other words, it demonstrate photo-conductivity; which the phenomenon of material becomes more electrically conductive due to the absorption of electromagnetic radiation such as visible light or infrared light (Dewerd & Moran, 1978)

One Wire Digital Temperature Sensors (DS18B20)

The one wire digital temperature sensor is chip for measuring temperature. Each of these sensors has unique 64-Bit serial number etched into it, which allow for huge number of sensors to be used on one data bus. The unique number allows large number of data-logging activities and temperature control project.

Luminosity Sensor Breakout (TSL 2561)

A luminosity sensor breakout is a sensitive and sophisticated light sensor, which has flat responses across most of the visible range. The sensor provides digital outputs that provide data from level of light condition (lux) and temperature in degree. Each of the components of Luminosity sensor breakout is unique and addressable. Unlike simpler sensors, the TSL2561 measure both visible light and infrared to better approximate the response of the human eye and is capable of measuring both small and large amounts of light by changing the integration time.

Multiplexer (Analog/Digital MUX breakout)

Multiplexer is an electronic device that selects one of several analogue or digital input signals and forwards the selected input into single lines, which are used to select which input line to send to the output. In the final project *Unfold,* in order to form a one-wire system in sequences, three multiplexers are used in order to output the data signal from thirty Luminosity sensor breakouts which running at same time.

Voltage Regulator (DC voltage regulator / DC stabilised voltage supply

A voltage regulator is device to protect against thermal overload and short circuit and is able to display a warning LED in the event of a fault condition. The current and voltage are displayed on a separate backlit analogue meter.

1 INTRODUCTION

According to a recent survey by the Energy Information Administration (EIA, 2013)[1], buildings consume more energy than the transportation and industrial sectors. While this example is the first survey to date which measures total energy consumption in the United States, these statistics show that energy use by buildings has increased by such a degree that it now exceeds the industrial and transportation sectors (Pérez-Lombard, Ortiz, González, & Maestre, 2009). This is due to a majority of people spending up to 90 per cent of their time indoors (Bougdah & Sharples, 2009). These figures vary across different developed countries but they highlight a consistent global pattern towards higher energy consumption by buildings (Knaack & Klein, 2009).

Historically, buildings have provided shelter and protection to people from external conditions such as extreme heat or cold. The building envelope acts as a physical barrier between interior and exterior environments[2]. It functions as an outer shell to help maintain indoor comfort while facilitating climate control. Today improvement of building services application such as in lighting, heating, ventilation and air-conditioning (HVAC), have been assigned to enhance the performance of indoor environment and thermal comfort. As a consequence, external building envelopes are starting to lose their role as a moderator[3] of energy and comfort and as a consequence, a building place a significant energy burden on maintaining optimal condition in building indoor environment and this

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[1] http://www.eia.gov/

[2] Physical separator between external and internal environment of a

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[2] Physical separator between external and internal environment of a building

[3] Envelope as filter, reflector and absorber in respond to the solar radiation and temperature in protecting the building.

problem contributes to one third of total greenhouse gas emissions[4].

Although, buildings are seen as part of the problem contribute to global warming (Loonen, 2010), this issue presents significant opportunities for the building sector. The International Panel on Climate Change (IPCC) classified buildings as a sector that has the potential to minimise this problem in a cost-effective way. In order to mitigate the problem, in regards to building emission and energy usage, the effectiveness and the seriousness of the implementation requires more vigour than has been previously witnessed (UNEP, 2009). However, current practice has shown it is unlikely to succeed in solving this issue. Nonetheless it is suggested that climate change will transform the priority we give to energy efficiency (WBCSD, 2009). In both new and existing buildings' low energy implementation should become a part of the practice of designing a building, rather than the novelty of the project (WBCSD, 2009). From this perspective, building innovation and technology should be a catalyst that provides the necessary momentum for a significant leap in ideas with implementations moving forward.

It is sensible to consider the role of the building envelope (Loonen, 2010) as part of any strategy in dealing with this issue. Building envelopes consist of different components, which include the foundation, roof, walls, doors and windows. However, in the context of this discussion, the focus of this research is on building facades with emphasis on the windows and walls of the envelope.

Among strategies and solutions used in discussing the problem of a buildings' energy consumption, the buildings' facade should function as a mediator between the external and internal environments. Facades can be entrusted with multiple vital functions that dictate the building's energy consumption and which determine indoor environmental quality (Loonen, 2010). Traditionally the design of a buildings' facade is 'static',

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[4] http://www.aph.gov.au/Visit_Parliament/About_the_Building/Environmental_Management/Energy_and_greenhouse_gas_emissions

where the external environmental boundary conditions are designed to be constantly changing. As a result, traditional facades are not capable of adapting and responding to various changes that they are exposed to.. According to a recently completed project of the International Energy Agency—Energy Conservation in Buildings and Community Systems Programme (IEA-ECBCS, 2011), the development, application and implementation of responsive facades provides a necessary step towards creating improvements for energy efficiency within building environments (Loonen, Trčka, Cóstola, & Hensen, 2013). However, through the use of responsive facades, the buildings have the ability to react to these conditions (Drozdowski, 2011; Loonen et al., 2013) with improved energy efficiency in the building (Bahaj, James, & Jentsch, 2008; Hammad & Abu-Hijleh, 2010; Lee, Selkowitz, 38 Hughes, & Thurm, 2004; Lollini, et al., 2010).

Facades[5] that respond to the environment, also known as responsive facades are considered as part of the buildings' envelope in a primarily different way. Responsive facades actively adapt their behaviour over time in response to changing environmental conditions and performance requirements (Moloney, 2011). The term responsive in architecture has been described as the ability of artificial and natural systems[6] to adapt to varying environmental conditions (Beesley, Hirosue, & Ruxton, 2006). The term responsive is used throughout this exegesis to describe the interaction between external environmental conditions and facades systems.

Consequently, the concept of responsive facades has been described using multiple terms in the literature, however

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[5] Facades are positioned alongside other terminology such as envelope and skin. However in this discussion, it refer to the vertical exterior panel of the building.

[6] Natural condition is referred to reaction to an environmental condition and forces (Moloney, 2011)

the definition of responsive facades shows that the term presents a specific form of response which is a kinetic response (Fox & Yeh, 2000; M. Fox & Kemp, 2009; Moloney, 2011; Razaz, 2010). In this case, responsive is defined as the kinetic ability to respond according to the changing stimuli in relation to mechanical elements, pattern of use, and material properties (Fox, 2003a, p. 200).

From the description above, kinetic facades, which interact with environmental conditions, are discussed in this exegesis. Thus, environmental conditions can encompass a range of different elements such as daylight, wind and heat. However, for the purpose of this exegesis, the terms 'environmental conditions' are associated with solar radiation: daylight and heat.

The application of kinetic facades is not a new concept for reducing the energy demand of lighting and space air conditioning. According to a recent publication for the International Energy Agency of Energy conservation in Building and community systems (IEA-ECBCS, 2011) kinetic facades are put forward as a *"necessary step towards further energy efficiency improvements in built environments"* (ECBCS - Annex 44 - Integrating Environmentally Responsive Elements in Buildings,2011). In addition, it has been adopted in creating facades that can respond to environmental conditions since the 1920's.

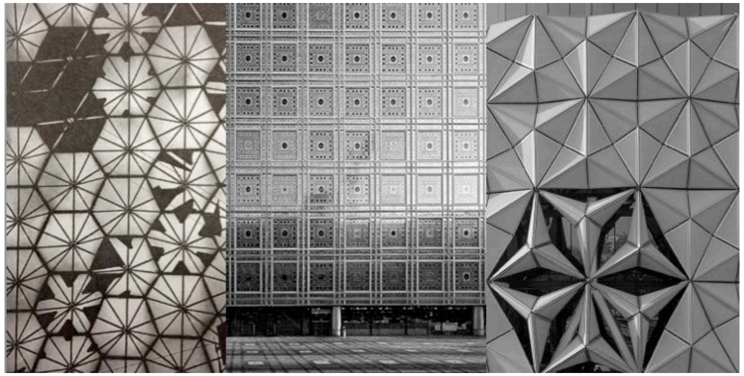

Figure 1: (Left) American Pavillion, Expo67, 1967; (middle) Institut Monde de Arabe, 1987; (right) Al Bahar, 2012

Recently, growing interest in investigating this topic has been seen in a number of publications and research projects (Ritter, 2007; Klooster, 2009; Schumacher et al., 2010). Parallel to this interest, there is a similar increase in the numbers of buildings that are adopting kinetic facades for environmental strategies (Figure1). Even though the application of kinetic facades has been used as a driver to achieve this objective, both in the past and in contemporary research and practice (Moloney, 2011); the significant gap in demonstrating how this concept can be implemented for improving building energy performance at the early design stage is still not clear in the literature. Furthermore, even if the advantages of kinetic facades are obvious, they are yet to be embraced by the mainstream. Even though facades that move and respond look uncomplicated, they have yet to prove that they can be constructed simply (Linn, 2014).

The development of kinetic facades that are present in the literature are mainly concerned with the functional possibilities and enabling technology (M. Fox & Kemp, 2009; Linn, 2014) rather than focusing on the potential of kinetic application for improving building performance. Fox and Kemp (2009) present a comprehensive overview of kinetic application in current interactive architecture by distinguishing between 'ways and means'. It is explained in various ways in which kinetics are manifested, 'folding, sliding, expanding, shrinking and transforming and the means by which kinetic are realised; the devices, ranging from mechanical to chemical technology (M. Fox & Kemp, 2009; Moloney, 2011). The advanced technology and materials exploited are due to the recent widespread availability of sensors and actuators, hardly creating any obstacles for creating kinetic facades to respond to changing environmental condition. However, the study on exploiting the potential of kinetics in creating is not publicly available, if it exists at all. This study is significant in providing an alternative approach to implementing effective kinetic facades for environmental conditions.

Based on this discussion, I extend my review of current literature and precedent studies through a similar research focus. However, most of the applications of kinetic facades, which are designed for environmental control, demonstrate very minimal data on how the designer exploits the kinetic patterns for environmental control. Since the term kinetic architecture was introduced - a term coined by William Zuk and Roger H.Clark in the 1970s, limited discussions exist that show how designers consider the potential of kinetic in relation to environmental conditions (Moloney, 2011). Despite the large amount of literature in this area, the emphasis of this exegesis is on the design process of allowing the facades to response to environmental conditions. My research is concerned with this discussion dealing with the design potential of kinetic patterns[7] to create responsive surfaces that have the capacity to protect internal building environments such as Monde Arabe Institute, design by Jean Nouvel[8] in 1987.

A recent survey published in *Interactive Architecture* by Fox and Kemp shows that a majority of activity is concerned with the functional possibilities and enabling technology, rather than investigation of kinetics per se (Moloney, 2011). Thus, the significance of creating facades that respond and adapt in order to improve a building's performance not only requires technological development, but also requires an effective design process related to it, besides financial, legislative and social barriers (Hoffman and Henn, 2008; Williams and Dair, 2007; Zerkin, 2006). In theory, this barrier can be traced back to a lack of knowledge and fundamental understanding for applying responsiveness to the design of kinetic facades (Loonen et al., 2013). While I am aware that an understanding of financial, legislative and social barriers can stimulate an awareness which will prompt the implementation of this concept, it is not the focal point of this research.

There are great demand for effective tools and instruments that can be used in the early design process by implementing this concept through kinetic facade systems (Addington, 2005; Loonen, 2010; Moloney, 2011). This tool should be able to assist the designers to identify and evaluate the performance of a kinetic facade in its early design stages. Identifying and evaluating kinetic performance are crucial because designing dynamic movement involves significant considerations of

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[7] Kinetic pattern which refer to cluster of individual moving components form various surface configuration

[8] Jean Nouvel, French architects was born in 1945. He well known for designing the *Arabe world Institute* in Paris. He also was awarded *Pritzker Prize*, architecture's highest honour, 2008 for his work on more than 200 architectural projects

the design of kinetic pattern and the components that enable the facades to be responsive. As opposed to static design, the process of evaluation are aims to locate the frozen moment of the object, where dynamic design involving kinetic facades that are dealing with constant change.

Jules Moloney in his book '*Designing kinetics for architectural facades*' (Moloney, 2011) has described in detail what ranges of kinetics motions are appropriate for architectural facades. This study is generated from digital animation, using precedent art and history as a background to inform his research on this area. Furthermore, Moloney (2011) identifies that kinetic movements (motions) have the kinetic potential of kinetic to be applied in the facades from an aesthetical point of view. Even though Moloney (2011) provides insight into the potential through the study of kinetic patterns and design approach, the research does not extend to how this kinetic pattern can be implemented to create kinetic facade systems that respond to the changing environmental conditions.

The introduction of kinetic facades that respond to environmental conditions changes the traditional way building are designed (Loonen, 2010). Kinetic facades are naturally more dynamic; meaning that they involve complex systems, consisting of integrated components that are interactively working together across physical domains in response to external environmental conditions. Therefore, the use of kinetic facades should be a design of 'process' rather than an 'artifact' (Jules Moloney, 2007). The 'process' can be described here as a designing through making and testing different component of kinetic facades while considering the potential of kinetic patterns in interact with their environmental conditions. This includes a kinetic mechanism, material behaviour and kinetic pattern[9], rather than designing one component and finding a solution for other components to fit into it. Typically designers focus on the final stage that involves physical

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[9] Kinetic pattern in this discussion refers to the formation of an active surface on the facades that is created by kinetic responses

components or specification of materials (Moloney, 2011). In realising the opportunity offered by kinetic facades are to be realised, designers need to be involved in the design of input and the control system as well as the components. For these reasons, traditional design methods are inappropriate and not longer able to rely on past experience such as "rule of thumb” principle in designing responsive systems, which include kinetic facades (Loonen, 2010). In addition, the application area of responsive kinetic facades ranges from built examples, successfully operating for many years, to the wildest utopian concepts. Due to the outcomes of these developments which emanate from creative processes, they are rarely published in scientific literature (Loonen, 2010).

The development of kinetic facades for environmental conditions has often involved the challenge of the materiality and the kinetic pattern in physical, architectural facades. Current approaches in the design of kinetic facades, which involve mechanical systems and moving components are always borrowed from mechanical and electrical engineering (Asefi, 2010). However, there is significant potential and demand for this knowledge and application, which can be extended into architectural contexts to inform the designers in the early design phase. This will provide a more in-depth view for the designers on the potential of kinetics, while helping designers to make more effective decisions in realising the facade system in response to environmental conditions.

In contrast to static facades, major applications of kinetic facades involve the element of kinetic pattern that creates the movement of the facades to respond to environmental conditions either at an intrinsic or extrinsic level (Beesley, 2006; M. A. Fox, 2001; Kirkegaard, 2010; Moloney, 2011; Pan, 2010; Schumacher, Schaeffer, & Vogt, 2010). The design of kinetic pattern always affects the ways that the responsive facades are designed of which ultimately affecting its performance since all the components of the kinetic facade must function efficiently in creating a movement. Based on this perspective, designs incorporating kinetic patterns actualising kinetic facades provide more engagement to the designer at the early design stage. Design research will educate the designers on specific qualities of kinetic patterns, which can be incorporated in the design of the facade in relation to environmental conditions and its potential to respond appropriately. This will set a different objective for the designers, who have traditionally worked towards finding the best static mix of performance and aesthetic (Moloney, 2011). Instead of fixed tectonic form, the outcome leads to kinetic processes, which interact with the designers (or users) and performs in respond appropriately to changing environmental conditions.

From this discussion, this research further elaborates on two main areas. The first being the kinetic pattern for the responsive facades system, the second being the evaluation strategies related to the performance of kinetic pattern towards responding to environmental conditions. Jules Maloney identified and evaluated the kinetics for architectural facades that were carried mainly through digital simulation approach. In contrast, these processes are explored and experimented through physical prototyping and testing and aided by digital modelling and simulation. These investigations primarily use physical prototyping and testing as the main tools to evaluate the presence and the performance of kinetic potential, and the significant approach to engage with kinetic movement for designing responsive facades, with adjustment to environmental control, at the early design phase.

The primary outcomes of this initial study lead me to the development of a 1:1 scale prototype of a responsive kinetic facade installation that responds to environmental conditions. Adopting physical prototyping activities supported by parametric design tools in the early design process is in order to suggest alternative design approaches for evaluating the performance of kinetic patterns for the responsive facades. Further integration with the sensors and actuators in this activity were used to simulate real boundary conditions (through physical computing), create alternative tools to assess the performance of kinetic patterns, which adjust to environmental conditions. From this development, a number of techniques and strategies for designing kinetic facades are proposed in relation to kinetic patterns that respond to environmental conditions.

1.1 Responsive Kinetic Facades for Environmental Condition

My motivation for commencing this PhD began with an enquiry into the absence of available data[10] for related to designing and evaluating the kinetic facades, and their performance in controlling environmental conditions. Even though various technologies and kinetic components exist and are available for responsive kinetic facades that deal with environmental conditions, my investigation does not intend to advocate the technologies and kinetic components, instead, the objective of this research is to focus on the design of kinetics, with emphasis on the motion itself as a main component and composition enabling the realising of kinetic facades. This is due to kinetic designs relying on the on the movement itself to respond and making decisions (Moloney, 2011; Razaz, 2010) based on changing of environmental conditions. The main objective is to identify its potential to serve as an effective zone[11] between inside and outside environments. This will help the designers to understand what is essential in designing kinetic facades that respond to the environment instead of matching them with the existing technologies as a solution to design the kinetic facade system. This approach will avoid some of the dilemmas that are evident in existing examples[12] of kinetic facades that do not perform and function, as they are intended to when incorporated into buildings.

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[10] Building owners and developers remain sceptical of the economic benefits and energy efficiency, often citing a lack of performance data from existing facades systems (Lee, Selkowitz, Levi, et al., 2002; Yudelson, 2008).

[11] Facades are define as a zone between inside and outside of architecture, generally oriented towards the vertical (Moloney, 2011).

[12] Further examples of the existing responsive kinetic facades are discussed in Chapter Two.

The design of movement in the kinetic facades, that respond to environmental conditions, are often adopted as part of the design strategies for building energy efficiency (Addington, 2005; Erickson et al., 2013; Linn, 2014; Loonen, 2010; Wigginton & Harris, 2013). However, it is rarely applied as a concept but as a functionally practical necessity in achieving its energy saving objective.. As it has been mentioned earlier, environmental responsive building facades associated with kinetic patterns have been implemented for many years (Moloney, 2011). Considering that two of the most frequently cited projects associated with this subject of discussion are the automated screens for at the US pavilion at the Expo 67'[13] designed by Buckminster Fuller, and Jean Nouvel's Institute du Monde Arabe at Paris; both demonstrate that they were farsighted projects ahead of their time in comparison with contemporary technology then available. However, there is very little evidence which demonstrates how the designers applied kinetic movement as a mechanism to respond to environmental conditions (Moloney, 2011). Even though this project demonstrates a kinetic transformation of the building based on dynamic weather inputs, which affect the energy demand, the innovative moving elements in responsive systems are always overly complicated, which leads to technical problems[14]. For

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[13] The United States pavilion was an enclosed structure of Buckminster Fuller's 250-foot diameter geodesic dome. During the day its acrylic skin sparkled in the sunlight, and when the daylight decreased, its interior lighting gave it a varying coloured glow. A sun shading system based on automated blinds was integrated, and the ambitious goal of tracking the sun's position through the use of a computer-controlled system was implemented. The blind motor mechanism that was controlled by 600motors (one mounted at the centre of the hub of each group) constantly failed during the operational of the building (Massey, 2006).

[14] Institute du Monde Arabe remains somewhat of an enigma, since mention of its mechanical function inspires confident statement from both admirers (it's always worked) and critic (it's never worked), but it is certainly a foundational building in that it demonstrate in dramatic fashion how the facades of a building could

instance, a consequence of this technical complexity issue will lead to problems for a buildings' energy performance. Thus, the vision of the future that these facades provided for buildings remains largely illusionary.

Recent interest among designers within an architectural design context concerning environmental performance has led to an interest in incorporating kinetics component as responsive element to adapt to different environmental condition. Ranges of environmental sunscreens have been constructed, and new systems and technology are continually being developed. However, limited knowledge exists which describes the implementation of kinetic pattern and composition, in constructing responsive facades that achieve this objective and avoid similar issues that have been discussed previously.

This issue further reinforces my motivation to investigate the functional aspect of the kinetic systems in creating kinetic composition and surface that are responsive to environmental conditions. These investigations are validated through a process of constructing and reflecting physical kinetic properties through prototyping and digital simulations, during the design stage. The main focus of this investigation is on the early design stages, where it forms a crucial part of the decision-making process, often accompanied by a time constraint.

This research is driven by the potential of kinetic movement to create an interactive surface in response to environmental controls, as discussed earlier. Motivated by this potential, it will serve as an alternative approach for incorporating kinetics as part of an approach in response to environmental conditions. The emphasis on the potential of kinetics and composition in creating responsive kinetic facades at the initial design stage, allowing the designer to evaluate the physical performance of the kinetic in casting an interactive surface and maintaining the objective of the facades' function. By maintaining the objective of designing

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be subjected to constant tuning to affect the interior environment. It's real switch from expecting internal systems to make excuses for a poor performing architecture (Linn, 2014).

facades early in the design process, it will prevent the design from failing (Kontovourkis, Phocas, & Tryfonos, 2013).

These processes are explored through a holistic approach to architectural design. It is conducted through an interactive process between physical prototyping and physical testing aided by a digital prototype. This process reflects the alternative solution for designing and manufacturing kinetic designs and prototypes. This investigation covered different types of kinetic movement, which are effective for integration as part of a responsive facade. Furthermore, the investigation will evaluate the performance of interactive surfaces generated from compositions of kinetics through real boundary conditions using physical testing. Even though the materials used in this investigation are not the actual materials used for the building facades, the materials applied in this investigation possess similar attributes to the actual materials intended to be used during this investigations. Despite this, it should be noted that kinetic and responsive materials are not the focal point of this research, which is mainly aiming to investigate the design and performance afforded by kinetics and its design incorporation in regard to building facades.

The proposed design process for evaluating kinetic facades are incorporated into a feedback loop mechanism within the performance based design process (Phocas, 2012). In this exploration, control mechanisms and responsive systems are incorporated to provide a holistic design approach. This holistic design approach is represented as an interactive process that moves repeatedly from *'creativity'*, generated from the physical prototype to '*effective*' given by digital simulation and physical testing processes.

Therefore, these strategies explore the design and performance of kinetic facades through physical prototyping with the integration of physical computing and digital software. The development of the investigation evolved through careful strategic experiments to understand and explore the alternative possibilities of design and evaluation techniques to improve the kinetic facade's performance. This was developed through three main bodies of investigation, which led to the final prototype experiments. Every strategy involved investigation of the elements of kinetics and how they will contribute towards actual building facades. Further investigation focusing on kinetic performance towards building application in response to environmental conditions will be undertaken. This is significant, as kinetic facades should consider basic environmental factors, which include temperature, lighting levels and humidity in their early design phase (Moloney, 2006). Lessons learned and understanding developed from the previous two investigations are projected to actual one-to-one scale prototypes which are tested in the actual building context with the integration of physical testing and digital simulation tools.

1.2 Research Aim

The aim of this research is to investigate the strategies for designing kinetic facades, which respond to environmental conditions through kinetic pattern and composition. The investigations are demonstrated through the design evaluation of kinetic movement and composition of kinetic facades performance through physical prototyping and physical testing aided by digital simulation tools. The goal of this exploration is to establish early design processes, which are effective as alternative solutions to isolate design problems associated with kinetic facades design that respond to environmental changes.

1.3 Research Question and Hypothesis

The historic nature of kinetic movement is a physical reaction derived from physical forces to their surrounding environment, such as friction and gravity (Parkes, 2008). *How do designers design the physical transformation of kinetic patterns and evaluate the performance of kinetic facades in response to environmental conditions?* While designers have numerous techniques and tools to evaluate the performance of facades systems, similar methods for creating ways to visualise and model the kinetic transformation of kinetic facade systems through space and time are lacking. The emerging field of kinetic responses creates a basis that provides designers with a guide through the physical process kinetic transformation (Parkes, 2008). However, to mediate this new field, the development of evaluation tools and kinetic design based on the environmental conditions become necessary.

From these questions, I hypothesise that, through an exploration of response and composition, the facades will effectively respond to changes in their environmental conditions. The performance of these facades can be evaluated at the early design stage using physical prototyping and testing. Through consistent experimental framework of design, prototype and testing kinetic movements, a new design approach and alternative tool to the design of kinetic facades for environmental control can be established.

My investigation intends not to lead to perfecting technology and design tools for responsive kinetic facades; rather it is to establish the parameters used to design facades, involving kinetic movements. From this outcome, it will allow potential design possibilities that that will emerge as a result of this investigation.

Essential for defining responsive kinetic facades in the design process and realisation, is the word ‘effective’ that is used often throughout this exegesis. The term implies that the performance of kinetic facades should be deliberately considered in the design of kinetic patterns in designing responsive behaviour and not based on ‘coincidence’. In reflecting on the application of current facades, they tend to be developed in layers, resulting in facades which are divided into a subdivision conflicting with another subdivision; which resulting of the facades function as partial solution only. Thus, Lichtenberg (2009) describes it as construction that has evolved in a way called ‘innovative by addition’; an approach that leaves room for substantial improvements.

Making the kinetic move effectively in response to environmental conditions is significant in constructing kinetics. Previous applications of kinetics, which involved complicated control systems, have tendency to break during the building operation.

A well-cited example of facades that adopted kinetic movement as a strategy to respond to environmental conditions is the Institute du Monde Arabe. The Institute du Monde Arabe applied Arabic screens that implement kinetic elements as a way to control light and heat. The facades are design with intricate responsive mechanisms, which involved heavy mechanical components embedded with multiple pistons, were developed throughout its facades. This mechanism was integrated with very complex kinetic components to create a transformation for opening and closing the facades. As development of the facades were driven by environmental agendas (Moloney, 2011), the breakdown of the mechanical components of facades, affect the building performance to function accordingly. However, the designer, Jean Nouvel, appears to have less interest in investigating further the kinetic problems of the 25 000 shutters, and defends the operational failure by saying, the movement is too slow and that most people assume that it is not working (Moloney, 2011). Even though there are a number of publications and blogs, which criticise the functional condition of the facades, there is minimal discussion about the impact of the kinetic and the composition of the facades towards environmental conditions.

The use of kinetic facades has been adopted since the 1960s. The earliest recorded example is from 1962 being a design by Richard Neutra. Neutra designed the responsive brise-soliel[15] of the Los Angeles County Hall of Record (Borden & Meredith, 2012). Even though the technologies in kinetic facades field is developing, there are no clear indications or discussions on the kinetic response and design composition in the context of environmental control has been largely absent. Even though development of technologies is growing in the kinetic facades area, there is very little discussion on the kinetic composition and the kinetic performance toward environmental conditions. *What are the strategies for*

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[15] Brise-Soliel in architecture refers to a variety of permanent sun-shading structures, ranging from the simple patterned concrete walls popularised by Le Corbusier in the Palace of Assembly to the elaborate wing-like mechanism devised by Santiago Calatrava for the Milwaukee Art Museum or the mechanical, pattern-creating devices of the Institute du Monde Arabe by Jean Nouvel.

applying kinetic composition in kinetic facades as environmental performance? In designing effective kinetic facades for environmental conditions, focusing on the early design stage is crucial as determining appropriate types of kinetic compositions will deliver effective functionality toward environmental conditions are essential. The ability of the designers to interact with the performance of the kinetic response as early as possible during the design stage provides an opportunity to engage and foresee the problems and the challenges in designing and evaluating performance of kinetic facades. These activities help designers to effectively evaluate the facade's performance through the design and application process. The current discussions, outlined in the literature reviews, present on how the kinetic composition should be approached in the early design stage, are minimal. Through physical prototyping and testing with the integration of physical computing and digital simulation, insight will be provided into how the design's kinetic response can be realised. Based on this insight, I am led to this question:

How do designers identify and evaluate the characteristics of kinetics in architectural facades that respond to environmental conditions, during the early design phase?

This main research question requires me to conduct investigations into this subject throughout my PhD candidature. Along with the literature review and precedent studies, my investigations are conducted through project-based research[16]. Project-based research involves experimental projects that generate a new design understanding, informing the design decision during every project experimentation activity. In addition, the outcomes generated from this research are qualitative.

I do not intend that the outcome of my research question serve as a perfect tool to evaluate the kinetic facades performance. Rather I seek to establish the design

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[16] This PhD research degree may be undertaken in thesis mode or through an architectural research project documented with framing exegesis. See http://www.architecture.rmit.edu.au/Courses/PhD.php

possibilities to evaluate the kinetic facades performance that suggest alternative parameters and approach in design facades that deal with kinetic movement and composition.

Through these activities that integrate alternative design tools and physical and digital testing for evaluating the performance of kinetic facades, I suggest that the ability to interact with and '*tune*' the kinetic components and composition. This provides an insight that reveals unforeseen material tendencies and thus, enabling the exploration of complex kinetic aggregate behaviour, which is difficult to explore during the early design phase.

This will suggest alternative tools and platforms for the designer in evaluating the kinetic facades for environmental control. Through prototyping and physical testing, an outcome will be demonstrated by using accessible kinetic facade materials and components with the integration of sensing devices and parametric design tools. Thus, through this exploration, my research will expand different patterns, movements and compositions with the potential to fit in with the current technologies and application.

1.4 Research Methodology

'Design is a way of inquiring, a way of producing knowing and knowledge; this means it is a way of researching.' (Downton, 2003, p. 2).

The extent of my exploration on how kinetic patterns can be explored through physical prototyping and testing with the integration of digital simulation in designing kinetic facades for environmental performance requires an action research method. An action research method involves designing and performing tasks, which will be directly executed by the digital and physical tools and reflecting on their performance. It is approached within the context of designing a model where the designer is more or less reflecting on the current understanding of the problem and the validity of the emerging outcomes and solutions (Lawson, 2006). For this reason, my research has been structured around three sets of practical investigations and is presented for examination as research by project.

Upon embarking on this research in 2010, my assumption was based on the literature review and both my experience and inexperience, of how digital and analogue technologies might address kinetic response in identifying and evaluating a kinetic facade's performance. How could physical prototyping and digital simulation address the gap between design intention and execution of kinetic facades for environmental conditions by facilitating a “direct link from design through to construction”? (Kolarevic, 2005).

As part of my investigations into the subject, I simultaneously undertook a literature review exploring the historical and contemporary design of kinetic facades for environmental control and carried out series of case studies related to the design and evaluation to discover suitable kinetic composition for responsive facade design and performance. Through physical and digital testing, this research has not been focused on a single particular design technique or evaluation process; instead it was allowed to evolve through three different practical investigations, each forming the basis of the design of the subsequent one. These investigations have enhanced the understanding of how physical testing might strengthen the relationship between the kinetic design and performance evaluation of kinetic facades for environmental control.

1.5 Research through design

Through undertaking these investigation and experiments, I have adopted an approach of research through design in analysing results. This exploration of knowledge partly through making artefacts has brought a new dimension to design research as the design researcher not only created artefacts in the process of making them (Mäkelä & Nimkulrat, 2011a). This family of research methodologies allows designers to elicit reflection in on their working process (Schon, 1983) than can be considered new knowledge gained in action. Bob Dick (1999) suggests that: *“In most of its forms it does this by using a cyclic or spiral process which alternates between action and critical reflection* (Dick, 1999)*”*. Furthermore, action research refine methods, data and interpretive capacity in the light of the information developed, and understandings gained in earlier cycles. Dick concludes that action research is: "*an emergent process which takes shape as understanding increases; it is an iterative process which converges towards a better understanding of what happens* (Ibid)".

In addition to Dick's definition, the editors of the handbook of action research: Participative inquiry and practice explain that: "*good action research emerges over time in evolutionary and developmental process, as individuals develop the skill of inquiry, it leads not just to new practical knowledge but to new abilities to create knowledge. In action research, knowledge is a living, evolving process of coming to know the origin in everyday experience; it is a verb rather than noun* (Bradbury & Reason, 2009; Reason & Bradbury, 2001)". Upon reflecting on this assertion, each of my investigations has been devised and carried out in response to findings and reflections from earlier practical work and complimentary theoretical explorations, as opposed to structuring my research around a predetermined set of projects.

In addition, knowledge is intertwined in the practice of design (Cross, 2001). Cross argues that the knowledge of the design resides in people, process and products. Part of this knowledge is inherent in the activity of designing and can be gained by engaging in the reflecting on the activity conducted. Furthermore, knowledge also resides in the artefacts themselves in the form of materials (Cross, 2001). Some of this knowledge is inherent in the process of manufacturing the artefact, gained through making and reflecting in exploring and creating these design artefacts. Thus, the triangle of designer-making-artefact seems to provide a useful means through which it is possible to approach designer's ways of knowing (Mäkelä & Nimkulrat, 2011a)

Therefore, this approach has allowed me to move beyond my original assumptions and ideas, with unexpected outcomes and insights that address my inquiry in a more comprehensive manner than I could have imagined prior to undertaking this research.

1.6 Reflection in action

During my investigations, this research has adopted the concept of reflection-in-action from Donald Schon (1983). Schon closed the distance between action and reflection that is involved in working with architectural design. This is a useful tool for dealing with complex practices such as designing kinetic facades, which provide a considerable amount of information for the designer in the decision making process – or the capacity to 'think', 'do' and 'test' simultaneously.

In addition, Schon describes that: *"When someone reflects-in-action, he becomes a researcher in the practice context … He does not keep means and ends separate, but defines them interactively as he frames a problematic situation. He does not separate thinking from doing, ratiocinating his way to a decision that must be converted later to action* (Schon 1983, p. 68-69)".

My research has focused on evaluating the performance of kinetic facades through digital and analogue prototyping, the notion between thinking and doing – between the virtual world of ideas and tangible world of kinetic facade performance. As a result, this investigation acts as a powerful metaphor for my action research. In addition, awareness of Schon's concept has enabled me to identify and critically analyse findings. From this analysis, I was able to gain insight from my investigations and outcomes by producing and testing them. The structured nature of my investigations through action research methodology has allowed me to immediately inform the kinetic design and performance, and in turn, the modified the designs based on the information gain for further design developments.

Through conducting my research via a project-based approach, it allowed me to point out what the specific outcomes led to. Through stages of exploration, to an intervention or the sudden recall of useful information, resulted in a new direction of inquiry (Downton, 2003). In addition, through design investigation that was adopted in this research, it generated what Downton (2003) describes as 'design knowing', where the process of designing produces new insights and understanding for the designers. The moments of knowing in this process become knowledge, which has the potential to develop, spread and become recorded as collective knowledge. This method of investigation is appropriate for my research subject as it involves learning and knowing through the process of feedback, which is another aspect of designing (Downton, 2003). Downton (2003) further describes this subject, by stating that *"designing is an ability which requires and utilises both doing and reflexive thought about that doing. Part of the process is constantly concerned with reflecting on the process and improving it"* (Downton, 2003, p. 99).

The reflection and investigation of this research is developed through design simulation for evaluating the performance of the kinetic design and the facades themselves, which involves interdisciplinary reality (Groat & Groat, 2013). This includes simulation research that involves control replications of real-world contexts or events for the purpose of studying dynamic interaction within the setting (Groat et al., 2013). Colin Clipson refers to replicate contexts as '*virtual worlds*' and the content of these environments as '*synthetic elements*'. The philosophical assumption for this approach, in Clipson's words, is that*: "synthetic elements of the virtual world are accurate representations of the real world in all effects"* (Groat et al., 2013, p. 278). The experience of these elements is similar to what one would experience in the real world".

From these statements, investigations using the simulation process occur when the replication of a real-world context (or a hypothesised real-world context) contains within it, a dynamic interaction that is the result of manipulated factors. These interactions are reflective of the interaction that occurs in the real world, and thus, simulation research design is one an approach that can collect data on these interactions for application into real world contexts.

Engaging with the fields of computer science and interactive architecture, there is a need to involve simulation, as it is fundamentally different to visualisations. If visualisations operate within a representational paradigm, it is aimed to design a system's actual behaviour rather than visual similarity. Here, the data is seen as a parallel instantiation of a data-scape based upon the measurement and combination of real life events (Groat et al., 2013). As it involves climate-based simulations of weather, where these descriptions depend on processing real data streams which indicate detailed changes in environmental conditions such as daylight and thermal heat. Through simulating the weather within a computational system it becomes conceptually 'as real as' the weather that we experience (Tamke, Nicholas, & Thomsen, 2012). As a result, the tradition of representation is replaced with the cultural paradigm, in which data is extractable and calculable in meaningful ways.

The proposed design investigation for kinetic response for kinetic facades are based upon a process of combining physical prototyping, and parametric design tools to evaluate the performance of the kinetics of the facades system presents the possibility of kinetic building configuration components to respond to environmental conditions and changing state of facades. The sensory devices cause the facades to respond and trigger the configuration of changes. This experiment uses a combination of physical and digital model configurations because of their ability to provide a simultaneous conceptual manipulation of spatial/configuration, physical/behavioural and material/construction aspect of kinetic design. This process also facilitates the discussion of design ideas and analytical tests combined with existing computational simulation tools like *EnergyPlus*[17] and *Ecotect*[18] at multiple points during the design process. Experimentation through this method ultimately results in an iterative design process that supports kinetic conceptualisation, materialisation and construction information (Schon, 1983).

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[17] EnergyPlus is a whole building energy simulation program that engineers, architects, and researchers use to model energy and water use in buildings. -http://apps1.eere.energy.gov/buildings/energyplus/

[18] Autodesk® Ecotect® Analysis sustainable design analysis software is a comprehensive concept-to-detail sustainable building design tool. - http://usa.autodesk.com/ecotect-analysis/

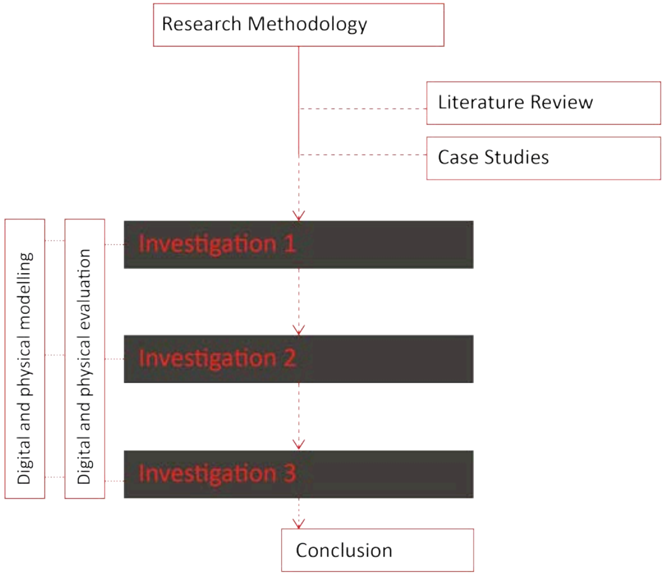
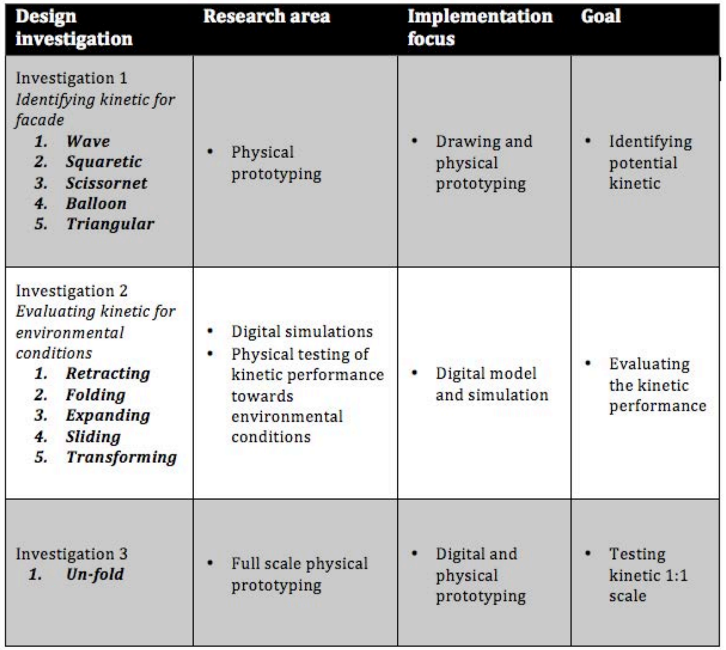


Figure 2: diagram of action research and investigations

1.7 *Tools, techniques and technologies*

To conduct this research, I have engaged directly with range of computational design tools and become familiar with number of digital and analogue fabrication processes. These tools are explored in an organic way to ensure the kinetic design work effectively in order to achieve specific design objectives. Throughout the investigations, different types of tools and techniques are used (Table 1).



Design investigation	Research area	Implementation focus	Goal
Investigation 1 *Identifying kinetic for facade* 1. ***Wave*** 2. ***Squaretic*** 3. ***Scissornet*** 4. ***Balloon*** 5. ***Triangular***	- Physical prototyping	- Drawing and physical prototyping	- Identifying potential kinetic
Investigation 2 *Evaluating kinetic for environmental conditions* 1. ***Retracting*** 2. ***Folding*** 3. ***Expanding*** 4. ***Sliding*** 5. ***Transforming***	- Digital simulations - Physical testing of kinetic performance towards environmental conditions	- Digital model and simulation	- Evaluating the kinetic performance
Investigation 3 1. ***Un-fold***	- Full scale physical prototyping	- Digital and physical prototyping	- Testing kinetic 1:1 scale

Table 1: Overview of projects and three investigations conducted throughout this research projects. Source: Author.

Investigation One: Identifying kinetic patterns for responsive facades. From the beginning of this research, I believed that adopting large scale physical fabrications can revolutionise the process of architectural design-to-production of kinetic facades. This can be achieved by facilitating the direct construction of infinitely complex architectural form and physical realisation of kinetics without the difficulty posed by complicated representations and potential misinterpretation. Working with physical prototyping with the aid of digital tools at a more manageable scale will reveal important insights for kinetic facades design and performance in dealing with kinetic patterns. Therefore, Investigation One, which previously discussed in Chapter Three, describes on the process of designing and producing a series of kinetic patterns for application in kinetic facades. The prototyping and fabrication of kinetic facades prototypes involves different approaches and techniques, which inform one another.

Investigation Two: Evaluating kinetic patterns for environmental conditions. These series of experiments engages with a performance based design approach for integrating kinetic facades and environmental performance. Parametric modelling software called *Grasshopper* was used in order to develop different types of kinetic facades. The environmental software, which was tested and employed for this investigation was *Ecotect* and *Climate Consultant*[19]. This was in order to study the performance of the kinetic facades throughout the year in Melbourne, Australia. Both software systems were used and were integrated with generic evolutionary software called *Galapagos* [20] as a tool to integrate different parameters (i.e. size of opening, geometry etc.).

Investigation Three: Full-scale Physical Prototyping of Kinetic Facades. This investigation further explores the evaluation techniques for the performance of kinetic facades' by using physical testing. The setups were tested using physical simulation techniques in an attempt to replicate the existing boundary conditions. Further elaboration of this investigation will be presented in chapters three and five of this exegesis.

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[19] http://climate-consultant.software.informer.com/5.4/

[20] http://www.grasshopper3d.com/group/galapagos

1.8 Exegesis Structure

The structure of this exegesis reflects the action research methodology that I explored between a critical examination of theory and reflective account of practice. These two components inform one another and are presented in such a way to emphasise the emergent nature of my research. Throughout this exegesis, theoretical research is compiled in chapters, where research projects are presented as investigations.

CHAPTER ONE: Introduction. This chapter provides an overview of the research on kinetic response. I explain how it relates to the realisation of facades that respond to environmental condition. It explains the motivation behind conducting this research as well as the current issues involving current building practices in the adaptation of kinetic facades design for environmental strategies. This chapter also outlines the research question and demonstrates the significance of reflective in action research methodology for framing the exploration and answering the question and test my hypothesis.

CHAPTER TWO: Background Research. This chapter states the problems and challenges that exist when exploring kinetic facade design in response to environmental conditions. The aim of this chapter is to identify fundamental problems that arise from dealing with kinetic systems through kinetic response for responsive facades. Furthermore, it will elaborate the process of design thinking towards the process of making the physicality of a kinetic system. I explain my central position - that designing physical prototyping with the aid of digital tools can become an active driver in order to understand the main problem of kinetic facade systems. This will lead to the question of: How much information can the designers learn from the previous application of kinetic facades, by adapting kinetic response and composition, in making decisions during the early stage of the kinetic facade design process?

CHAPTER THREE: Identify kinetic responses for responsive facades. This chapter identifies learning experiences and information that can be gained from the process of fabrication for kinetic systems. From these experiences and information, a better understanding can be obtained and ultimately applied to different media for evaluation. Furthermore, this chapter explores the design of kinetic facades mainly through physical prototyping with the aid of digital drawings in order to understand how the kinetic systems perform toward responsive facades. I draw on selected architectural literature to focus my research within the contemporary discourse and propose the initial question that my research addresses. Numbers of kinetic responses type have been discussed in the literature review and precedent studies. However there is very little discussion on what type of kinetic responses are appropriate for responsive facades and how they are identified. Even though there is very little discussion on the subject. Summaries of the literature and precedent studies identified types of motions that can effectively respond towards environmental conditions. This leads to the question in the first Investigation - How to identify and evaluate the kinetic responses for responsive facades? This question is explored in Investigation One.

Investigation One: This investigation discussed six small-scale prototypes and the outcomes are reflected in Investigation Two and Three.

CHAPTER FOUR: Evaluating kinetics for environmental conditions. This chapter provides the next phases of my research investigation, which were designed to answer the question: how effective are the digital simulation tools and small scale prototyping for informing the designer and providing experience for designing the kinetic facade system during early design phase? Furthermore, in this chapter, performance-based design is identified as a paradigm associated with better-informed computational simulation. From Investigation one, I elaborate further on how to enhance the kinetic facade performance. Furthermore, I also discuss new ways of designing kinetic facades through an integral design to production strategy, where material, structural and fabrication logic that are used to constrain early design exploration are within a context of rational and buildable structures and forms.

Investigation Two: Investigation Two begins unravelling this question by modelling kinetic facade design, informed by reflecting on Investigation One. This process reveals that a crucial aspect of utilising digital technologies for evaluating the kinetic responses for responsive facade system is their potential to put the designer in a position to make an informed decision. From the lessons learned and the findings from Investigation One, this investigation suggests that a multi-criteria simulation needs to be established in order for the designer to gain significant information and make informed decisions. Furthermore, this investigation suggests that possible outcomes may be achieved by integrating modelling software, environmental analysis, and form finding software during the kinetic facade evaluation stage.

CHAPTER FIVE: **Scalability: full-scale prototyping. Continuing on from Investigation One and Two.** This chapter discusses the design and testing of the full-scale models developed and their installation in the real boundary conditions, as described in **Investigation Three**. During this investigation, full-scale prototyping was utilised and tested in the actual environment. The studies show that linking generative digital prototypes to material explorations via physical modelling techniques provides a better-informed design exploration of kinetic facade systems.

CHAPTER SIX: **Discussion.** In this chapter, the outcomes of the three investigations are presented in the context of the literature review. The discussion suggests the potential of kinetic responses type that can be applied to the design of kinetic facades for environmental control. Furthermore, in this chapter, tools and effective evaluation technique are suggested for the designers to apply in the early design stage are discussed in this chapter.

CHAPTER SEVEN: **Reflections and Conclusion.** This is the final chapter of this exegesis. This chapter presents the discussion of effective design evaluation and techniques for designing effective responsive kinetic facades through the application of kinetic responses.

2 BACKGROUND RESEARCH

This chapter will introduce the application of kinetics for responsive kinetic facades in three sub-sections. This will provide an overview study to the emergence of kinetic response and contemporary discourse on kinetic facades in current practice. This review will include three main areas of background study. First, application of kinetic responses for architectural facades, second, contemporary practice of kinetic facades that respond to environmental conditions and third, the kinetic facade's performance. This chapter will discuss the relevant kinetic components and responsive kinetic facades designed within an interdisciplinary field. This overview supports a critical reflection of my multiple research projects and suggests alternative way for kinetic facades to design and evaluate in response to environmental control.

2.1 Toward Kinetic Facades: Designing with Movement

In theory, the challenges of designing the physical state of a building's elements such as the facade lies with the complex interaction of a very large set of physical components (Biloria, 2011). The application of kinetics for the facade system plays a major role in this interaction. This research contributes knowledge for architects about the potential of kinetics for the facade system to respond effectively to changes in its environment. However, there are very few coherent theoretical references, nor is there sufficient building evaluation data to critique the type of kinetic façade design that could be adopted for environmental control (Linn, 2014; Moloney, 2011).

Today, the application of responsive elements in a building, such as kinetic facades plays an important part in a building's operation. However, the architectural design principles and construction methods of kinetic facades have been under explored (Park, 2011). As a result of this lack of exploration, there is a demand for a new design approaches to integrate kinetic facades with the building's performance strategies. This demand comes from the need to generate a better design application in contributing to the building's energy performance. In response to this request, the need to understand the 'ways and means' of kinetic for building facades to respond to these issues are critical. Knowledge associated with the design of kinetic facades is incorporated among various disciplines that are not only involved with design from an architecture field but also the technology adapted from engineering and computer science. Therefore the need to establish design strategies and evaluation techniques when designing kinetic facades to aid designers in discovering the constructability and workability during the early design stage is vital in achieving the intended goal of integrating kinetic facades into the building. Consequently building facades with adaptive and kinetic properties need to be designed, constructed, and evaluated with a new approach, rather than a traditional design approach (Maloney, 2011). The needs of kinetic facade design to be designed and evaluated is critical in the early design stage to ensure the functionality of facades to respond to environmental changes and enhance the building 's performance.

One of the biggest hurdles in advancing the development of kinetic facade designs and the components that emerge from them is a struggle to design and evaluate the performance of actuated systems (Maloney, 2011). Significant time, energy and commitment are necessary in order to determine if an interaction achieves the desired effect and performance of kinetic design in response to environments. What is missing is an equivalent kinetic tool and materials that facilitate easy prototyping, which is general in both the static physical world and the digital world.

The integration of these interactions in one behavioural simulation creates major physical modelling and computational challenges. In adopting kinetic elements for building facades in order to respond to environmental conditions, the challenges are more difficult in assessing the façade's performance in the early design stage becomes more challenging. The ability to deal with the increasing complexity of scale and diversity of component interactions is crucial to be evaluated before the design are constructed in relation to building performance (Hensen, 2007).

The design approach for adopting kinetic components is not a new concept in architecture. Kinetic architecture was first introduced by William Zuk and Roger H.Clark in the early 1970s, when spatial design problems were encountered in mechanical systems (Zuk & Clark, 1970). However, there is limited discussion on the identification of the kinetic response itself for facades responding to environmental factors, despite the development of various types of technologies.

To develop a further understanding on the potential of kinetics to contribute to environmental response in facades, it is worth considering other disciplines such as an aesthetic and engineering point of view in understanding the 'language of kinetics'[21] (Moloney, 2011) to be implemented in kinetic facades that respond to environmental conditions. Therefore, what is missing from this understanding is an equivalent kinetic tool that can facilitate easy evaluation of kinetic responses for building facades, which is general in both the physical and the digital world.

Jules Moloney (2011) describes this as kinetic composition. Composition is mostly used as a broad and open-ended term, facilitating direct and indeterminate approaches for the design of kinetics. The discussions of kinetics in this chapter are focussed on kinetic composition, which includes kinetic control, structure and active surface. The discussion of Kinetic composition always related or involved mechanisms that determine the outcome of the design. Even though kinetic

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[21] How the designers form the kinetic phrases, sentence, or creating a dialogue interaction in composing kinetic facades (Moloney, 2011).

mechanism is broadly discussed in mechanical engineering field, there are very little discussion on this subject in architecture especially for building facades application.

Most of the history of the mechanisms used in the mechanical engineering is developed long time ago. When in 1875 Reuleaux published his extensive scientific analysis of mechanism namely the Theoretische Kinematik, he had to admit that nearly every example he studied had be known and in practical use for quite amount of time. His attempt to analyse and invent new mechanism lead to the old-established solutions, which is still better and significantly practical. Between 1724 and 1739, Jacob Leupold, an engineer, published a first book in this field called *Theatrum Machinarum,* explaining about this basic mechanism. He reviewed and discussed number of significant basic mechanisms and at the same time judged their practicality. He suggested that any machine consists of number of basic mechanism in which has its own function. Through combination of such basic units of the mechanism the designer ensure that the machine is well performs for the task it is designed for.

One potential source of inspiration that exists dated back to the eighteenth century between 1772-1779. Swedish engineer Kristofer Polhem[22] created Letters from a Mechanical Alphabet (Figure 3), which consisted of a series of small wooden objects that describe the mechanical elements. The alphabet consisted of 80 letters, each demonstrating the simple movement that is contained in the machine (A. Parkes, Poupyrev, & Hiroshi, 2008). For instance, in translating rotary movement into reciprocating movement, these objects serve to demonstrate a very direct relationship between

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[22] Christopher Polhem (18 December 1661 – 30 August 1751), also know as Christopher Polhem, which he took after his ennoblement, was a Swedish scientist, inventor and industrialist. He made significant contributions to the economic and industrial development of Sweden, particularly mining. His alphabet of machines demonstrated the basic elements of mechanism used by later machine builders. His rolling mill was later adapted by Henry Cort to the production of wrought iron in England - http://en.wikipedia.org/wiki/Christopher_Polhem

kinetic form and mechanical motion. His Mechanical Alphabet[23] principle demonstrates dissecting form and mechanics into an observable behaviour. Earlier, Polhem established five basic principles of his mechanism – the lever, the wedge, the screw, the pulley and the winch in what he describes as vowels, "*Not a word can be written that does not contain a vowel*", he stated; "*neither can any machine limb be put in kinetic movement without being dependant on one of these*" (Ferguson, 1994, p. 137; Ziman, 2003). In comparison with works demonstrated by Leupold, is unclear or missing from description which lead to the mechanism does not work or not working appropriately (Strandh, 1987). However, Polhem wooden models, which also pioneer in the area, demonstrated fully functional models of basic mechanisms, the collection which contained model of finished machines and fully developed construction. More scientific study of mechanism was initiated in France by the end of the 18th century. The *Ecole Polytechnique* introduced the subject in their syllabus as "analytical geometry". It categorised mechanism by the type of transformation of motion their demonstrated. For example, among the categories was the transformation of continuous rotation into an up and down linear motion. More than 21 categories were identified in these categories, on the basis of motions along curved and straight lines circles and spirals. This established some fundamental new mechanism categories that potentially developed on the basis of analogies. However, in this categorisation, the kinematic theory does not consider the effects of acceleration forces, friction and the performance of the mechanism which the studies only focusing on direction and speed of movements (Strandh, 1987). This limitation resulted to large number of designs but nevertheless impractical.

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[23] Mechanical Alphabet is part of the pedagogy that established by Christopher Polhem to teach, research and demonstrate mechanism movements. Mechanical Alphabet is the name he gave to collection of wooden models that demonstrated simple principles for motion conversion and used for teaching. The collection was returned to Stockholm after his death and become part of the Royal Model Chamber.

Even though there are shortcomings pointed out, number of scientist eagerly expands the study of kinematics. For instance, Franz Reuleaux, elaborated a details system of categorisation, complete with a functional coding of the variation type of kinetic movements. This categorisation of kinetic composition was published in 1875. Eventhough the introduction to this new categorisation do not have much practical benefits, later on Reuleaux discover that old-established mechanism solution usually proved better than all kinds of new fangled experiments and he mentioned that the best point of kinematic theory is, by applying the theory, further improvements could be made to establish and existing mechanism. Further, he added, “if you can acutely dissect a machine into its composing mechanisms, you will be able to formulate the best form for each separate mechanism” (Strandh, 1987).

From the previous works demonstrated by early scholars, the understanding of kinetic control provided a basic understanding as well as creating clear kinetic arrangements, which transmitted number of ideas to be implemented in kinetic facades. However, even though this principle has been adopted as part of our understanding for the design of complex mechanisms, there is no further discussion on how the principle of kinetic composition and kinetic mechanism for facades can be implemented in creating responsive building facades.

Due to copyright issues this images has been removed, Please find it at: http://www.alexdenouden.nl/artikelen2/labmech.htm

Figure 3. Christofer Polhem, letters from mechanical alphabet (A. Parkes, Poupyrev, & Hiroshi, 2008)

Antonino Saggio (2013) and Jules Moloney (2011) in their discussion of kinetic composition and interactive architecture, asserted that the aesthetic challenge permeates technology and functional logic. The particular challenge addressed here is that kinetics require the consideration of (as William Zuk’s states) ‘a sense of motion, itself’ (Zuk & Clark, 1970).

Ruben Hyden Margolin[24] created an intricate kinetic compositions inspired by the movement observed in nature such as waves and a bird flapping its wings. His exploration and experimentation through iterative processes for designing and testing that were involved in physical composition of kinetic movement demonstrate a clear manipulation of kinetic pattern and a composition for creating a spectacular kinetic sculptor. One of his installations called ‘Nebula’ is installed 45m in the air at Hilton Anatole Hotel in Dallas. This installation consists of 445 cables connected to 15,000 reflectors, generating a jewel like light in creating a kinetic composition, which imitates a swim-like effect. Margolin’s other works have a similar approach like “The magic wave” and “The square wave”, which demonstrate the ingenuity of kinetic composition that focuses on geometry and mechanical movements. Most of his installations, when combined together become, which Margolin refers to as ‘the matrix’, the intricate web of over *“2000 pulleys and four kilometres of cable, which produce different configuration of amplitudes and frequencies in casting water like, fluid movement”* (Soraya, 2012*).* As opposed to using digital tool to creating his art, Margolin described the physical movement he created and ultimately alert to the unnoticed movement of nature[25]. The kinetic sculpture by Margolin provided some insight into kinetic patterns

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[24] Reuben Margolin makes wave-like sculptures that undulate, spiral, bob and dip in gloriously natural-seeming ways, driven by arrays of cogs and gears. As a child, Margolin was into math and physics; at college, he switched to liberal arts and ended up studying painting in Italy and Russia. Inspired by the movement of a little green caterpillar, he began trying to capture movements of nature in sculptural form. Now, at his studio in Emeryville, California, he makes large-scale undulating installations of wood and recycled stuff. He also makes pedal-powered rickshaws and has collaborated on several large-scale pedal-powered vehicles (http://www.ted.com/speakers/reuben_margolin)

[25] www.ted.com/talks/reuben_margolin_sculpting_waves_in_wood_and_time

for kinetic facades, in terms of a design approach and exploration, that is - through a cynical process of physical testing and re-making in finding the 'beautiful' solution for his kinetic movement and composition. However, his work purely demonstrates kinetic sculpture as an aesthetic without considering any of facade's application or responsiveness to the environmental.

In a similar approach demonstrated by another kinetic artist, Theo Jansen kinetic work that takes an advantage of mechanical movement and wind in creating '*Strandbeest*'[26], a mechanical structure that walks in response to wind forces. His work demonstrates an integration of art and engineering in creating 'sport legs', which claimed to be more efficient on sand than wheels. The kinetic 'living' machine was created using very lightweight structures, plastic tubing (PVC[27]) and recycled plastic bottles containing air that can be pumped up to high pressure by the wind to create movement[28]. In comparison to Ruben Margolin kinetic sculpture, Jansen demonstrates the manipulation of kinetic movement through simple adaptation from wind energy and lightweight structures and mechanisms. From this manipulation of kinetic composition and mechanism, he was able to create a large-scale kinetic transformation from a series of kinetic components that have helped designers to understand kinetic mechanisms and movements. Reflecting upon these activities, he has demonstrated that artists appear to be significant in composing kinetic forms that influence kinetic facades.

Another kinetic sculptor is George Rickey, who developed an interest in the theory of motion in kinetic sculptures. One of his most successful kinetic works is the slow and graceful movements of Rickey's Counterweight which, operates on micro scales

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[26] Wind-walking structure - http://www.strandbeest.com/

[27] Poly (vinyl chloride), commonly abbreviated **PVC**, is the third-most widely produced plastic, after polyethylene and polypropylene

[28] http://www.strandbeest.com/

(Moloney, 2006). He wrote theoretical text called '*Morphology of Movement*' which described his observation and experience from the natural environment such as movement of the wave at the sea. Rickey created a steel sculpture based on a system of precisely engineered counterweights and bearings, which were activated by air currents and the pull of gravity. Rickey's essay demonstrates a few attempts at 'movement itself' such as moiré effects; transformation due to the motion of the observer; machines where mechanisation causes 'orchestrated' movement; light play; and 'movement itself' (Rickey, 1963). As most of the expressions are described as self-evident except for 'movement itself'; the unique movement in creating his kinetic art cannot be replicated as it combines space and time. Furthermore, he also described that the ontology of kinetics is best addressed by dealing directly with actual movement, rather than optical effects (Rickey, 1963). The classic movement of a ship at a sea described by Rickey; pitch, roll, fall, rise, yaw and shear provide a possible syntax for kinetic art. However, Rickey's kinetic references are always described as free standing sculptures, while the kinetic facades involve multiple moving part, oriented on a vertical plane (Moloney, 2011).

The works of Len Lye[29] also contributed to the language of kinetic art. Lye's analysis on the body of work developed as 'one artist's perspective on the art of motion' (Horrocks, 2010). Lye studies particular motion figures (figures, Lye meant as form and shape) involved in repeatable performance. Lye's kinetic sculptures are different compared to other artists, as he did not interested in the kinetics that involved mechanical motion; instead, he focused on the raw kinetic nature. His approach in exploring kinetic patterns resembles

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[29] Len Lye is well known artist within world of film and kinetic art for his singularity. In the word of painter Julian Trevelyn, 'He describe as man from Mars who saw everything from different viewpoint, and this attribute that made him original'. Lye is significant figure in kinetic sculptor and he was referred to as 'Tangibles". He saw film and kinetic sculpture as aspects of the same "art of motion", which he theorized in a highly original way of his essays (collected in the book Figures of Motion)

working in practice, or physical engagement (Moloney, 2011). His physical testing used a sheet of metal or a bunch of rods and experiments by hand, shaking, flicking and twisting in a form of physical doodling (Moloney, 2011). Furthermore, his early works, Blade (1976) and Trilogy (1977) demonstrated his approach to experiments the kinetics by identifying the morphology of motions. However, his works show a comprehensive understanding in composing kinetic patterns, which are valuable examples to the designer who intends to explore the components and the facades, that deals with kinetic components.

The works demonstrated by Margolin, Jansen, Rickey and Lye provide examples on how kinetic patterns can be manifested in creating kinetic art. The exploration of kinetic patterns through drawing and physical engagement, as well as testing and re-making, displays a strong approach for designing kinetic movement and creating abstract kinetic composition. From Lye and Margolin's exploration and approach to move away from digital animation during the exploration process to fully engage with the physical material in creating the kinetic sculptures, Lye demonstrates an alternative approach in identifying kinetic pattern and composition.

These precedents suggest definite possibilities for approaching kinetic patterns. Beyond a kinetic sculpture, the approach of exploring kinetics through physical engagement is highly relevant in providing examples for designers to deal with the kinetic movement of responsive kinetic facades, mainly during the early design phase. Even though, most of the artists provide some reassurance that kinetics can be conceived through an abstract morphology (Moloney, 2006), the discussion on how it can be applied as part of a kinetic facade in response to environmental conditions is not visible to the designers.

Engineer and artist, Chuck Hoberman, was involved in the prototype and full-scale building component for creating kinetic components that are expandable for adaptable design where he manipulated the scissor like structure in most of his works. His approach to the Hoberman sphere is perhaps his most well known invention that illustrates different scales of kinetics, focusing on the kinetic responses and build-ability. Recently, these interests have expanded towards creating components of the building, which have a similar behaviour, especially with indoor-architectural screens. Among the projects and prototypes developed by Hoberman[30] and partners, are the Tessellate surface, which was designed to have a continually changing surface pattern and opacity, which were integrated with refined detailing and adaptive performance strategies. These could be applied in the design of kinetic facades system in response to environmental conditions.

Similar in focus of this exploration is the recent installation by Asif Khan[31] on MeganFon pavilion designed for the 2014 Sochi Olympics in Russia. It consisted of 11000 kinetic actuators and pistons that were arranged in a triangular pattern that can be extended up to two meters which have the similar application with iconic Aegis Hyposurface, designed by dECOi (Goulthorpe, Burry, & Dunlop, 2001). This project transformed the building's facade into a three-dimensional portrait of a visitor who visited the building where their three-dimensional image was taken[32]. Each actuator carries a translucent sphere and the tips contained an RGB-LED light and formed an interactive surface based on the input gained from the three-dimensional images of people faces. This allows an image or video to be simultaneously physically displayed and projected within the three-dimensional pattern and configuration of the facades. Even though the kinetic components are used to create visitor portraits, there are encouraging possibilities that this installation can inspire designers to create kinetic facades for environmental

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[30] http://www.adaptivebuildings.com/

[31] Asif is British Architect. His work embraces the fields of architecture, industrial and furniture design, pushing the disciplines in interesting new directions.(http://www.asif-khan.com/)

[32] (MegaFon Pavilion, Sochi 2014 Winter Olympics | Atelier Ten, 2014)

control in terms of the application of actuators and kinetic composition and movement.

The works demonstrated by Ned Khan, '*wind veil*' at a domestic car park, Brisbane (2011) and Marina Bay Sands Hotel, '*Wind Arbor*' (2011), and Singapore presented simple environmentally reactive surface. For instance, the installation of the '*Wind Arbor*' demonstrates kinetic composition that has the potential to be applied as a kinetic facades system in response to environmental control at least, in the early design exploration. The wind walls created by Khan were created by using nets that are hinged on a metal disc, based on the 1950s advertising signage techniques produced a stunning visual effect[33]. Khan applied the similar concepts of kinetic response to create the effect of 'wind, rippling on water' on the vertical panels. The installation of '*Wind Arbor*' for example was embedded with half million hinged kinetic components that sway with the wind which in turn casted a physical pattern of the wind. The installation functions as a shade for the lobby, blocking half of the sunlight and heat. Intricate patterns of the light also provide light and shadow, which is projected on the walls and floor as sunlight passes. The art installation by Khan provides some consideration of environmental response and kinetic composition in creating a re-active kinetic surface. From Khan's work, designers can gain an insightful understanding for designing and manipulating kinetic pattern and composition of vertical and responsive facades. The application of kinetic pattern from this work has opportunities to provide basic knowledge and understanding for the design of facades that respond to environmental conditions.

Even though different types of kinetic patterns are used to create the sculpture and aesthetic of the kinetic facades, further identification of kinetic patterns for the facades that respond to environmental conditions are crucial. The next subsection discusses further, the existing kinetic facades that respond to environmental conditions. The discussions intend to identify types of

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[33] http://www.nedkahn.com/

kinetic pattern and composition that can be applied in order to effectively respond to changes in environmental conditions.

2.2 *Kinetic Facades for environmental condition*

Even though kinetic patterns have been used as a responsive component for creating kinetic facades since the 1960s, there is no smooth genealogy tracing the development of the kinetic facade (Linn, 2014). Kinetic design plays a significant role in building facades that are designed to respond to changes in environmental conditions. Even though the use of kinetics looks simple, they are not easy to create in order to respond appropriately to changes in environmental conditions (Linn, 2014). The requirement for effective kinetic application does not solely rest upon the technical expertise to achieve the transformability but it also relates to the effective response to environmental conditions.

This subsection discusses further, from the previous chapter on spatial kinetics in the practice of identifying the potential of kinetic to respond to environmental conditions. The spatial kinetic is discussed through the areas of structure, kinetic control, and active surface that form the kinetic facades. These areas are further subdivided according to translation, scaling and rotation and additionally material deformation, where appropriate.

Through a review of existing applications of kinetics, there are multiple ways in which kinetics are manifest: 'folding, expanding, sliding, shrinking and transforming' (Moloney, 2007). Even though there are a few terms describing these types of motion, most of them describe similar behaviour types of motions for kinetic facades application. One of Richard Neutra projects, the brise-soleil provides an example of early application of kinetic pattern in casting the kinetic facades.

Pavilion 67, designed by Buckminster Fuller (1967) is an early example that demonstrates kinetic application for environmental conditions using a motion of scaling. The self-regulation shading system is integrated sensors and actuators which thermostatically controls the structure's interior environmental conditions (Massey, 2006). The Pavilion is the large-scale test of Fuller's approach to buildings as an 'environmental valve' regulating, transmitting energy, light, air, moisture and providing a barrier between the interior and exterior. In Fuller's exploration of kinetics, he conceived a prototype of retractable shades made of plastic and photochromatic[34] glass, overlaid with tinted and metallised plastic film that feature 'oxygen porous silicon firms' permitting the enclosure to breath (Massey, 2006). The hexagon panels (Figure 4) are embedded with light sensors, which function to adapt to the changing conditions, shielding the occupant from direct sun exposure, while maintaining the greatest possibilities of openness[35].

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[34] Photochromic - lenses are lenses that adjust to the amount of Ultra Violet (UV) light directly exposed to the lens (http://www.worldoptic.com/lenses/photochromatic.html)

[35] Accounts of the US Pavilion have sometimes described its sun-shading system as computer-controlled, but the shades seem to have responded directly to solar stimuli rather than being governed by computerised feedback loops. In a technical analysis conducted during Expo 67, George F. Eber wrote that the US Pavilion sun-shading system 'consists of mechanically actuated, triangular sunshades controlled by 600-odd motors (one mounted over the center hub of each group of three interior hexagonal frames). The sun's rays striking it at a predetermined angle activate each of the motors. When the motor goes into action, it starts to pull at three sets of cables (six cables per set). These cables, in turn, are wrapped around window-shade-type rollers overlaid on the interior hexagons.' (Massey, 2006)

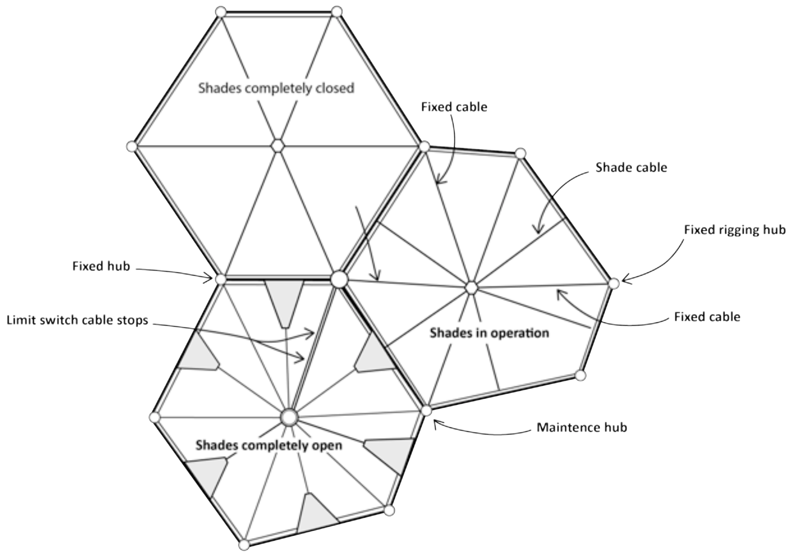

Figure 4: Hexagonal Shutter of American Pavillion 1967, designed by Buckminster Fuller (Massey, 2006) Sources: author

The shades designed by Fuller were linked by a central computer control was so that they could all be reset six times per day to track the movement of the sun. However, this vision was never fully implemented (Massey, 2006). Fuller presented highly visionary applications for an architectural responsive skin that had the ability to respond to environmental conditions, which were ahead of their time in terms of technology, however, they represent something that is feasible with the current technology. His innovations are now feasible utilising current technology. However, in this particular project, there is no clear discussions on the effectiveness of the shutters modulated that can contribute towards external environmental performance.

While, this kinetic response are designed and installed in 1967, an almost identical kinetic pattern is demonstrated by the famous Jean Nouvel kinetic facades, Monde de Arabe (1980). The incorporation of kinetic patterns and composition demonstrates a similar design to the US pavilion, designed by Fuller. While it was manifested on a different scale, the geometry pattern of the shutters in Monde de Arabe demonstrates a similar application of kinetic composition throughout the 25,000 photoelectric cells similar to a camera lens (see Figure 4). As discussed earlier, these facades received a number of critiques due to the failure of their kinetic shutters to respond to their environmental conditions due to mechanical problems. Institute Monde Arabe's facade showed continuous considerations for the surface that can actively respond to changes in environmental conditions. The south of the facades is composed of a 24 x 10 grid of square bays that consist of a central circular shutter that was set within a small grid of shutters – the design was adopted from the geometry of traditional Arab screens.

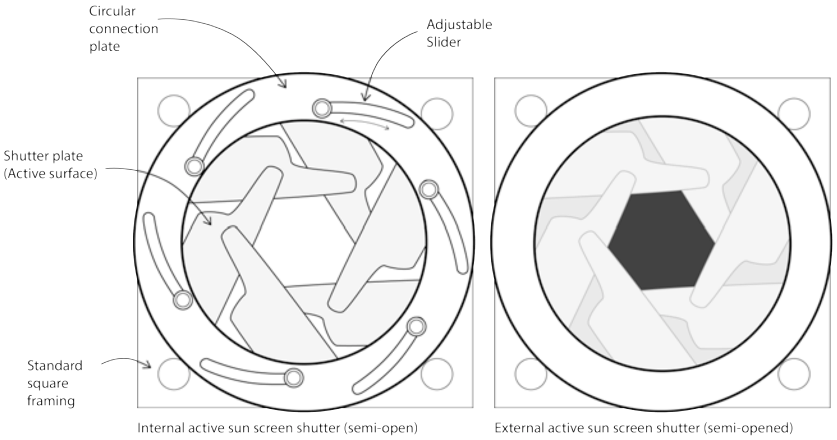

Figure 5: Kinetic Shutter panel of Institute Monde Arabe. Six shutters are used to create an open and close behaviour to respond to the daylight condition (Nouvel, 1987) Source: Author.

Kinetic composition becomes ambiguous in this facade (Moloney, 2006); where the shutter mainly involved rotational movement, where the opening and closing creates the scaling effects. The movement of the shutter set evoked a contraction[36] and expansion[37] effect with the facade system. Among other characteristics of Nouvel's facades, the central interest is on the facade that creates active boundary conditions and a modulating micro-climate (Hensel, 2013). This idea is related to the characteristic of building performance as described by David Leatherbarrow which, fulfilling the aspect of building efficiency by accomplishing the practical purpose and serving legible articulation between appearance and the operational performance (Leatherbarrow, 2009). However due to the sophisticated mechanism which allows the facade to respond to varying light intensities in the building by creating opening and closings, some of the kinetic shutters are no longer

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[36] Contractions referred to the decrease in size or shrinking, which form the shutter to create opening and allowing light into the space.

[37] Expansion occur when the shutter becoming larger and more extensive which lead to the shutters to close.

functioning (Mazzoleni, 2013; Moloney, 2011). The operability of a building becomes the main challenge in the architectural design process, in fact, the mechanisms must be designed to match the life span of a building (Mazzoleni, 2013). While, the kinetic facades design involved a heavy mechanical system in actuating the kinetic response, a similar pattern of design was adopted on the Abu Dhabi Investment Council designed by AEDAS[38] in Abu Dhabi. Despite the kinetic response used in this building, it is commonly identified to promote and warn designers of the perils in developing this type of aperture system.

Abu Dhabi Investment Council's headquarters, which was completed in 2012, consisted of a membrane clad kinetic facade with a similar hexagonal pattern in the construction of the active surfaces. The design of the dynamic *Mashrabiya*[39], adopted a similar concept by Nouvel to create a responsive kinetic facade. The dynamic *Mashrabiya* includes 1,049 units for the west and east side of the building, which claim to be the world's largest, computerised facade built today for 150 metre high towers.

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[38] http://www.aedas.com/

[39] The Arabic term given to a type of projecting window enclosed with carved wood latticework located on the second storey of a building or higher, often lined with stained glass. The *mashrabiya* (sometimes shanshool or rushan) is an element of traditional Arabic architecture that has been used since the middle ages up to the mid-20th century. It is mostly used on the street side of a building; however, it may also be used internally on the sahn side (Samuels, 2011).

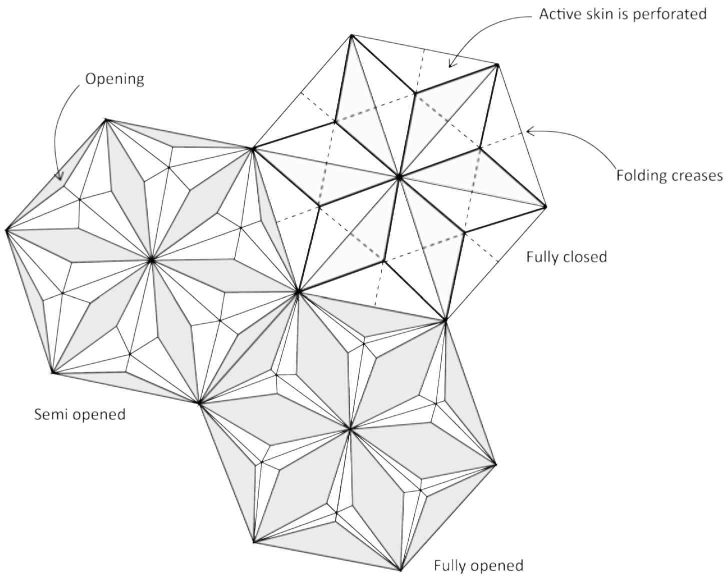

Figure 6: Abu Dhabi Investment council headquarters kinetic facades panels designed by AEDAS. Source: Author.

The kinetic facades create a folding and unfolding movement, which adapts to the sun and changing environmental conditions. The kinetic elements are programmed to transform into three kinetic states. The first of these states is totally closed. The second is mid-open. The third, fully open, which describes the scaling type of kinetic. The control systems of the facade adopt the piston mechanism, which categories into sliding type of kinetic pattern, in casting the facade's movements to regulate the environmental conditions. In terms of kinetic pattern for the whole composition, it creates an expanding and contracting effect to produce random surface patterns in response to local climate conditions. Even though the facades were embedded with recent technologies, they still required heavy mechanical systems to create the kinetic pattern for the facades. However, there is no clear indication on how effective the kinetic mechanism adopted for the kinetic facades have been in response to the environment.

A small-scale kinetic application example can be found in Milsertor Service Centre, in Tyrol Austria which uses folded sunscreens with banded pattern of prefabricated concrete elements for their main facades. Each folding screen is made of 6mm thick white plexiglass panels that, when closed, allow diffuse light to enter the interior space (Schumacher, Schaeffer, & Vogt, 2010). The facades of the building have s total of 1504 elements that are fitted to the facade. Each element consists of two panels that are attached to one another by a hinge, which is fastened by rubber mounted point fixings. In total, 18 different individual adjustable sections of the facade are fitted with sunscreen, each with 25 elements.

The kinetic systems are controlled by rods that act as two guide rails, one at the top of each section and one at the bottom, containing a gliding rod that is controlled by a toothed belt[40]. Half of the vertical posts are mobile and slide back and forth with a gliding rod, while the other half is fixed in order to open and close. The motor is embedded at a lower guide rail that is adjacent to the solid construction of the central section of the building. To ensure the kinetic movement is working effectively; a bevel gear system drives a synchroniser shaft that connects the upper and lower guide rail. This strategy is to ensure that the parallel movement of both the upper and lower gliding rods is correct so that the vertical post does not snag or twist (Schumacher, Schaeffer, & Vogt, 2010a). However, from this application, there is no clear verification on the kinetic movement or composition that is designed in response to environmental conditions.

The showroom for the company Kiefer Technic demonstrates another type of sliding application designed around its kinetic pattern. The kinetic movement on the facades are elements that are conceived to develop facades that change their appearance (Moloney, 2011). The active surface of the facades using 112 aluminium panels in the form of horizontal folding shutters have been mounted on a 7.75m high, supporting aluminium framework arranged in front of the showroom, along with glazed facades which create vertical composition, translation and scaling. The facades utilise electrical operated motors, which allow to the active surface to be raised, lowered and folded together. The 56 shutters are anchored to the building using stainless steel brackets to create a carefully designed an orchestrated and design harmonious effect. The motor accelerates gradually and comes to a gentle halt (Schumacher et al., 2010a). This demonstrates the significance of time as a consideration in the effectiveness of constructing the kinetic movement. Each kinetic element on the facades of the building is

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[40] The toothed belt is a flexible belt moulded with teeth, often referred to as a cogged belt.

individually controlled using a programmable PLC-BUS[41] system. This allows controlled elements to retract and expand to the degree that they are required. Albeit, the kinetic facades demonstrate the ability to respond appropriately to changes in environmental conditions; however, there are minimal descriptions on how kinetic pattern and composition are conceived in response to environmental conditions (Baird, 2013). Furthermore, the kinetic demonstrated in this application is typically uniform and regular tuning in relation to sun position.

Different applications of kinetic movement on the Nordic Embassies in Berlin (1999) are designed by Berger and Parkkinen and demonstrated a rotational approach to screens panels. The horizontal and orientation of panel are rotated through 90 degrees where each panel is individually controlled. The large fin slowly tracks the movement of the sun using thermo-hydraulic drives (Moloney, 2011). This similar approach also applied at the Melbourne Council House (CH2), which was built in 2006. In the CH2, kinetic patterns are integrated on timber, forming set of louvres to protect the building from harsh western sun (Newman, Beatley, & Boyer, 2009). These louvers are programmed by computer-control,[42] and the panel are embedded with a hydraulic system to control the closing and opening of the facades. Another example of a building façade which claims to adopt a responsive kinetic facade towards environmental conditions, is the building discussed by Alan Davies (2014). Davies examines the effectiveness of the Royal Melbourne Institute of Technology (RMIT), Design Hub's facade. In his article, Davies (2014) points out that

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[41] PLC-BUS is a power-line communication protocol for communication between electronic devices used for home or office automation. It primarily uses power line wiring for signalling and control (http://www.plc-bus.info/)

[42] Computer-control is used to program according to seasons for most of the facades that integrated with kinetic panels. Other buildings used this system includes Al-Bahr, FLARE and United State Federal Building, MORPHOSIS.

a number of design flaws exist that give an impact to the facade's ability to moderate environmental changes, which contradicting to the claim made by building's owner states that the facades are function not only as shading devices as well as energy collector. For example, it was originally claimed that the building's facade could harness (solar) energy in order to be able to power the building. This happen when the "cells" of the kinetic facades are upgraded from their current material, which is sandblasted glass, to incorporating photovoltaic (PV) collectors (Davies, 2009). Furthermore, Davies continues to point out that the building is claiming to be "green" *"it has no PV solar collectors at all"* which further poses the question of, was it meant to at all? (Davies, 2014). Additionally, the building's current materials limit the kinetic ability of the facade (the "cells" on the east and west having the ability for horizontal rotation only), which further restricts the facade's ability to perform environmentally controlling functions. For example, the discs are located inside metal cylinders; therefore there should not be an issue for the discs to provide shelter from the sun especially during the middle of the day (Davies, 2014). However, as a result of the cells circular shape poses a problem, as the cells are unable to tessellate, therefore, the kinetic facade is unable to completely protect the building against morning and afternoon sun. The facade consists of circle shaped cells may lead to another problem as the gaps exist between the circle which cover 21 per cent of the entire facades surface area (Davies, 2014). This means that 21 per cent of the facade is unable to respond to changing environmental conditions, such as the angle of the sun during periods of the day. This is an obvious, yet very important aspect of the Design's Hub facade that should have been rationalised in the early design stage.

In 2009, the building's vision statement claimed that the buildings facade had the ability to respond to environmental conditions, namely daylight (among others), rendering the building energy efficient (Davies, 2009). Based on Davies' first analysis of the building in 2009, he identified that the building was constructed without fulfilling the promoted vision. Further current assessment shows the visisonary claims remain unfulfilled (Davies, 2009)

Davies's concern predominantly lies on the lack of building analysis data (Davies, 2014). Prior to construction and post construction of the building there is no environmental analysis to validate the claim of the facades ability to respond to environmental conditions. This raises a number of questions such as from the buildings conception in 2009 and during the construction period, on what happened to the vision of having responsive facades that enhance the building energy performance? Furthermore, Davies suggests that a potential reason that these claims were never fulfilled were due to financial constraints and that it might be the cost of PV is high that resulted in the implementation of sandblasted discs. However, as a result of Davies' article identifying that the facades were in fact not "green" because of their inability to harness solar energy, the claim was modified by the building owner by saying that the facades *"had the potential"* to harness solar energy through the implementation of PV. In contrast, according to the architect, the design of the steel structures which holding the circular panels are designed to fit with different type of application such as PV panel if happen the sandblast glasses need to be replaced in the future. However, this strategy will have to observe specific design constraint, as the integration of PV will involve different level of component requirements such as different electronic and wiring application to fit with the existing facades structure.

Furthermore, once construction had been completed, and occupancy levels of the building increased, the implementation of a third skin was applied. Due to the excessive heat and light from the sun on the west side of the building, fitted controllable blinds were introduced in order to mitigate the effects and increase comfort for the occupants. The implementation of a third skin appears to be compensating for the kinetic facade's inability to provide adequate protection from its environmental conditions. In one sense the implementation of the controllable blinds and kinetic facades at the same time showed redundant of the facades functionality.

In contrast to the rotational movement of kinetic facades, the Media-TIC building in Barcelona, Spain demonstrates different types of kinetic composition to react to environmental conditions. Media-TIC[43] uses the ETFE[44] material to create an elastic responsive kinetic facade that is designed to improve thermal insulation as well as acting as a shading device using a pneumatic system. The first layer of the facade is transparent; while the second and third layers have a reverse pattern design (Cabrera, 2010). Once these layers are inflated they will join together creating a shade or in other words a single opaque area (Chilton, 2013). The inflatable facades use three air chambers, where the movement of the air manages the entire facades. With the integration of air and nitrogen augmenting the ETFE cushions, the systems are designed to be responsively active with the temperature sensor network integrated within the facade system. The ultimate idea of the facades is to create a 'cloud' that protects the building interior by using a combination of nitrogen particles and air form the ETFE (Chilton, 2013). Albeit, these kinetic facades demonstrate design considerations of the scaling type of kinetic that produces their expanding and contract behaviour. Again, there was minimal discussion of how the kinetic composition is considered in the design of the aforementioned facades.

From the review of current activity of practise in realising and prototyping the kinetic facades, there are a range of compositional opportunities for the kinetic that can be implemented in designing kinetic facades with ability to respond effectively to environmental conditions. The literature and precedent studies demonstrate that kinetic facades are designed for its environmental conditions and

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[43] The building design by architect Enric Ruiz Geli with the skin designed as inflatable ETFE available up to three air chambers. This strategy not only improved thermal insulator, but also allows the casting of shadow through tire, the layers which create shade. The first layer is transparent, the second and the third have a reverse design pattern that deflate together and create a single layer shade opaques.

[44] ETFE is a hybrid material (Ethylene Tetra Fluoro Ethylene) that is used for large structure and transparent building envelopes.

constructed with various controls, scales, kinetic patterns, as well as different materials. Moreover, the projects described in this chapter highlight a number of designers who are theorising architecture that is responsive and reactive by implementing kinetic facades that respond to environmental conditions.

To advance beyond the obvious kinetic compositional approaches (such as the proliferation of wave forms), some basic research needs to be undertaken, especially to evaluate the performance of the system. This includes an understanding of the variables that determine kinetics, iterative design and the evaluation of studies in order to explore the possible range of kinetic forms, and a shared set of terms to inform critique and evaluations.

2.3 *Towards evaluating Kinetic facades design that respond to environments*

The process of designing kinetic facades is complicated by the integration of kinetic systems and physical interactive reconfigurations for a facade's performance (i.e. responding to changes in light). Traditional development design tools centre on static design, where the need to design kinetic facades is a process that involves interactive elements that are essential in order to ensure effective function. As a result, this requires an alternative approach to the process of identifying and evaluating the appropriate kinetics for a façade's system in the early design phase, in response to environmental conditions. Evaluating the interactive components of a kinetic facade, involves various strategies and techniques, which inform the initial early design. This raises the question of:

What are the tools that are effective in evaluating kinetic facades in response to the constant change of environmental conditions, taking into account the constraint of limited time during the early design stage?

Physical Prototyping

Prototyping has always been an important part of the architectural design process. Prototypes provide designers with the ability to test and simulate how a particular design performs under a range of conditions (Fumar, 2011). For designing responsive components, it provided effective feedback in terms of understanding the material behaviour and the mechanisms involved (Björn Hartmann Jennifer Gee, 2006; Zarzycki, 2013). Albeit, digital tools are also important for dynamic design such as kinetic facades, physical prototyping allow the designer to have direct engagement with the material properties and behaviours that are hardly visible to the designers in the early design stage (Sharaidin & Salim, 2012). Digital engineering software such as *MatLab* [45] imitates the material behaviour as well as calculating the forces, which may be present. However, it is only involved in static design and is time consuming due to its complexity.

In contrast, building prototyping and physical mock-ups provide alternative tools for evaluating the kinetic design. Physical prototyping or building a mock up of kinetic facades is seen as a form of automatic and almost mechanical form of output, like printing, but not act as an integral part of the creative-problem solving process (Zarzycki, 2013).

Developing techniques and tools to evaluate the performance of the kinetic components of facades is essential to ensuring that the facades are working as effectively as intended. This approach can serve as an alternative strategy in the design process of responsive kinetic facades as it enables a move towards ‘interactive prototyping environments’ that provide new creative and technical opportunities for designers while improving the design and prototyping process. For example, the project of *Hygroscopic*, explored by Linn Tale Haugen (2010) demonstrates the process of prototyping through direct engagement with wood in casting the responsive building skin. During the early stage of her design experiments, Haugen engaged with the standardisation, tolerance and

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[45] http://www.mathworks.com.au/products/matlab/

liability of the material properties to design the responsive skin. This process further informed Haugen's decisions as a designer as it provides her with a better understanding of the behaviour of wood for creating an interactive skin. For example, the behaviour of wood is different according to which tree species the wood is harvested from and its growing environment (Hensel, 2013). Therefore, through direct engagement with physical prototyping, an informed understanding of the behaviour of the material is affected. This assists the designer to make more effective decisions for designing kinetic facades in the early stage of design.

For centuries architectural practice has used physical prototyping, especially physical scale models, to explore design alternatives in evaluating the design performance. Architectural, physical models are evaluated and interpreted in different ways as almost all tools are modelled in some way, or another. A physical model can be customed made to suit a particular goal; construction outcome, spatial qualities, studies on environmental conditions (Stavric, 2013). Consequently, their ease and use of tactile feedback affords the opportunity for designers to intensively use and learn through the physical models (Zarzycki, 2013). This is because, building and working with a physical model provides immediate feedback on the design. Since physical models are, in most cases, easy to adjust, varying types of information relating to changes in environmental conditions (i.e. temperature, light) can be observed that may not necessarily be obtained through digital simulation (Stavric, 2013).

In the context of designing kinetic facades in the early design stage, exploring the kinetic patterns through the development of a physical model generates interactive feedback to the designers in terms of their engagement of material properties and physical behaviour (Zarzycki, 2013). However, while current computational tools solve some of the design problems, they still leave many of them unresolved (Zarzycki, 2013). Geometric precision and physical forces are usually taken for granted by designers when involving the dynamic movement of facades during the early design process (Sharaidin & Salim, 2012; Zarzycki, 2013). The geometric precision and physical force are the main elements that determine the functional objective of kinetics used in responsive facades (J. Parkes, 2008). Through close engagement of physical prototyping of kinetic, with design of the kinetic facades, the challenge and problems in dealing with kinetic movement can be identified and potentially avoided by designers.

The works of Margolin and Lye for instance, which were discussed earlier, demonstrated systematic activities in physical prototyping for exploring kinetic composition. Margolin's works showed an example from his design of kinetic sculpture through physicals prototyping and re-making through physical models while searching for aesthetic movement in creating kinetic sculptures. In his design, for example, the centre of gravity and points of rotation are important factors for the effective operation of kinetic assemblies (Zarzycki, 2013). This hands-on engagement provides effective input to inform the designer in effective kinetic response. This is important as designing kinetics involves material-to-material interactions-friction and fatigue can become a critical design driver (Zarzycki, 2013). This approach to designing with kinetics will be further discussed in Chapters Three and Five.

Physical Testing and Computing

In the previous section, I discussed an alternative approach for investigating the kinetic movement of responsive facades during the early design stage. I also explored how this kinetic movement could be examined in response to environmental conditions. This section discusses the concept of physical testing with the aim to investigate alternative techniques for evaluating the physical outcome of kinetics in response to environmental conditions.

Physical computing is an essential evaluation technique in kinetic façade design as it creates new ways of exploring design that involve interaction and response. The role of physical computing in this research context is to transmit data between a physical prototype and an open source electronic platform such as *Arduino or Raspbbery pi.* When physical alternatives of control of kinetic facades are invoked, reverse synthesis (movement), is reflected by interpreting data generated from a *Grasshopper* and *Rhino* platform. Data flow from sensor nodes that are attached to physical models is transmitted to *Arduino* boards. *Arduino* sends an action command to the actuator. The *Arduino* and *Raspbbery pi* are synchronised to perform by themselves bi-directionally.

In the context of physical computing in architecture, it simply can be described as bridging the dialog between the physical environment and digital environment of the computer (O'Sullivan & Igoe, 2004). In the context of responsive design, it generates a conversation between responsive physical artefacts and the modelling of environments. In this section, the central discussion is based on integrating the computation as a strategy that evaluates the kinetic performance in the design of responsive facades. John Frazer, in his book, *An Evolutionary Architecture* stated that evolutionary architecture should be responsive to progress virtually as well as in real environmental conditions (Frazer, 1995). Frazer with his students at AA from 1989 to 1996 further developed this approach. Later Gordon Pask joined Frazer and his students to work on the same area, which involved architecture and cybernetics (Frazer, 2001). The works required the development of an algorithmic approach towards self-generating architecture for casting new design tools and creating models of responsive kinetic systems.

The application of cybernetics became appropriate to responsive kinetic facades as it concerns on control systems and feedback (Frazer, 1993). Control systems that integrate with feedback are considered as basic physical computing, which involves actuators and sensors. One of the projects demonstrating this application is the BIX installation at Kunsthaus, Graz and another project of Bollinger + Grohmann with Peter Cook and Colin Fournier, which demonstrates the use of a control system that gains feedback from building facades (Peters, 2013).

From the continuation of Frazer and Pask's works, the latest development in the field of micro-sensors and microprocessors is the *Arduino* open-source micro-controller. The *Arduino* has provided an affordable way for a designer to collect real-time data (Camarata, Gross, & Do, 2003; Peters, 2013). The sensor, actuator and microprocessor can be used to evaluate the kinetic behaviour and response to external environmental conditions. These tools are able to assist the designer to engage and interact with the physical and kinetic to evaluate the use of kinetics in responsive facades.

One of the difficulties in the early phase of design is to perceive the responsive performance of the kinetic movement while the kinetic facade is responding to the environmental conditions. Through the use of sensors and actuator the designer can gain feedback in real-time. The ability of modelling environments to feed back to the physical world through sensor-triggered interfaces allows the prototype to interact with the material and kinetic performance (Peters, 2013).

This process of designing kinetics in a physical environment allows "interactive trial-and-error" testing, which supports the iterative design process for kinetic facades during the early design stages. Thus, it will allow the designer to engage directly with the physical kinetic performance, resulting in more detailed feedback.

As physical computing becomes more visible to the designer, it creates an opportunity for the designer to explore and evaluate the response of kinetic facades to environmental conditions and a new way to simulate the effectiveness of the kinetics of facades. The opportunity integrates open-source parametric software such as Grasshopper and Firefly with an electronic application, which provides new possibilities for designing and evaluating the effectiveness of responses by kinetic facades.

Digital simulation tools

While the previous section discusses the opportunity of physical computing for evaluating the kinetic facades response to environmental conditions, this section will elaborate further on how digital simulation tools can be incorporated to evaluate the performance of kinetic facades.

The role of simulation tools for the design of buildings has been firmly established over the last two decades. Simulation speeds up the design process, increasing efficiency and enabling the comparison of a broader range of design variants, leading to more optimal designs (Loukissas, 2012). Simulation provides a better understanding of the consequences resulting from design decisions, which increases the effectiveness of the design process (Loukissas, 2012,). With most of the groundwork done in the 1960s and 1970s, a rapid improvement in advanced simulation packages for many aspects of building performance has taken place over the last twenty years. This provides the challenge of the next decade to better integrate simulation in the design process as a whole, to increase quality control.

However, although design tools are limited, they still can be used to completely execute an application on a simulated facade. They are tailored to one specific facade (Loonen, 2010), and they neither support interactivity, nor do they provide opportunities to model and simulate the surroundings of the kinetic facades for environmental conditions. Although many architects retain drawings as a means of expressing ideas, they are also adopting simulation as a mean to validate the performance.

The computer simulation of building performance aims at predicting and understanding the way the design will appear and behave (Radford 1993). The architectural practice faces the dilemma that it simply cannot possess all the knowledge in all the fields of expertise required to perform successful simulations. In this field, specialists not only deal with the development of the tools but also their application (Degelman, 1990).

Through taking over a lot of work of the designer, the advantages are easy to define. For instance, the designer can foresee and thereby react to the various aspects of the design before it is realised. This is very significant in the process of designing kinetic facades. Having to inquire about the design while it is underway is also a significant shortcoming for a simulation or analysis. In order to begin a simulation, the designer of the kinetic facade must have a solid understanding on the directions of the design and what it is exactly that is being simulated. The process of simulating and analysing is mainly one directional; based on the model used which a set of data is generated (Kilian et al., 2008).

In this discussion of my research, I identify the requirements for simulation that constitute the evaluation of Kinetic facades throughout out the analysis of my projects, which are climate and timescales.

Kinetic Respond to Climate

One of the requirements for successful modelling and simulation of kinetic facades in response to environmental conditions must use an appropriate set of weather data (Loonen, 2010). Throughout my investigations and experiments in this research I used Melbourne weather data in determining the specific location for the design simulation as my research are conducted in Australia. Even though there is other weather context are potential to be adopted in this research, to chose the weather context that closed to my research location are appropriate for the purpose of my kinetic facades installation and physical testing activities. Albeit the design intention in the construction of kinetic facades to be applied universally, using local climate condition is a crucial step to investigate the performance of the facades in the context of design simulation and testing.

To design and test the kinetic component in specific site condition is crucial, as different context require different setting and requirements. Even though the kinetic mechanism can be replicated to fit in with different context, the appropriate material and shading device sizing need to tune to fit the requirement of specific location. This strategy will maximise the potential of the kinetic facades to control or response to different weather requirements.

The set up of digital experiment and simulation to test the kinetic facades design are straightforward as most the current digital simulation tools are embedded with the weather data throughout the year that can be used accordingly. In contrast to the set up physical simulation for testing the performance of kinetic facades required a control of specific boundary condition such as temperature and humidity. One of the ways to create control boundary condition is to conduct the physical simulation and testing in the thermal chamber as specific level of temperature can be set up according to specific weather requirement. These setups are suitable for conducting physical testing of kinetic facades, to evaluate the thermal heat or humidity performance. In addition, different physical setup are required to test and evaluate the daylight performance as it require setup of artificial skylight in order to replicate the real boundary condition. By implementing appropriate weather condition during the physical testing, this strategy will allow the kinetic facades to be evaluated and modified accordingly during design development to avoid any issue after the facades has been installed in the building.

Kinetic Movement Timescale

Kinetic facades are subject to various impacts. The changing or the response of kinetic facades occurs from change over sub-second intervals to change over the building's entire lifespan. The responsive actions observed in designing kinetic facades are either continuous or discrete. Discrete responses are suddenly triggered after certain threshold-value or period of time has been exceeded, whereas the continuous response typically follows a gradual transition path (Loonen, 2010). The characteristic of timescale can be divided into seven types; seconds, minutes, hours, diurnal, seasonal, annual and decades. However, in the context of my project investigations, seconds, minutes, hours and annual are only taken into consideration in the process of evaluating kinetic facades.

Chapter Three will discuss three types of investigation, which reflect the literature review and precedent studies of designing with kinetic patterns in response to environmental conditions.

2.4 Summary, Chapter 2

The process of designing kinetics and evaluating the kinetic performance that involve various interactions is becoming more dynamic through the integration of different tools with a constant change of environmental boundary conditions. Integration of digital and analogue tools in visualising and simulating the dynamic behaviour of kinetic facades provides alternative solutions in designing and evaluating the kinetic design for kinetic facade developments.

Kinetic facade designs need an alternative way of designing and evaluating them since they are involved with mechanical products in comparison with conventional building systems. Building facades that interact with changes of environmental condition are an active element (Rafael, 2010); therefore it is unreasonable to conceive the design of facades as simply a dividing entity between the interior and exterior . (Jang, Lee, & Kim,2013). Technologies such as wireless sensor networks (WSNn) composed of sensors and actuators, which are mentioned as the Internet of Things (IoT) have become integrated into building systems. For instance, sensory modules which are installed on the building skin which can detect external environmental changes and actuators can make it react based on the procedural routine (Jang et al., 2013a). IoT(Weber & Weber, 2010) are also able to cope with dynamic and complicated boundary conditions and limitations. Therefore, kinetic facades can function with the help of mechanical systems, working with various sensors, actuators and computer programming. The kinetic facades are mostly combined with various application such electronic, mechanical behaviour and material system, therefore an alternative[46] method and strategy to evaluate kinetic facade design as opposed to the

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[46] Alternative method: has power in evaluating the performance of a design solution due to; a) uses performance measures with actual quantifiable data and not rule of thumb; b) aims to develop a simulation model of a complex physical system; c) uses the model to analyse and predict behavior of the system; and d) produces a quantifiable evaluation of design (Oxman, 2008).

traditional method[47] which needs to be conducted in the early design stage in order to avoid inefficiency or failure of operation of the kinetic facades.

The next section will elaborate and discuss further on kinetic design with physical testing and physical computing. This will further reflect and explore the kinetic design performance in the following chapter.

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[47] Traditional Method: has certain drawbacks because; a) it includes simplified assumption based on rule of thumb that can be imprecise (for example, forcing an aesthetic feature); and b) may not be accurate in relation to performance measurement design solution (Ming, Aksamija, Hodge, & Anderson, 2011).

3 IDENTIFYING KINETIC PATTERNS OF ARCHITECTURAL FACADES

The previous chapter discussed an approach on how designing kinetic patterns for facades that response to environmental conditions can be evaluated. Through engaging with different types of design components of kinetic facade systems and their evaluation, a new kind of synergy between the processes of architectural design, engineering and, construction emerges. For designers, understanding the affordance of kinetic responses for operable kinetic facades allows the designers to foresee the potential of achieving a higher degree of continuity between the design intent and the built outcome than is currently achieved by conventional tools from the industrial era as well as during the manufacturing process in the early stage of design.

Chapter Three describes my initial engagement with kinetic facades from the concept of designing a kinetic system to fabrication of a façade prototype. This process proceeds largely through the exploration of physical model prototyping. The main objective of this exploration is to experience first-hand and understand the intricacies involved for designing and testing the different types of kinetic responses by using physical tools primarily and digital technology in part. These kinetic patterns are primarily adopted based on what is commonly used in kinetic architecture and building industry. This approach seeks to investigate and develop an informed understanding of how kinetic facade components can be designed and evaluated in the early design phase.

3.1 Kinetic Model Prototyping

The current state of architectural research and practice is roughly categorised by an interest in the material practice of making. For example, in engineering, this is through a combination of digital simulations and empirical testing and iterative development of construction techniques (Sang-Hoon Lee, 2010 and Orr, 2013).

The design of kinetic facades establishes different agendas for the architects (Asefi, 2010; Mazzoleni, 2013; Moloney, 2011; Sheikh & Mansour, 2011) and designers who have traditionally worked towards finding the best mix of performance that can respond to changes in environmental conditions. Typically, designers focus on the final stage – the design of the physical components or specification of the materials (Moloney, 2011). However, in realising the kinetic facades, designers need to be involved in the design of the input and control systems, as well as the components, construction methods, and technologies. Capabilities and scope can greatly vary, which leads to the development of processes and tools that are tailored to one specific setting.

Therefore, the objective of this investigation is to enable designers to create more functional prototypes early in the design process. However, when designing kinetic facades, no common ground or experience exists in creating prototypes. Therefore the question that must be raised: *What are the challenges in constructing prototypes that are powerful and flexible enough to understand the performance and interactive installations for kinetic facades?* This especially refers to a model, which can be transferred from one kinetic facade to another, independent of the kinetic facade's form and its technical specification, not tailoring the developed application to one specific setup. Answers to this question are found in the huge variety of kinetic facades and the dynamic public contexts in which they are deployed. While certainly not all features are sufficiently captured within a prototyping environment, the need to identify the key features is essential for providing a generalised simulation framework. The prototype's exploration builds upon the aforementioned ideas, with the aim of providing a more general and flexible approach, which supports the integration of interactivity with different modalities and input devices. Additionally, it includes full integration of existing applications into a virtual representation of a kinetic facade in response to environmental conditions.

Within the scope of this research, exploring the design intent of small-scale kinetic facades, comparing their virtual and physical situations, constraints exist in three main factors; materials, mechanical behaviour and kinetic structure. In Investigation A, the focus is on prototyping a small-scale model for kinetic facades using more readily available additive fabrication technologies.

Hence, designing kinetic facade systems, I believed that a direct involvement with analogue scale models can serve as a platform for more information and understanding the benefits and limitations of more or less direct translation between design and production. Direct engagement on the performance of the kinetic facades design through physical testing are described as determinant approach in creating architectural form (Oxman, 2008) such as building facades. In certain circumstances, digital design deviates from a design paradigm in which the formal manipulative skills and preference of the human designers externally control the process to one which the design are informed by internal evaluative and simulation process (Ming, Aksamija, Hodge, & Anderson, 2011; Oxman, 2008). In avoiding this issue, design generation of physical prototypes by regulating series of parameters driven by performance-based factors need to be addressed during early design phase in designing kinetic facades.

3.2 *Kinetic pattern*

Kinetic pattern and configuration play significant role in the elements or component that involved with group of singularities in the process of movement. The images from Kwinter (1992) (Figure 7) closely described and represent the moments in time of a transformational process, or what is referred to as singularities or points in a continuous process. The concept explored by Kwitter (1992) and Maloney (2011) are used as the fundamental concepts to inform the design of kinetic patterns.

This transformational process adopted from this concept is used as a basis in exploring the prototypes of kinetic design in the (section 3.3 to 3.8). Furthermore, the complexities of kinetics are likely to involve the interaction of more than two parameters. The visualisation of the interaction between parameters over time provides a strong idea for conceiving the variables, which determine the kinetic pattern (x and y axes, with the time represented as the vertical axis) (Moloney, 2011). Variables are described in this context as types of geometric transformation, which includes folding, siding, retracting, transforming and expanding (inflating and deflating). These variables are used throughout kinetic architecture literature in describing the kinetic movement. However, there is very little data on the effective kinetic response that can be used for kinetic facades. These variables are explored throughout the design of the prototypes.

Due to copyright issues this images has been removed, Please find it at: http://www.exploratorium.edu/complexity/CompLexicon/catastrophe.html

Figure 7: Diagrams of catastrophe surface that show control space, event space, fold and its projection (original by Joseph Macdonald in Kwinter, 1992) Source: Moloney, 2011

In addition, according to Moloney (2011), the significance of visualisation that is as complex as parameter interaction within kinetics is, perhaps, that it is the most explicit design activity requiring conception in terms of a field of forces. This concept will informed and contribute to the criteria used for the evaluation of the kinetic facades in the early phase of design.

Therefore, dealing with the physical transformational geometry and the behaviour of kinetic facades will lead to a better exploration of kinetic design that will respond appropriately to changes in environmental conditions. These are conducted through physical prototyping and physical testing based on three evaluation aspects, which are 1. kinetic pattern, 2. kinetic structure and active surface, and 3. kinetic transformation. Dealing with actual behaviour by using tangible materials and forces provides a more tactile approach, in contrast to analysing those mechanisms through drawings and digital models.

3.3 *Investigation strategies*

Kinetic patterns

The five projects listed here are exploring the potential of kinetic responses to the influence of the mechanism and design of the successive kinetic systems that are explored in Investigation One. The kinetic patterns involved in this investigation are generated during the assessment of precedent studies and literature review. The kinetic patterns are selected based on their potential for the kinetic facades to be applied for the effective control of the environmental conditions.

Kinetic Structure and Active Surface

Through exploring how the structure of the kinetic facade relates to the use of mechanisms, this exploration provides more detailed information about how the design of the facade should be developed. This includes the evaluation on physical forces activated by kinetic movement.

From gaining a better understanding of the relationship between the mechanical systems, the materials performance and how they are relate to each other – that is, how the mechanical system inform the design - the development of the active surface was explored. The developed understanding on how the mechanical system of the facade influences the choice of materials, based on the required kinetic patterns, ultimately influenced the iterative design of subsequent projects after completing the initial project.

Kinetic transformation

The responsive feedback gained from kinetic transformation through designing physical prototyping provided critical information in, not only the effectiveness of the mechanical system, but also the effectiveness of the control systems when integrated with a skin, and in turn the materials used to develop that skin. It provides much needed insight into the early stages of the design process so as to ensure that the mechanism of the kinetics is working effectively and as it should, prior to the aesthetic implementation of the design.

Based on case studies and literature of existing buildings which incorporate kinetic facades, there are a number of motions that have been identified and applied to architecture (Moloney, 2011). From this study, five types of motion that are commonly being used in kinetic facades are identified in order to get direct engagement with the challenge and difficulties in designing and evaluating kinetic facades. Through physical prototyping and testing, enhanced information can inform designers of the functionality and the performance of kinetic facade designs (Zarzycki, 2013).

3.4 Wave: Sliding and Rotating

The motion of sliding and rotating demonstrated one of the examples of motions that are used through building facades either for functional kinetic such as for environmental control or simply for aesthetics (Moloney, 2011; Razaz, 2010; Schumacher et al., 2010a; Zuk & Clark, 1970). These types of motion commonly used in the engineering field are generally applied in realising kinetic facades. The most common application of sliding and rotating are pulley system. Despite this application being well known in engineering, this system is seldom applied in architecture, especially in buildings, which integrate kinetic facades. . The building facades of the Nordic Embassies reflect rotating movement through series of horizontal panels. Every panel of the Nordic Embassies have the ability to rotate 90 degrees and track the movement of the sun using a thermo-hydraulic drive (Schumacher, Schaeffer, & Vogt, 2010b). The panels are integrated with rotational movement to create their kinetic responses. The rotational movement of kinetic facades creates slow responses on every panel of the facade, which avoids any noise or distraction for the building's occupants throughout the day. These individual movements of the facade to create openings or closing are programmed based on the sun's angle throughout the day. Even though the application of rotational movement is adapted to the facade of this building, it is fully automated in a way that it is not responsive to external conditions.

A second project that incorporates this type of motion is the *Laser Interferometer Gravitational Wave Observatory* (*LIGO*) in Pasadena, California. The *LIGO*'s facade applies vertical rectilinear aluminium sections that are suspended on low friction bearings at their centre of gravity, with electromagnet sections embedded at the ends, so that motion and movement can be fully distributed to adjacent sections. This kinetic facade demonstrates a vertical wave effect on the facade of the building. Similar design applications have been developed by sculptor and artist, Ruben Margolin, which also integrated with the wave structure (Soraya, 2012). These two projects demonstrate strong links between small-scale prototypes and the actual building scale. One significant observation from these two projects is the application of technology and kinetic systems to create similar effects on the buildings' facades. The mechanism embedded in LIGO's facades integrates electromagnetics in order to power their movement. Even though a sculptor develops the facades, the complexity of the facades depends on the scale of the facade itself.

Furthermore, as this project demonstrates physical wave behaviour, there was no intention in LIGO or the Nordic embassies facade's to incorporate strategies, which respond to environmental conditions. In order to develop an understanding of this type of motion to be applied in kinetic facades, I explored this motion through small-scale prototyping in order to develop an understanding of making and construction of kinetic facades that aim to respond to environmental conditions. Based on these existing case studies, this exploration gives further insight into the challenge and issue of constructing this type of motion. My first investigation was conducted through the prototype called *Wave (Figure 8)*. The aim of this investigation is to engage with physical kinetics and mechanisms to understand and experience the challenge and difficulties of designing a kinetic system and configuration for kinetic facades. The outcome and lessons learnt from the *Wave* are reflected upon the subsequent prototype called *Squa-tic* (refer to section 3.4)

Wave explored the type of motions that are commonly adapted as part of strategies featured in existing buildings and academic research. The idea for creating these prototypes were adopted from American-born artist and sculptor, Ruben Heyday Margolin, who is known for designing intricate kinetic mechanisms when creating his kinetic sculptures. In this prototype, I explored the possibilities of this motion to be integrated as an effective component towards developing kinetic facades. The aim was to engage with the physicality of the kinetic when generating the transformation through rotation and sliding mode in creating the composition of the kinetic *Wave* (Figure 8), which consists of thirty sliding panels generated by a two-rotation mechanism. The predominant material used to construct this model was medium density fibreboard (MDF). Using a flatbed laser cutter[48] machine as a prototyping tool to cut out the sections prior to constructing this physical model, a few points of rotation were tested in order to ensure that the mechanisms fitted together correctly and was able to create the motion.

The initial idea of this prototyping was to generate flexible sliding movement for the panels and create a random active surface. The sliding panels were not fixed to any other kinetic component to create their flexible movement, thus allowing flexibility and transformation. In this initial idea, I tend to design by taking advantage of gravitational forces, to allow the sliding panels to be flexible and interactive. However due to difficulties

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[48] Laser cutter machine majorly used throughout this investigation as a main tool during this exploration. This tool are used as prototypes fabrication technique and it is one the facilities that available to the author during the investigation period.

integrating panels together in creating the sliding movement, I initially attached each panel to one of the rotational structures. This decision allows more control of kinetic movement of the prototypes. However, through design exploration while constructing this prototype, I introduced an elastic material and attached it to every sliding panel of this prototype. This exploration allowed me to achieve what I intended in the early exploration of *Wave*.

Figure 8: separate components of the Wave. During the assemblies of these components, the kinetic mechanism performance is unidentified and the tuning process of making the kinetic mechanism function effectively, are carried out throughout this process.

Kinetic Structure and Active surface

The model was constructed by considering the possible behaviours of a kinetic surface that is described by the rotation of thirty panels (see Figure 9). This panel is resting on a 3mm thick elliptical shape that is attached to two parallel wooden rods that are 8mm in diameter (Figure 10). The two rods, which are made of wood are the agents used to create the sliding motion that moves the thirty panels at the same time to create the dynamic surface. (Figure 11 and Figure 12)

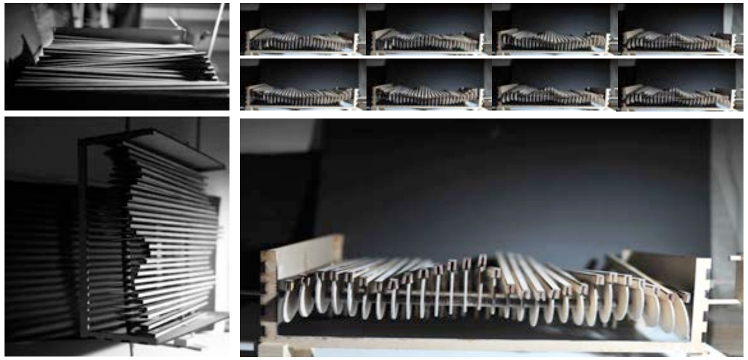

Figure 9: First prototypes constructed called the Wave demonstrated number of challenges during the process of designing and operating it. Source: Author.

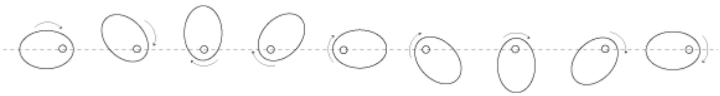

Figure 10: Full rotation of the kinetic panels of the wave producing different surface and configuration. Source: Author.

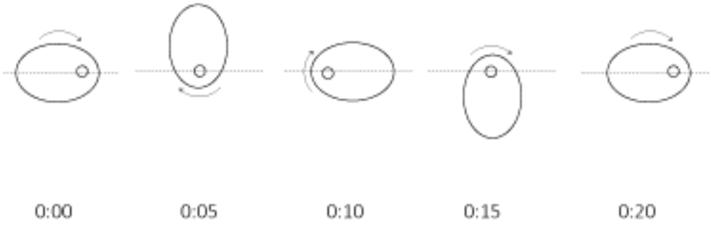

Figure 11: Duration of the full rotation of the kinetic component based on one focal point. Source: Author.

Both the structure's plates and surfaces are actively moving together as they rotate. The panel relies on varying positions of the planes, which are located at different angles in response to the elliptical shape. The motion is triggered manually by using hand movements.

The structure and the surface are both actively responsive based on the rotational mechanism design for this system. However, after several movements of the sliding motion, I discovered that the friction between the structure and the sliding motion created difficulties for the panels to move consequently. To improve the movement, I redesigned the panels by creating more gaps between the sliding structures with the aim of reducing friction. Through a couple of iterations in reducing the friction between the structures and sliding panels, I lost some control of the sliding movement as it 'sat' according to the structural gap and created larger movements.

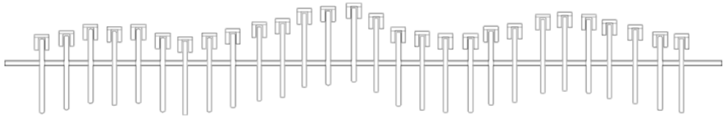

Figure 12: Front view of panels components with the rod which producing different dynamic motion. Source: Author.

Figure 13: Side view of kinetic movement during rotation. Source: Author.

Kinetic transformation

Furthermore, through the development of this experiment, the complexity in creating the rotational movement proved to be a challenging task, as this involved considerable friction between a numbers of moving elements. The integration of sliding and rotational movements creates possible interaction to changing stimuli. The initial idea that I had in mind was the possibility of creating intricate movement in response to various state conditions. However, the mechanical transformation generated from this prototype is not effective for application to a kinetic facade's. Early engagement with the experiment demonstrates how the kinetic mechanism and kinetic control play major roles in creating the kinetic transformation.

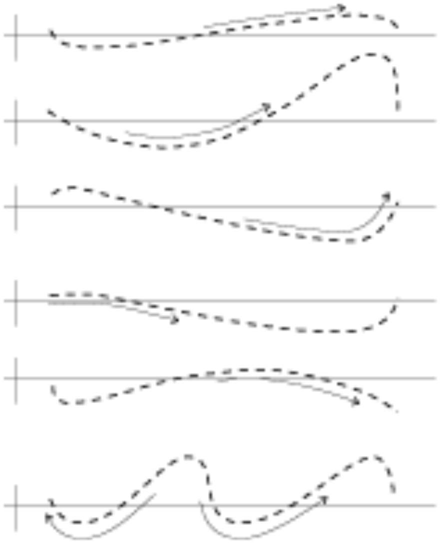

Figure 14: Different results from rotation are able to produced different kinetic configuration and dynamic surface that be able to be integrated into kinetic facades application. Source: Author.

The implication from this experiment is creating the intricate sliding motion and rotation through the *Wave* project shows that the model is conceptually easy. However, there is a hidden level of complexity in its construction that is not visible without the direct engagement of the physical kinetic model.

The design of the *Wave* provided significant findings in terms of design and making kinetic prototypes to be incorporated into building facades. One of the main understandings gained from this exploration is that scale and mechanism play a major role in effecting the workability of the kinetic system. The elements such as material forces and friction play a significant role in creating an effective a kinetic system. The scalability of the system affects the kinetic pattern and configuration. The more components involved in creating the kinetic facade's system, the higher the complexity involved in designing and constructing the kinetic prototypes. This is due to the kinetic mechanism needing more components and robust systems to control the movement. Macro moving components involved in the construction of the *Wave* play a significant part in making the kinetic system operate effectively. The *Wave* is developed through a couple of iterations when replacing the use of timber to *MDF* and replacing the mechanism from using string to rubber, finding the optimal gap between each component and the finding a proper way to reduce the friction by adding some powder and grease to the moving parts in order to create effective movement. Problems such as friction are easily anticipated during the early design process as the challenge and resulting problems manifest themselves during the process of making and testing the model.

The findings and lessons learned from the *Wave* are further explored in the next prototype, which had similar objectives and goals.

3.5 Square-tic: Sliding and Retracting

One significant challenge in constructing and modulating the *Wave* is the complexity of controlling kinetic components forming the different configurations. Four times the design iteration was re-modelled in order to achieve perfect the operation of the kinetic system. Earlier designs drawn using 3-D models on *Rhinoceros* software did not demonstrate clearly whether the effectiveness of the system was working effectively or not. Even though the *Wave* may have more kinetic configurations, I experienced difficulties with the objective to synchronise the system. In square-tic, this issue had been highly considered when constructing the prototype.

Continuing from the lessons learned in *Wave*, *Square-tic* aimed to further improve the kinetic mechanism and kinetic control towards designing kinetic facades. Even though the *Wave* produced intricate and dynamic motions that were capable of creating significant transformations, the application of kinetic mechanisms and control were not effective in creating an opening and closing behaviour.

In this section I shall analyse the design of *Square-tic* whose aim is to improve kinetic application by integrating slide and retracting motion in kinetic application. Sliding and retracting are identified as a type of motion that is associated with deployable structures that create responsive structures. The kinetic system is able to be adapted using different responsive structures such as scissor structures. One of the widespread applications of sliding and retracting motion are in umbrella-like-structures. The motion involves a monolithic translation movement. Some of the sliding and retracting motions can be seen from Chuck Hoberman's scissor structure, with applicaton of retracting motion in creating the responsive kinetic movement (Hoberman, Davis, Drozdowski, & Wight, 2013). The structures allow various design interventions that respond to various dynamic conditions. In another similar application, *HelioTrace* designed for the Centre of Architecture in New York adopted overlapping-sliding panels that are retracted in response to lighting conditions. This application has similar applications, like shutters, in creating openings or closure, similar to those demonstrated by Institute Monde Arab.

From the precedent study, retracting and sliding motion demonstrated various responsive kinetic transformations for use in the kinetic facade. Thus, the motions are tested using elastic wire and plastic tube to create the flexible square structure on a *Square-tic* prototype.

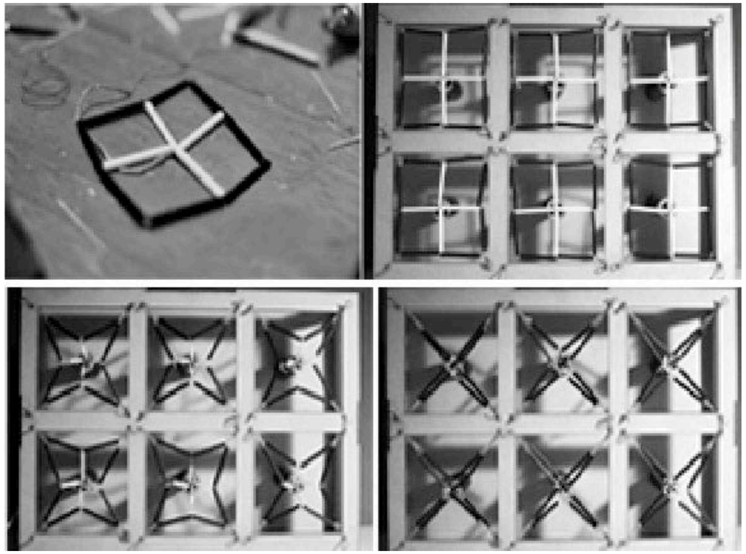

Figure 15: Prototype of Square-tic demonstrated three different kinetic states transform through sliding movement. Source: Author.

The *Square-tic* motion is fabricated with four panels of square elastic that respond to light. The structures are designed to be able to retract and slide. The differences between this prototype and *Wave* are, the design attempts to avoid intricate kinetic mechanisms which lowering the effectiveness of the behaviour of kinetic movement as this subsequently affects the functional performance of kinetic itself. The construction of the model involved an elastic joint that allows the structure to expand and contract through sliding movement of the structure. The elasticity of the material results in various types of geometrical transformation.

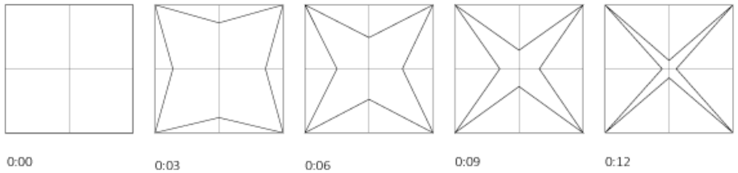

Figure 16: The panels expanding and contracting. Kinetic configurations are developed through actuating the central point of every single panel. This created various forms and shapes in the kinetic cycle of activation. Source: Author.

Kinetic structure and active surface

The elastic behaviour that was adopted in the construction of this model was accomplished by creating an active surface through the flexible structure. The structures are modulated by pulley systems that are pulled and released to actuate the expansion and contraction of the panels. The panels can be integrated to create a global control of the mechanism as well as local control.

The flexible structure demonstrates changing shape from the square panel toward the ‘star’ shape when closing of the panel occurs. Even though the *Square-tic* demonstrates improvement from the previous prototype’s experiment, *Wave,* there was still friction resulting from the kinetic mechanism. However, *Square-tic* demonstrates fewer mechanical problems during operation. Even though the issue of friction avoids the movement of the mechanism to be effectively opened and closed, slight improvements from the previous prototype are shown in *Square-tic*.

Kinetic transformation

The flexibility of each panel of *Square-tic* depends on its degree of opening and the kinetic control and mechanism. The rubber used as elastic mechanism to pull and release back the shape to the original state. The sliding motion creates square transformation geometry, when it is open and a star geometry transformation when the system is closed. These pull and release mechanisms are applicable in constructing kinetic panels designed for integration in building facades which respond to changes of environmental conditions – specifically changes in the amount of light and heat transferred. Modifying the radius of the rotation of pulling and realising the kinetic system can modify the actuation in this model to create minimal actuation to create maximum potential for opening and closing. From these *Square-tic* experiments further enquiry was prompted into which structure and surface could be formed with one single component that is elastic and flexible enough to form a similar shape and geometry in order to reduce the complexity of the mechanism thus reduce the amount of friction during the operational activity of the prototype,

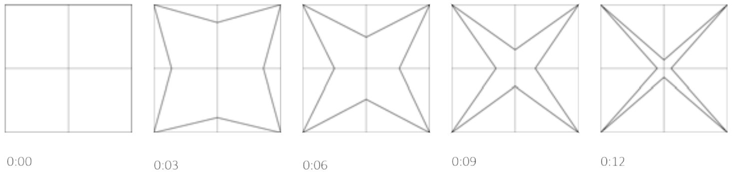

Figure 17: Stages of movement of the panels in the composition are map through every three second. The time interval of

movement can be programmed accordingly in responds to the specific environmental condition required. Source: Author.

In exploring the solution to reducing strong friction and lowering the level of intricacy of the mechanism, *Square-tic* demonstrated some insight into the possibilities that the kinetic structure can merge with the kinetic pattern and configuration. This could be one of the solutions to reduce the kinetic mechanism problems, particularly in this prototype. Even though, the kinetic configuration and pattern are applicable to implementation in the kinetic system of building facades, the scaling-up of the actual prototype will affect the kinetic mechanism and configuration. This is due to the difference in forces and energy applied to the facades once they are at full scale. Related to this issue, the efficiency criteria of the kinetic system, especially on reducing the amount of friction during the operation of the facade is crucial.

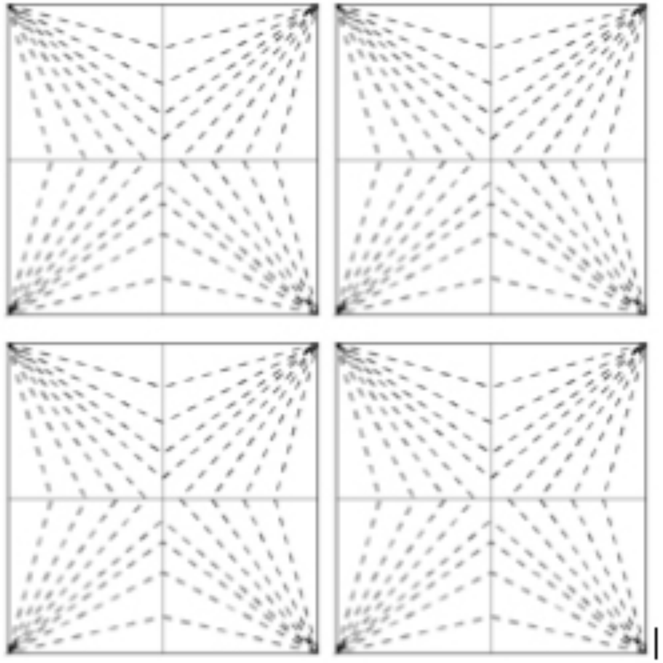

Figure 18: Stages of movement of four panels at the same time using single pulling and releasing mechanism. Creating local actuation for every single panel to create various kinetic configurations can modify this configuration. Source: Author.

As the amount of friction when applied at a larger scale can cause issues and weaken the system's ability to respond to changes in light, if at all, the next prototype attempted to integrate this structure together with a different kinetic system. The next kinetic model is given the name *Scissornet*.

3.6 Scissornet: Contracting and Expanding

Scissornet explores the possibilities of improving the kinetic mechanism from the previous application by integrating flexible structures as part of the moving components. The selection of materials and kinetic mechanisms applied in the facades are essential at the early design stage. A few selected materials that have characteristics to be bent out of shape and elastically deformed are selected which include 0.8mm polypropylene, 0.8 mm thin flat sheets of plywood and 0.6mm semi-transparent plastic, during the process of designing this kinetic system. These materials are tested, based on their common use by designers during the early design stage to test an idea by constructing physical prototypes. After three types of materials are tested in the process of selection, polypropylene proved the most flexible material to achieve the design objective of *Scissornet*.

Furthermore, *Scissornet* explores more in-depth on the motion of contraction and expansion as part of another type of motion explored for kinetic facade systems. While *Scissornet* reflected the outcomes of *Square-tic*, it develops its approach by adopting different techniques for actuating the models. *Scissornet* utilises a light sensor, step-motor, and *Arduino* microcontroller as part of this investigation.

Similar examples of application of Scissornet can be reflected through architectural-scale installation work commissioned by Festo called *Interactive Wall* presented at Hannover Messe in 2009. The installation transformed the wall from a static backdrop to a key part of a dynamic customisable environment. The prototypes are intended to invest in new ways of using and designing space, which incite people to explore new forms of embodiment through participation and locality (Hosale & Kievid, 2010). The prototypes also seek exploration through their development of installations that allow designers to isolate and explore problems effectively in interactive architectural design.

The interactive installation reflects fluctuations within the environment that surrounds it and alters its expression to these changes. In comparison to *Scissornet*, the Interactive wall is an interactive structure that expresses its state through combined modalities of indoor movement, light and sound. However, *Scissornet* is a prototype that seeks to understand the application of kinetic systems for building applications that react to external environmental condition. In addition, the varying qualities of movement, technical challenge and varied scale of installation underscore the difference, for each new method of actuation producing unique experiences of design process and results.

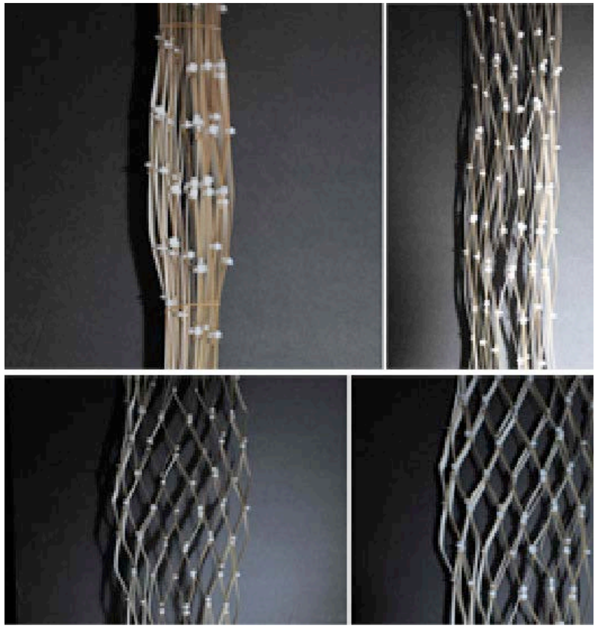

Figure 19: Physical prototype of Scissornet shown in three different states which design to crate an open and closed effect to be integrated for kinetic facades design. Source: Author.

Kinetic Structure and active surface

Scissornet is a modular system constructed by using an elasticated material that is able to expand and contract. The element in the system can be added and removed, change location and be installed in any order, which can be developed as self-contained kinetic panel. This motion is applied in order to create opening and closing characteristics, which respond to the lighting condition. Even though the exploration is tested using artificial lighting, the design is intended for development towards controlling the environmental conditions. Previously, the lessons learned from the two prototypes are based on the issue of isolation from the *Wave* and *Square-tic*, this design is explored with the aim of minimising the friction between the materials used in the components through the integration of kinetic structure and flexibility of the materials used in this prototype.

In comparison with previous prototypes, *Scissornet* incorporates the integration of the open-source electronic prototyping platform, *Arduino* (Figure 20). *Arduino* was integrated at this stage of design exploration to isolate possible design challenges and difficulties during early design activities. At the same time, this gave more information on integration of sensors and actuators as part of designing towards constructing kinetic facades system that can react to the external conditions.

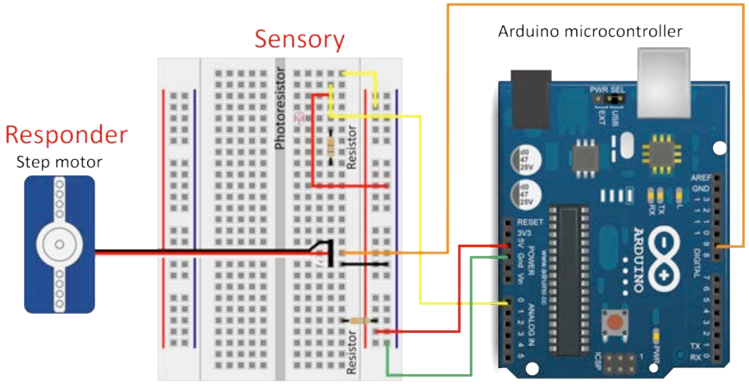

Figure 20: Arduino Uno setup are used for Scissornet to create responsive reaction with the presence of light using light sensors and servomotor as an actuator. Source: Author.

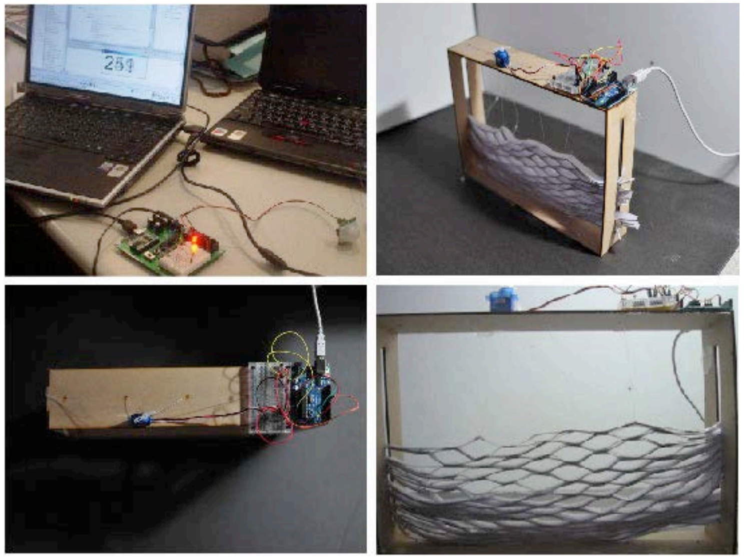

Figure 21: Integration of Arduino and stepmotor to create responsive kinetic surface and configuration. Source: Author.

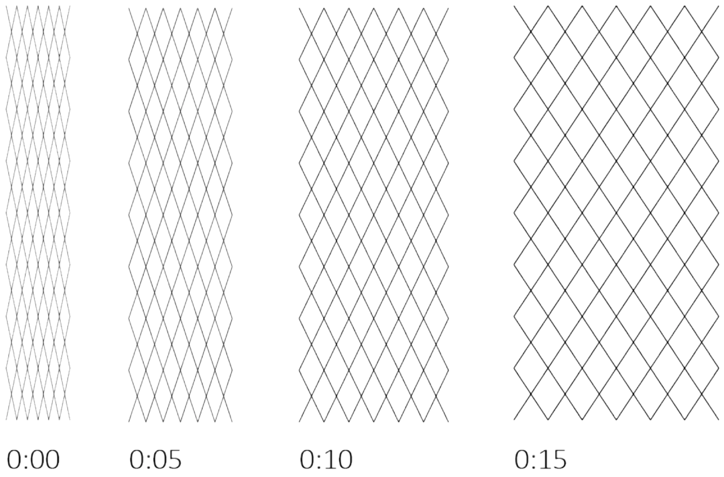

Figure 22: Duration of movement of the kinetic facade demonstrating the contracting and expanding behaviour. Source: Author.

Moreover, in comparison with *Square-tic,* the surfaces of the scissor joints cannot be controlled individually, as the design structure and control to create an opening and closing as it is inter-connected. This behaviour does not allow for smooth movement to occur on the surface. As the movement of the structures are interconnected, it is difficult to control the opening and closing of individual openings on the surface.

Kinetic transformation

The application of *Arduino*, sensors and the step-motor in *Scissornet* was implemented in order to create an interactive model activated by changes in light. Light levels act as an actuator regulating expansion and contraction behaviours. These responsive behaviours serve as a driver to inform the motion that interacts with the environment. The pulley systems applied in this mechanism are attached to the step motor in order to achieve their objective. This interactive system that is applied in this project could adapt with contract and expand the motion in realising kinetic facades.

The interaction through a sensor and actuator allows the geometrical transformation of the surface from lighting conditions. *Scissornet* exhibits reduced mechanical complexity compared to the previous experiments. *Square-tic*, has limited potential for kinetic transformation, which does not provide much flexibility in applying it to a kinetic facades system. The structure of the *Scissornet* consists of the alternating tension and pressure sides flexibly connected by rigid ribs. When one side of the flexible structure is pulled and subjected to pressure the flexible structure bends in the direction opposed to the force applied, exhibiting of high degree of opening with minimal effort. A micro Servo-motor SG90 9G with a 5V power source is used to activate the system, which is triggered by a thermometer sensor used to detect the presence of light during the testing. Through the integration of these actuators and sensors on this installation of this prototype, the approach emphasising the internal spatial response is visualised (Figure 23).

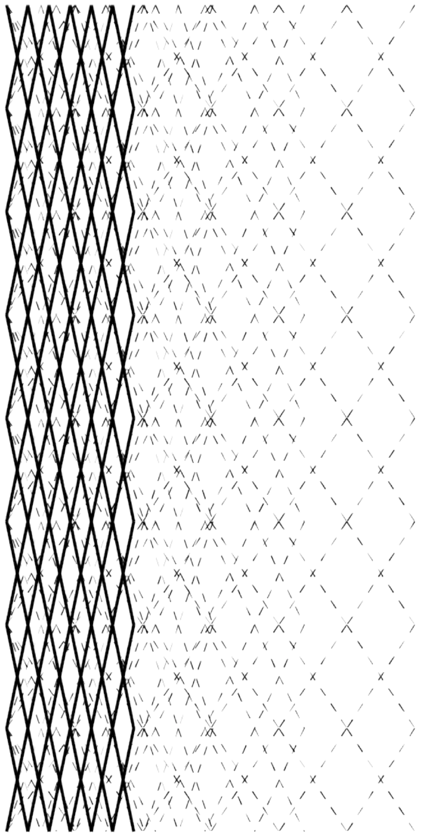

Figure 23: Diagram overview of the expanding and contracting motion. The constant respond of opening and closing due to the rigid structure and movement. This system allowed minimisation of the usage of actuators as the system can be moved from one point from the middle of the structure. Source: Author.

This prototype is visualised as a bottom up design research endeavour, with the *Scissornet* panels formed and constructed towards the application of kinetic facade application for the buildings. The spatial section is seen as completely wired prototypes to be developed for larger scales of building facades.

The kinetic systems developed and explored in the *Scissornet* are mainly inter-connected structures and points, which lead to a rigid system in kinetic facades. The system applied in this prototype does not allow for locally controlled opening or closing of openings due to the inter-connected nature of the structure and creation of the opening from stretching behaviour. However, allowing the kinetic facades to create local control of the extent of opening and closure would permit the system to respond specifically to different lighting and heating conditions. Kinetic façade systems tend to be more intricate with active components such as sensors and actuators compare to Scissornet.

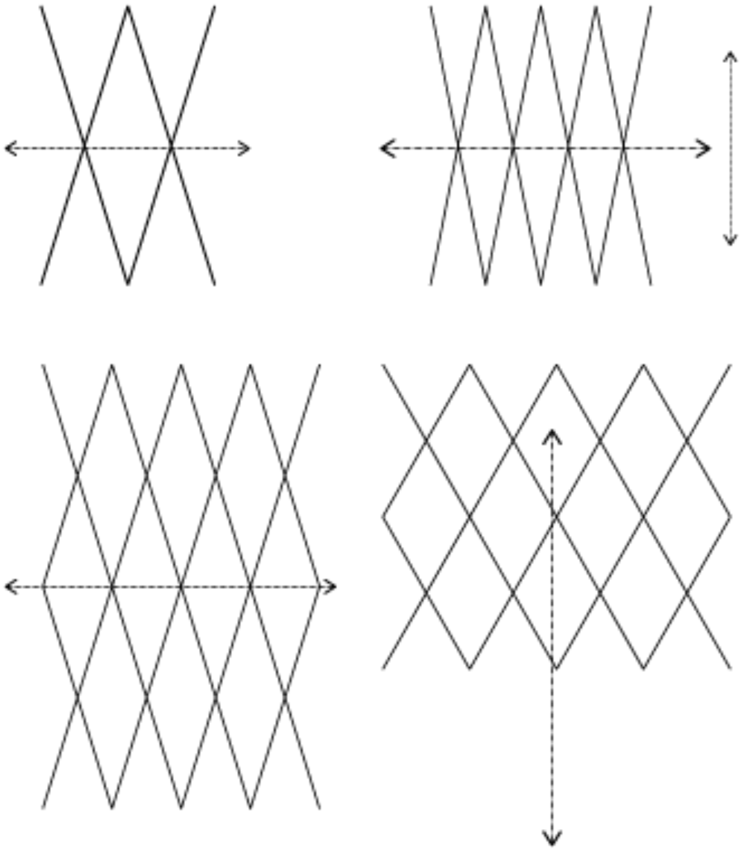

Figure 24: Overview of the direction of movement. The kinetic movement can be triggered either form horizontal or vertical points which allowed different type of scale in constructing this kinetic system. The advantage of this system allow for constants movement in creating opening and closing of the system and the kinetic component can be add-on or subtract based on the site condition and needs. Source: Author.

In relation to the next exploration, the prototype called *Balloon* attempted to move away from the rigid structure. This is to evaluate the possibilities of the kinetic system to effectively respond effectively to different lighting and heating conditions in integration with the building facades.

3.7 Balloon: Inflate and Deflate

Moving away from the approach taken from the first three prototypes, which exhibited the application of rigid materials for creating kinetic transformation, *Balloon* offers more flexible and soft components, rather than hard materials. The aim of this experiment is to minimise the amount of mechanical friction and forces while creating the kinetic movement. The kinetic movement generated will trigger the *Balloon* to inflate and deflate in reaction to opening and closing behaviour. In relation to the kinetic movement and composition, this application can be seen through the kinetic facades integrated in the Media ICT building in Barcelona designed by Cloud 9 architects as discussed in previous chapter. In this structure, kinetic facades use soft material surfaces to respond to the external lighting and heating conditions. One application is Ethylene Tetra Fluoro Ethylene (ETFE) pneumatic components that have the ability to inflate and deflate based on the air volume inside the pillow shape (Cabrera, 2010). The ETFE that forms the western facade of the building allows light to filter through but shades people inside from direct sunlight. This side of the facades will absorb six hours of sunlight daily. In this condition different application of ETFE are used known as the '*lenticular*' solution which two layer of the plastic are inflated and deflated and filled with nitrogen. This method creates a cloud-like solar filter from air density from the particles.

In relation to this project, *Balloon* (Figure 25) is constructed with similar application of kinetic movement that inflates and deflates based on the air, contained in every component of the *Balloon*. This project is informed by the following precedents for the kinetic application of soft materials in architecture: Media ICT building that applied ETFE pneumatic components that have the ability to inflate and deflate based on lighting and thermal heat conditions. From this precedent study, smaller scale experiments are developed to understand the behaviour of inflation and deflation motions, through making and constructing the kinetic system itself.

Kinetic Structure and active surface

Figure 25 shows the facades that were developed using soft materials and transparent plastic as they provided different possibilities in the evaluation of the kinetic pattern during the early design stage. In this project, individual panels inflated and deflated by inhaling and exhaling using air pressure. In addition, this application demonstrates the potential for creating less friction between the components shown in this section, an issue the previous projects struggled with. This system demonstrates a clear distinction between the integration of active surface and passive structure in kinetic systems. Where, as the model inflates and deflates it forms an active surface, the passive structure acts as the main support, which connects the whole system.

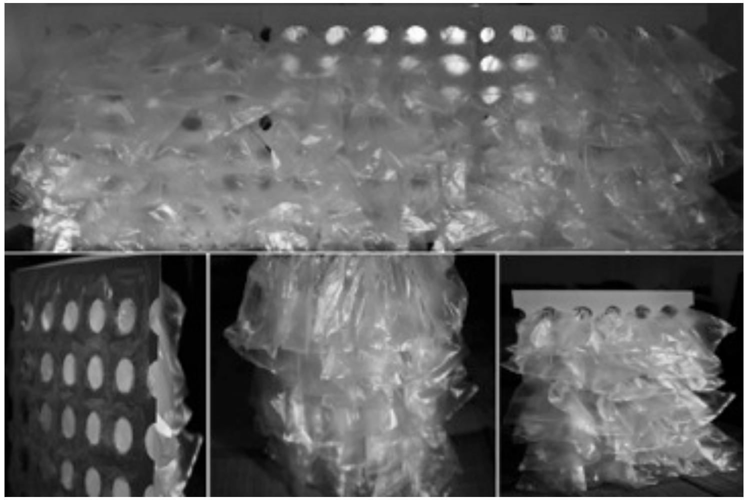

Figure 25: Physical prototype of the Balloon Project. Source: Author.

While observations made in previous projects showed *Wave* and *Square-tic* encountered friction, which *Scissornet* attempted to reduce, these experiments mainly considered the potential of motion to be adopted in realising kinetic facades. In these previous investigations I dealt with hard materials such as *MDF* as a main structural element that created friction and thus a hurdle for the functioning of mechanisms in the system. It also created the constant rigid movements that have constant opening and closing features. In this investigation different approaches towards the materials and actuations were applied.

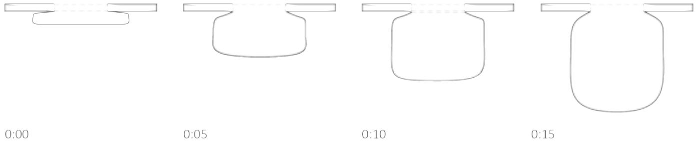

Figure 26: The Balloon is in deflated state to full inflation. Source: Author.

The Balloon consisted of three integrated kinetic panels that incorporate thirty hollow circular shapes with a diameter of fifty millimetres in every panel. The hollow circular shapes are attached with a transparent balloon tube. The air as an actuator is located at the back of each panel to initiate the inflation and deflation behaviour of the balloon. As the light sensors are attached in front of these panels, the small fan is turned on by the presence of the light and turn off when the light is minimal. The balloon inflates the whole kinetic system in order to allow the facade to act as a shading device that produces a diffuse light when filtered through the Balloon and at the same time it minimises the amount of solar radiation penetrating into the space.

At this stage of this experiment, the focus of developing prototypes is to observe how well the system can be effectively developed and constructed towards the kinetic facade's application during early design stages. In addition, the effectiveness of the motion and its kinetic system working effectively in response to light and heat were observed.

The first attempt to actuate the *Balloon* was using one fan that triggered the balloon to inflate. This decision of using one fan during the process of physical testing exhibited the kinetic behaviour of inflation and deflation causing kinetic motion. This is due to the pressure of the air force being poorly distributed during the physical testing of the prototypes. However, in the second attempt, three fans were allocated for every single panel in actuating the balloon. This decision improved the performance of the inflation of the balloon in comparing to the previous testing.

Kinetic transformation

The application of soft materials to create an inflation and deflation motion was able to reduce the issue of friction that was evident in the previous projects. However, in this project, the ability to control the form and kinetic movement of the material was limited as the pattern of motion and behaviour was unpredictable. The type and use of materials chosen minimised the issue of friction and significant force generated from the kinetic movement. In these prototypes, the issue mentioned previously was minimised, however this decision reduced the kinetic control on the form. The ability to control the components of the kinetic facade is crucial for creating a system that is able to effectively respond to changing environmental conditions. It is evident in the process of constructing a *Balloon* that the behaviour of the material is unpredictable; therefore it provides a basis for the design of *Triangular*. In response to the lessons learnt from the previous investigation of four prototypes, the next experiment was intended to create prototypes that provide a balance between kinetic controls and minimise the issue of kinetic movement, in regard to material friction and forces.

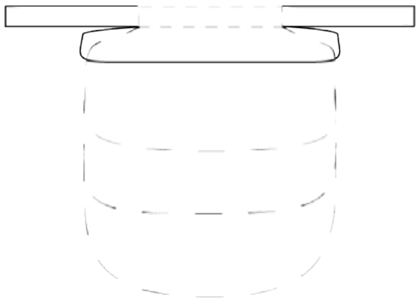

Figure 27: Overview of a single element of the facade from deflation to full inflation. The balloons are expanding according to the amount of air contained in the balloon. The inflation and deflation process creates the horizontal movement. Source: Author.

The solution to these issues is to use pliable materials that are flexible and the same time able to be controlled in specific ways. Through the exploration of *Scissornet*, p*olypropylene* was used in constructing the prototype. In this process, materials showed the potential to be developed in different ways and designed for kinetic systems. From the experience gained from *Scissornet*, a similar material application was applied in creating *Triangular*.

3.8 Triangular: Expand and retract

Triangular, took all the lessons and knowledge gained from the previous four projects into consideration. In this project, the prototype was tested to respond to similar subjects such as daylight and thermal heat conditions.

In *Triangular* the form is generated from the small components that were a maximum 120mm long. The intention of this design is to allow flexible design alterations of kinetic components through the exploration process. This will allow the designers to modify the design based on the design performance as kinetic facades during the design and construction phase which focus on the mechanical movement and physical material properties. Furthermore, the triangular shapes are connected to observe the possibilities of this component to be formed as kinetic panels for kinetic facades (Figure 28). Three circular hinges are established for every component, which allows it to connect and disconnect through the exploration process.

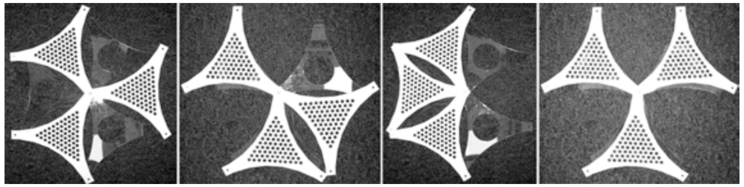

Figure 28: Exploration of different configuration and strategies of kinetic pattern based on movement rotation. These explorations are tested to identify optimal transparency when it been integrated with different layers. Source: Author.

The integration of the component is also developed through stretching the material to produce three-dimensional forms to replicate similar forms that have been developed in the Balloon prototypes. The design of *Triangular* attempts to minimise some materials used in order to create more flexibility in the material through creating a perforated design. This strategy also allowed the light to be filtered from direct daylight penetration and created diffuse light. The prototype is also tested with different types of material surface and colour. Two types of material were involved in this exploration, one was a reflective material that had a dark surface and the second one had a white matte surface. From the exploration of both materials, the white surface material was used due to its flexible attributes and minimally reflective surface. This material further developed with the integration of the component into larger scale prototypes that were later installed in specific site conditions.

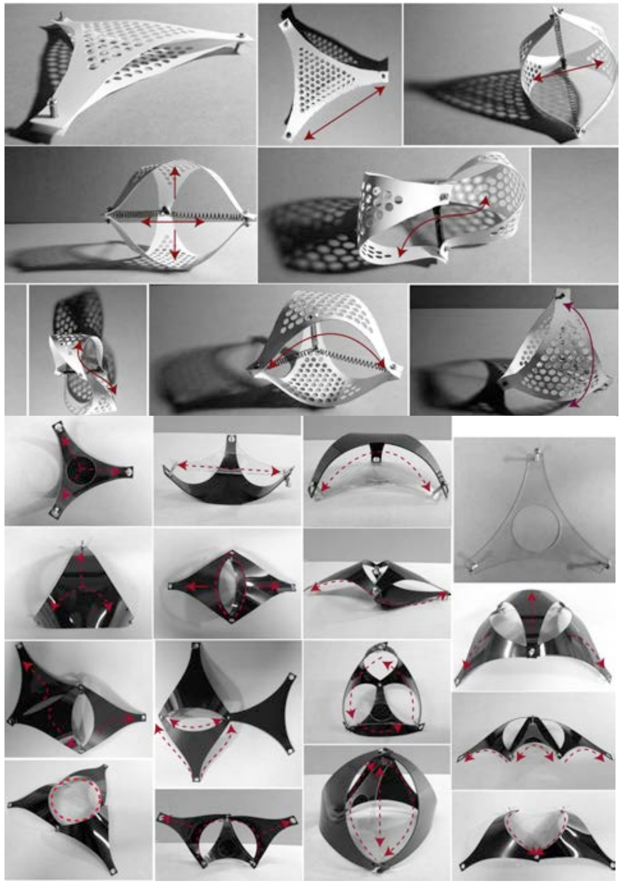

Figure 29: Two-dimensional plane are integrated to produce three-dimensional form using 0.8mm white and black Polypropolyn in form finding process in casting kinetic component. Source: Author.

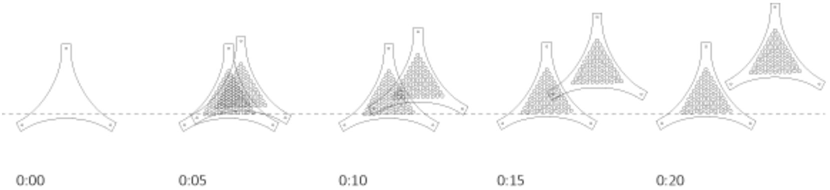

Figure 30: The Sliding motion of the two layers of kinetic components are demonstrated in different configuration. Source: Author.

The development of this project explores how the fabrication of a small component can be integrated to create a modular system that can be effectively fabricated. *Triangular* utilised the shape changing material, Smart Memory Alloy (SMA) springs as actuators, in order to respond to the levels of daylight within the space. This material has the ability to expand and contract at a temperature of 52-degrees, making it a viable choice for use with such environmental conditions.

In this experiment, the white perforated matte surface material, which is very elastic and flexible, thus has the ability to work well with SMA springs as actuators. Figure 31, shows the single cell and a combination of three components of the system to work with SMA springs that have the ability to expand and contract.

Figure 31: three component of physical prototype of Triangular are tested using smart memory alloy spring when the heat are supplied to the spring, the spring contract and pulling the two dimensional panels of triangular panels away from each other and affect the component to open. When the spring is cooling down it will return to the original state and the kinetic component return to the original state. . Source: Author.

The development of this component is to test different possibilities and to evaluate the material during daylight performance for controlling light. This exploration is also tested using reflective materials to measure the different performances of this material to control light.

After the information gained through the modelling phase, the prototype was iterated into specific material layers and adaptation topologies such as membranes with different transparency, rigid and elastic membranes, opening shapes, scale and size and relative positioning of components. In accordance with their performance criteria, the components were integrated to create a 2000mm by 1500mm prototype of a kinetic facade. In adapting a sliding and retractable behaviour, a rule system for mapping out the maximum and minimum structurally feasible adaptation per component was analysed through digital simulation and the process of making. Scripting routines for setting up parametric relations between each constituent part per component were developed using *Grasshopper* (a plug-in for *Rhinoceros*) and using the energy simulation to evaluate the performance. The prototype is divided into three skins that adopt a sliding behaviour as the main mechanism for the facade system to control the light conditions in the room.

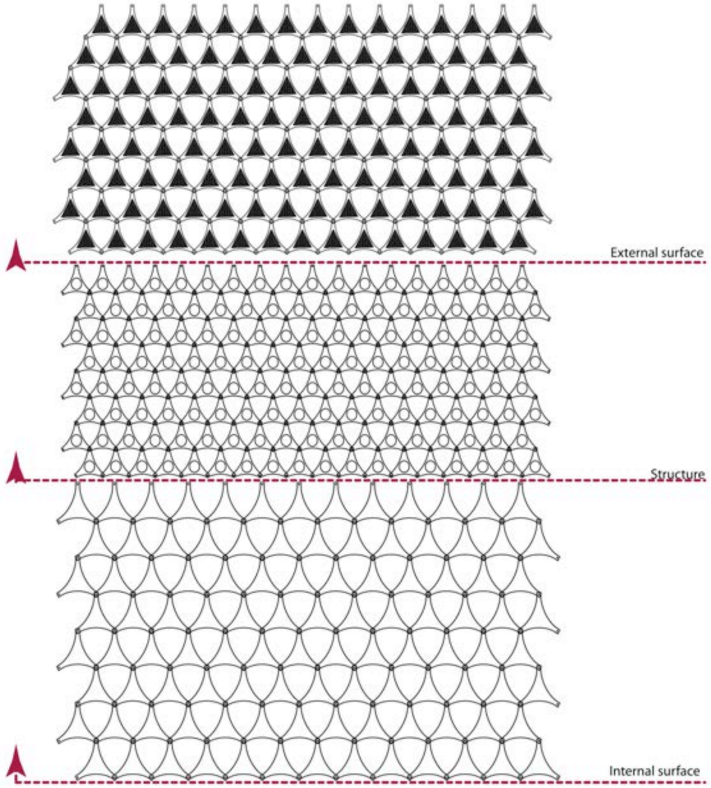

Figure 32: Three different layers of kinetic component that designed for the sliding movement; active surface, passive structure and active structure. This three different layers are located overlapping to each other. Source: Author.

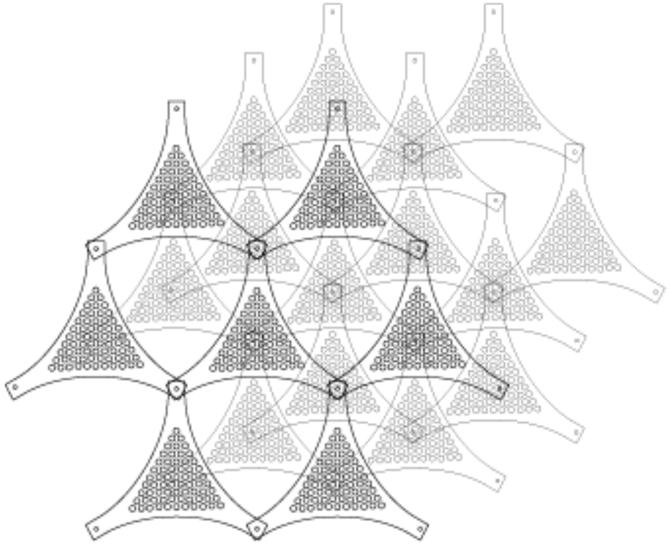

Figure 33: Part of the kinetic composition indicating movements of different layer to create different transparency. Source: Author.

A further consideration for this fabrication was to test this installation in a 4000mm x 2700mm x 2000mm room facing south west, with facades on 21 June which had a sun angle of 29 degrees in Melbourne, Australia to evaluate the performance of skin in moderating and modulating the sunlight entering the room.

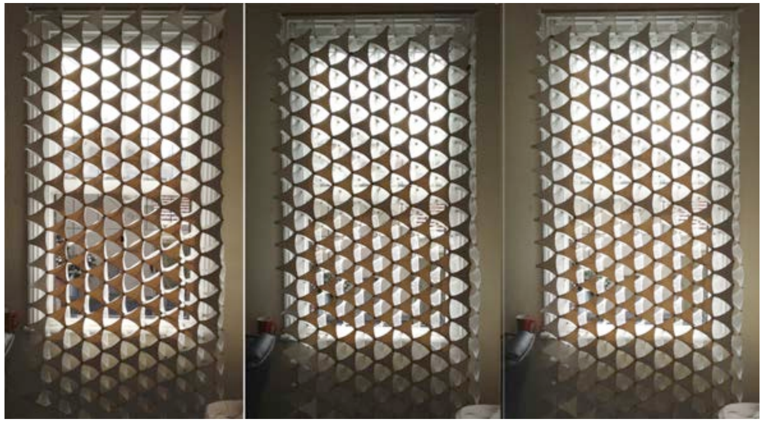

Figure 34: Installation of project Triangular is tested in real boundary conditions to evaluate the responsiveness of the kinetic design toward controlling the lighting condition in the space. During the afternoon period of time, these installations demonstrate an effective daylight control. However, the kinetic movement and responsiveness need to be improved for future developments as the kinetic system are not fully effective at this design stage. This issue are raised after the whole kinetic component has been installed and tested on the site. Source: Author.

3.9 Summary, Chapter 3

Even though the materials and fabrication methods used in previous projects were relatively fundamental in engineering field, to understand the behaviour and challenge associate with kinetic prototypes does not always have to be associated with high-end technologies and complicated mechanical system. In creating the prototypes it lies in a change of perspective inspired by and derived from the observation and analysis of the designer through developing and testing. In being able to observe and measure the light conditions, the performance of the kinetic facade. I was able to make further intermediate design decisions at different levels in the development process based on these observations:

a) Designing kinetic facades is strongly associated with kinetic component and mechanism that determine the operation of the facades to work effectively. By selecting the simple and effective kinetic mechanism during the design and testing process, it ensured the design of kinetic are able to scale up and avoid design complication such as additional energy or excessive kinetic forces required to modulate and trigger the movement of the facades to respond.

b) Engagement with physicality of the material and kinetic behaviour informed the designer's process of working with kinetic mechanisms and designing the form of the facades. By correlating the design of the facades and kinetic mechanism at the same time, I created an effective design process and development. For example the problem of friction during the kinetic facades prototype operational can be minimised by using the flexible material or reducing heavy active mechanical system while maintaining the robustness of the material properties and the kinetic structure in forming the kinetic movement.

c) Even though physical prototyping provides significant information about the kinetic system and behaviour. The information on how these systems respond to environmental control is barely observable during this process. For example in order to learn how the kinetic control responds to the daylight condition in Melbourne Australia throughout the year is not sufficient within this process.

In addition the gap between conception and making kinetic facades does not disappeared as designers move closer to the role of the craftsman in relation to their materials; nevertheless a transformation has occurred. Exploration through prototyping kinetic facades in the early phase of design has introduced and provided a new platform for feedbacks in order to reduce the distance between abstract conception and reality. The evaluation of kinetic facades using physical prototyping can be divided into:

a) The physical data acquisition.
b) The mechanism controlling responsiveness.
c) The output that actuates the movement behaviour of the physical prototypes.

Furthermore a prototype simulates the physical form and can then be evaluated in relation to its simulated context. The practice is fundamentally a bridge of informed conception, wherein the prototypes are more than a mute representation. Furthermore, the process of constructing the prototype involves tacit knowledge that varies with different designers. Tacit knowledge is a critical aspect of the design process and evaluation. It is also evident that the formation of tacit knowledge is associated with experiential learning and learning-by-doing. While the process of learning-by-doing can be informed by both digital and physical making, there is a particular benefit gained from bridging both modes of creativity. Since the end goal of the design process in creating kinetic facades is a building envelope, the ability to understand the connection between the digital design process and its physical actualisation is critical.

The opportunities provided by a prototyping platform combining physical making with digital tools, offers additional benefits in the product, by directly linking material, manufacturing and feedback as well as first hand experience in evaluating kinetic facades. The processing and craft of the prototypes at the one to one scale can be the closest answer to the design of kinetic facades. By means of one to one scale models, thinking by doing, designing by fabricating, the information gain through this process can be enriched.

In Investigation One, the kinetics present at this point are basic types of motion; the development from these prototypes will further reflect towards better improvement of technical solutions. The particular challenge addressed here is that the aesthetic requires the consideration of what is described by Willian Zuk as a 'sense of motion, itself' (Moloney, 2011). In developing the sense of motion, the need to experience through making and constructing the kinetic prototypes, not only using digital models but also, through analogue prototypes is crucial. This is due to the problem and issues related to kinetic systems that are not fully visible in early design ideas and intentions. This issue is discovered when dealing with the physical materials and kinetic mechanism itself. These unforeseen issues can be minimised during the early design stage to ensure the system works effectively and risk of failure of the system greatly reduced.

One of the issues in dealing with the kinetic systems in Investigation One is the challenge of material friction and the efficiency of kinetic movement. Through the iteration and improvement of the prototypes as occurred during the *Wave* and *Squaretic,* prototypes, the friction problems were minimised; but the problems were still an issue for the kinetic system to work effectively. The early decision in avoiding this problem by choosing an appropriate material and motion were significance in designing and constructing kinetic facades. Issues such as friction would become an excessive problem when the kinetic components were integrated into a larger array or scaled-up models for the application to building facades.

In exploring the types of motion and the kinetic movement, first objective is to enable precise control over the level of indeterminacy, or the design intent, which shows predictably, ordered composition (Moloney, 2011). The experimentation developed through Balloon exhibits the main problem of this issue. Albeit that these prototypes are reducing the friction on the mechanism, the kinetic pattern and form are hardly controllable. This is due to the materials selected for the prototypes, which did not afford a total contribution to enhance the kinetic control system in creating an intended form.

While the majority of the literature concerns the effectiveness of the implementation of kinetic facades, this investigation isolated the problems and difficulties in realising the kinetic prototypes during early design through conducting the investigation through the process of making and testing, providing an alternative to harvest more information on the kinetic system and functionality than visualising it through digital models.

In another way, exploring the kinetic design to be developed for building facades can include two concepts: diagrams and durations. These appear to be used productively by some of the designers as a way to explain kinetic activities (Moloney, 2011). The use of diagrams as creative representational devices could potentially be useful for kinetic facades (Moloney, 2011). The mapping of the outcome through physical testing gives a further understanding and reflects different possibilities of kinetic facades system configurations. This documentation aids the designers in accessing their previous design and avoiding similar problems in regards to kinetic systems and behaviour.

From investigation one, the outcomes observed from the studies are documented in the table of diagrams to compare and understand various outcomes reflecting the kinetic system. From the observation of experiments and discussion above, I have used this kinetic behaviour and motions (Figure 35) in this investigation to be evaluated towards environmental control through digital simulation in the next chapter 4.

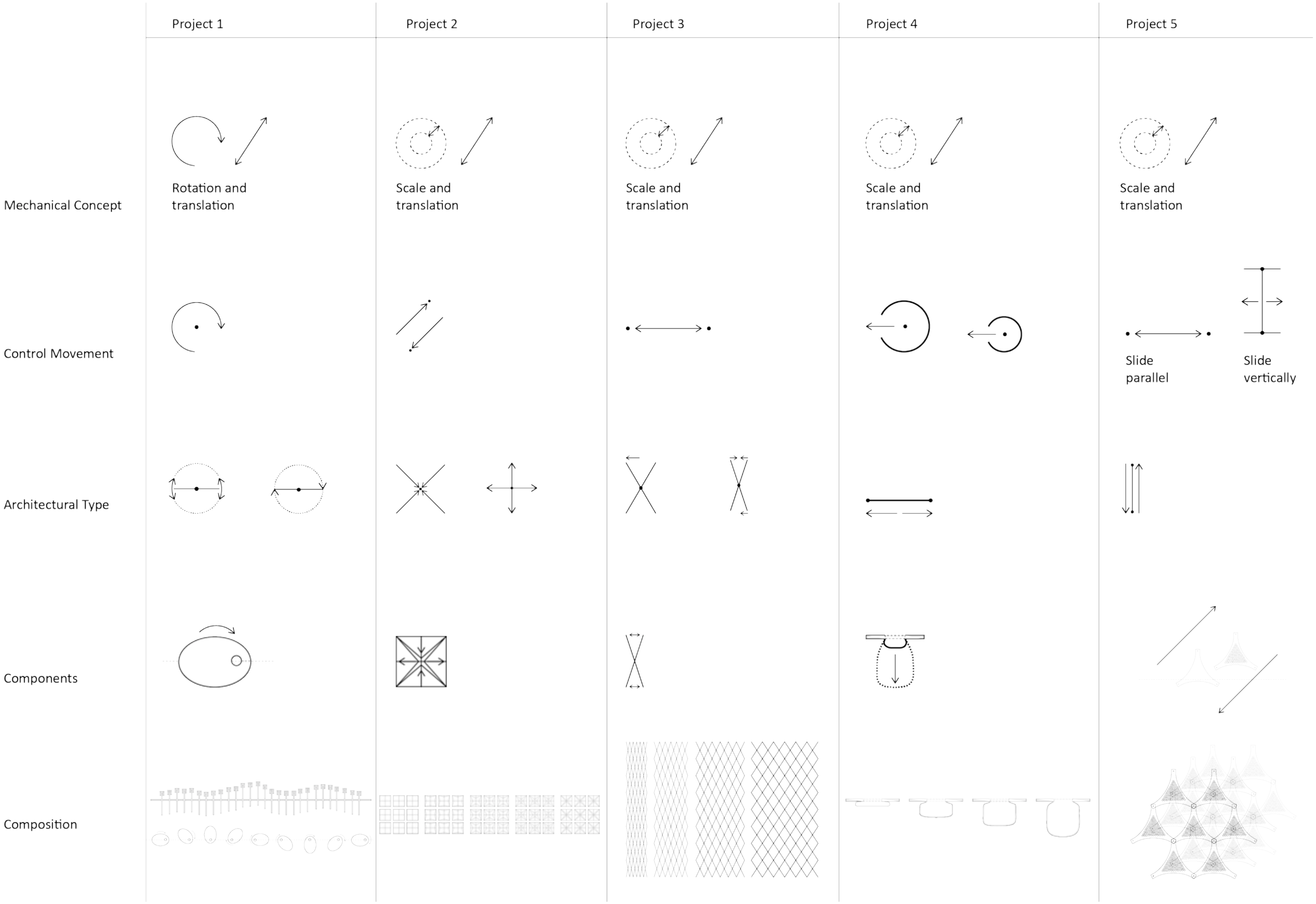

Figure 35: Summary of kinetic motion of the five projects. The diagram demonstrates the kinetic configuration and composition manifested from the kinetic movements and mechanisms. Source: Author.

4 EVALUATION OF KINETIC FOR ENVIRONMENTAL CONDITIONS

In the previous chapter, the study was focused on physical prototyping as a way to explore and understand schematic opportunities of kinetics in designing kinetic facades in response to environmental conditions. However, through the process of evaluating the physical prototypes, we identified that facades need to be evaluated throughout the year in order to ensure that kinetic facades are effective in adapting to changing in response to local environmental conditions. This will be conducted in two sections. First, the digital simulation will mainly focus on daylight conditions. Secondly, one of the potential types of kinetics is further tested through physical simulation conducted during the Smart Geometry Workshop in 2013, in London.

In practical terms, this investigation explored digital simulation techniques to further understand the performance of kinetic facade systems in the early phases of the design process. The outcomes of this research are producing a range of different prototypes that examined different types of kinetic patterns. The rationalisation and resolution for each prototype were evaluated through an extensive process of digital modelling, simulations, observations, reflections, and analysis. These processes ultimately became a methodology for exploring kinetic facades.

In relation to the first experiments, a series of other digital model prototypes were also presented in the chapter representing varying motions of kinetic facades. These prototypes explored alternate techniques and behaviours with the aim of improving the performance of kinetic facades concerning daylight and thermal conditions throughout the year.

Furthermore, this chapter defines digital model of kinetic facades as a scaled-down or simplified version of a particular design. This allows the designers of kinetic facades to observe the design in its abstract form in order to increase understanding of its intent. In this analysis, these models are not intended to be functioning prototypes but rather three-dimensional representations of ideas. This approach is consistent with the set of tools used in the pre-digital design paradigm, where scale and material substitutes were acceptable alternatives and did not compromise a model's representational value.

4.1 New modes for digital simulation and design experiment

Creating an effective simulation for testing and evaluating the environmental performance of a building is a challenging task. According to Augenbroe (2010), current computer-aided design and engineering (CAD) tools have provided designers with the ability to simulate and evaluate many different aspects of building performance such as thermal heat and daylight (Leighton, 2010). Due to their dynamic nature, kinetic facades are often required to perform contradictory functions in order to control the indoor environment through leveraging environmental conditions. Such leveraging can serve two purposes. For instance, the amount of solar radiation that enters the interior space can be used to increase the building's internal temperature, while at the same the facades response can reduce the amount of glare and ultimately maintain temperature control (Sharaidin, 2012).

4.2 Design problem

The drawback with existing digital simulation tools is that they are initially designed for static building elements. While existing tools are useful for static systems, kinetic systems are require dynamic evaluation tool or experiment setup to evaluate the design performance. Therefore, they must be analysed under a range of varying conditions for effective system sizing (Selkowitz, 2001). Figure 36 shows the differences between the design of traditional and kinetic facades simulation. Due to their dynamic behaviour the evaluation process for kinetic facades involves a few integrated variables, which are simulated in real-time. Furthermore, it is essential that adequate building performance simulation tools are developed to support the design of kinetic facades (Loonen, 2010).

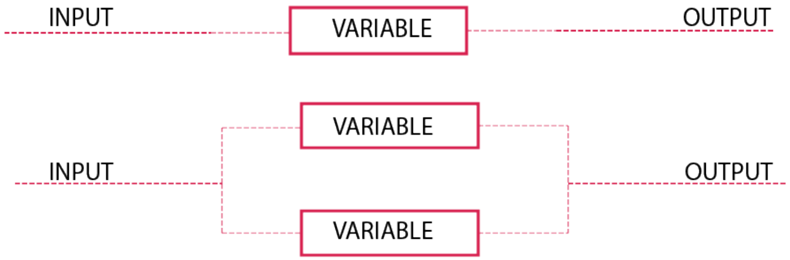

Figure 36: These diagrams demonstrate the traditional simulation method (left) and dynamic performance method (Loonen, 2010). Source: Author.

Simulation objective

Real world systems tend to trigger enquiries that can be explored through simulation in evaluating the performance of kinetic facades. However, before the performance of a kinetic facade can be designed, the facade system first needs to be translated into a conceptual model. A conceptual model is described as an abstraction of a digital simulation model, which defines the purpose, inputs, output, content, assumptions and simplification of the model" (Robinson, 2008). By definition, modelling and simulation implies an 'approximation', which is introduced in the abstraction process by means of assumptions (Robinson, 2008). Additionally, Robinson (2008) describes assumptions as ways of incorporating uncertainties and beliefs about the real world into the design of the model. While the model referred to here is not a model itself, but a model of the model's results that should be close to reality (Leighton, 2000). Therefore, the simulation that is conducted for the building components such as kinetic facades should be able to assist designers to foresee the design performance and outcome in early design phase (Fernandez, Rubio, & Gonzalez, 2013)

4.3 Environmental Considerations

This research involves an algorithmic and parametric design process, which was developed in *Rhinoceros/Grasshopper*, *Galapagos* form finding tools and *Ecotect* as a daylight simulation tool. The choice of these tools was based on their ability to be integrated as well as run simultaneously in parallel to provide real-time feedback. Within the framework of this study, *Grasshopper* can run a single process as the design space modeller, while, *Ecotect*, as the dynamic day-lighting tool, and *Galapagos* as the solver. The process of running these programs simultaneously to ensure the parametric tool can extract the designed geometry from the modelling space and send the inputs into the *Ecotect* component so that it can be tested for luminous distribution and daylight penetration depth inside the space (Sharaidin, 2012). As part of this process, *Galapagos* provides a few different variables, such as the maximum size, and pattern of geometry. These variables examine the suitability between these two variables (size and pattern), which is then calculated in a loop process in order to identify the optimal solution. This process is dynamic and allows the designer to perform various iterations during the design stage and thus refine and identify the best possible solution based on pre-determined criteria.

This research presents a methodology and tools that focus on performance-based design to address the design, simulation, and motions of kinetic facades, and their effectiveness to respond to changes in daylight. Within the scope of this framework, *Grasshopper*, *Rhinoceros*, *Galapagos* and *Ecotect* are incorporated into one integrated process that facilitates design options for obtaining real time feedback. The main objective of this study is to investigate:

a) What are the effective ways of using digital simulation as an early predictor of the kinetic facades performance toward daylight control and thermal heat condition?

b) What are the available options and possibilities to improve the performance of the kinetic facades design that can be identified by using digital simulations in the early stage of design?

This study is based on responding to the climatic conditions of Melbourne, Australia, which has a monthly average maximum temperature of 26.7 degree Celsius monthly average minimum temperature of 5.7°C. The critical surface of the location of this study is a third story room facing north-west of the building will be evaluated in during this investigation. This side of the building is exposed to direct solar radiation that has a maximum angle of altitude of 75° during summer and 29° at the winter solstice. In this exegesis, the number of kinetic patterns that have the potential to perform as environmental control have been identified and tested as part of this simulation process. Three different investigation stages are defined within the design components, of which the first has already been finalised in investigation one (refer to Chapter Three). The first stage explored the state of the art in kinetic facade design as well as further defining the problem. This exploration involved an extensive review of the literature as well as an analysis of various types of kinetic patterns for responsive facades. This exploration placed an emphasis on effective response to local climatic conditions as a focus of this exegesis. Additionally, this project developed into the process of physical prototyping, an area that was discussed in Chapter Three.

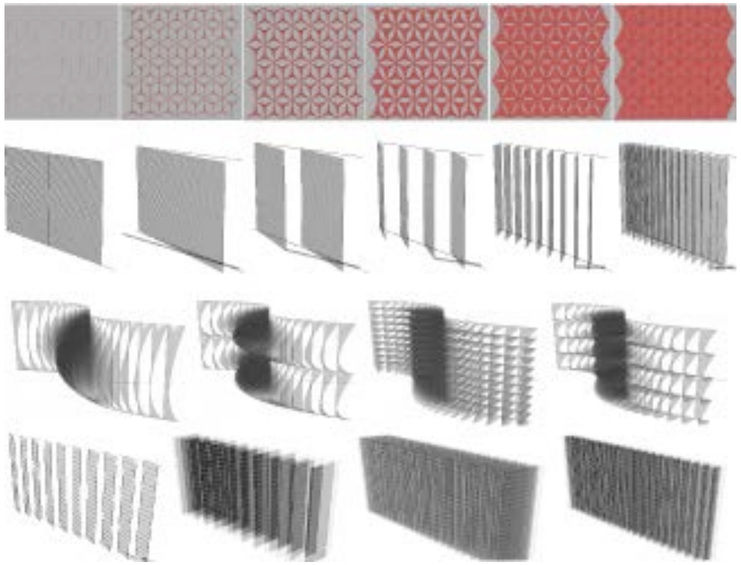

Figure 36: Example of representation of kinetic pattern and kinetic configuration in existing buildings for environmental control, which adopted during the simulation. Source: Author.

The kinetic geometry is chosen based on the pattern of motion, active surface, and the size of the surface. It is important to consider these elements in order to obtain effective results in this analysis and to avoid a phenomenon shown in Figure 37.

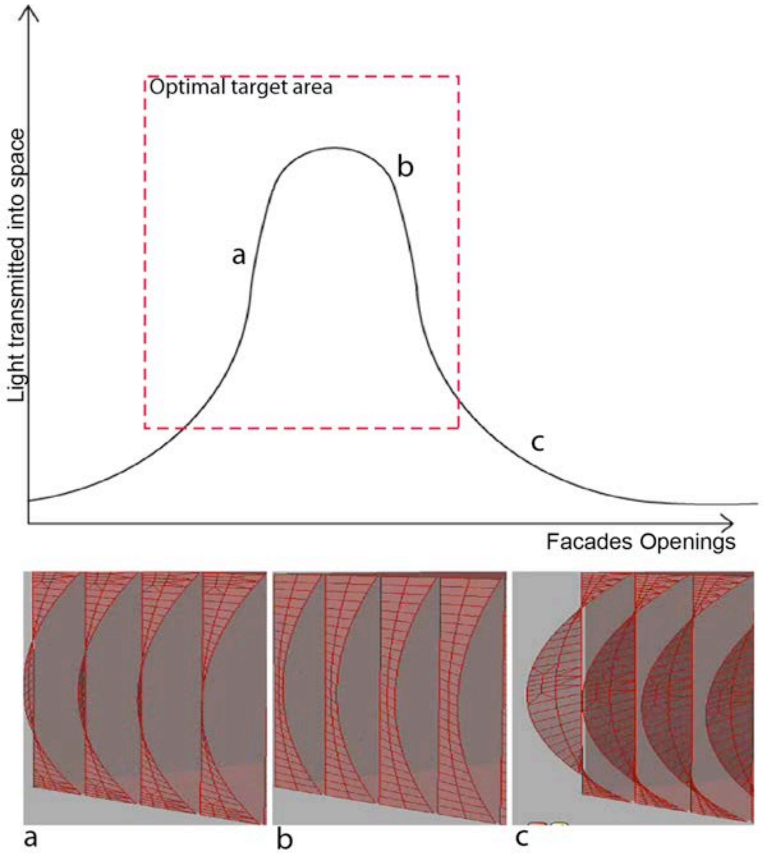

Figure 37: An example of phenomena that can be avoided in designing kinetic facades at the early design stage. Condition a and b is the optimal design for this kinetic system, where the condition c should be avoided as the shading devices are to too wide and over shadowing another panels when it is open. This analysis assists designers to avoid such problem when dealing with dynamic shading devices that have constant changing states. Source: Author.

Simulation strategy

Kinetic geometry plays a crucial part in a kinetic facade system's ability to respond effectively to daylight, thus making it an important component to evaluate. In this simulation the appropriate tools were required to meet four requirements: 1) kinetic patterns that are present in the conceptual model, 2) the kinetic performance at an appropriate level of detail, 3) the way kinetics respond and 4) support interaction between kinetic components.

The simulation processes were established by designing the kinetic pattern, which were embedded with 5000mm x 5000mmmm x 3500mm cubic spaces (Sharaidin, 2012). The actual weather data of Melbourne solar radiation from the 21 of June to 21 of December 2011 was entered into *Ecotect*. *Galapagos*, *Ecotect* and *Grasshopper* were used in combination to identify the optimal opening and closing patterns of the kinetic facade in response to daylight. Based on these results, the study identified five different types of kinetic patterns that were influenced by the geometrical configurations. The design parameters were categorised into three groups:

1. Response to general conditions.
2. Kinetic Structure and active surface.
3. Defining the potential behaviour of kinetic facades.

Additionally, these simulations identified the optimal pattern, size of the surface, and form of the kinetic facades. The proposed alternative design tool accepted additional parameters and variables (type of kinetic patterns), which enabled the transformation of complex geometry. However, the advantage of complex geometry in the design output is more dynamic.

The main objective for using *Galapagos* in this study as an algorithmic process to evaluate the responsiveness of the facade, through a series of kinetic louvers that were actuated in response to dynamic daylight.

Galapagos operates by using a pre-defined set of parameters, therefore, leaving only the ability for calculation. A genetic algorithm has been incorporated as part of the definition in order to enable a search for the most suitable skin configurations for specific dates and times or under a range of sky conditions. The genetic algorithm works by finding an optimal solution that is controlled by certain parameters and conditions (Sheikh & Mansour, 2011). For instance, these parameters range from users desired illumination levels, to externally reflected daylight components. These parameters are the main factors in determining the optimum level of the light condition in the environment. From these parameters, it generates various options and solutions. Therefore random geometric parameters and transformation based on described criteria are created through evolutionary iterative process.

Throughout the complete process, the materials allocated for the external louvers had a high reflectance of ninety per cent. *Ecotect* components are fed by geometric output from parametric tools, *Rhinoceros/Grasshopper* to be tested for the daylight condition. The process could be done again providing an iterative development cycle.

Some limitations to this simulation existed such as the inability to evaluate complex behaviours like hybrid motion. However, this would be possible with a more complex simulation configuration. This motion combines two very different types of motions - elastic and sliding - both of which require a more complex simulation approach. In ensuring the simulation did not violate the simulation process while the behaviour of the model needed to be simplified, which involved less detailed analysis (Sheikh & Mansour, 2011).

4.4 *Design implication*

As a parametric design tool, *Rhinoceros/Grasshopper* allows the creation of kinetic patterns that can respond to multiple inputs (variables) and outputs through genetic algorithms (*Galapogos*). In the context of an application, the facade's ability to respond is represented by variables, mathematical functions, and benchmarks (Sharaidin, 2012). In other words, the ability for a system to respond is limited but flexible enough for the system to simulate certain desired tasks for better response to daylight.

These simulations identified a number of parameters, which were classified into definitions, variables and design categories. The motion and changing position of the surface defined the positioning and patterns that were relative to the external environment, which resulted in higher or lower levels of daylight within the space. For example, the active surface was identified for an expanding type of kinetic pattern, which was flat, singly curved or doubly curved as seen in Figure 38.

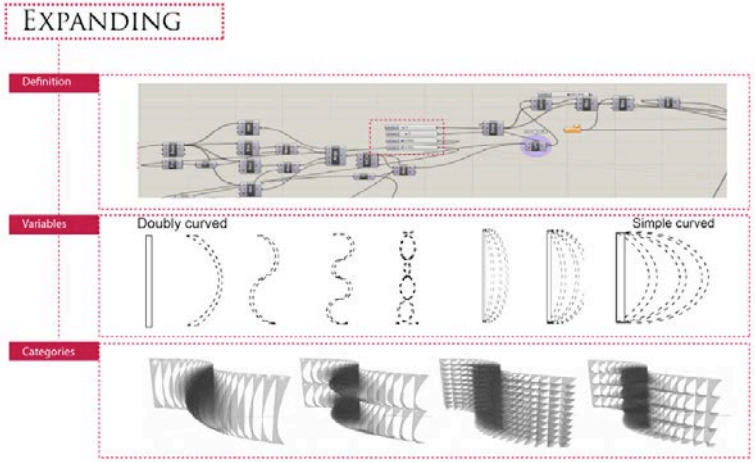

Figure 38: Expanding, is one of the kinetic pattern and configuration which are able to response and transform by changing in material properties such as by using smart memory alloy or Biometel . Source: Author.

After a comparative study of various potential geometries and patterns of motion, five models representing different kinetic patterns were selected. Motions of transforming and expanding were proposed because of their more dynamic material behaviour with an integrated dynamic structure. Both motions in the Figure 39 show the possible geometry transformation that is effective for particular places and micro-level behaviours by integrating with dynamic materials. The suggestion of the geometry and surface can be represented by a value in the simulation, which involves dynamic behaviour. For the configuration of these two motions, it is important to understand what type materials properties can be associated with self-adjusting and elastic behaviour in order to choose the right material in *Ecotect* during the simulation process.

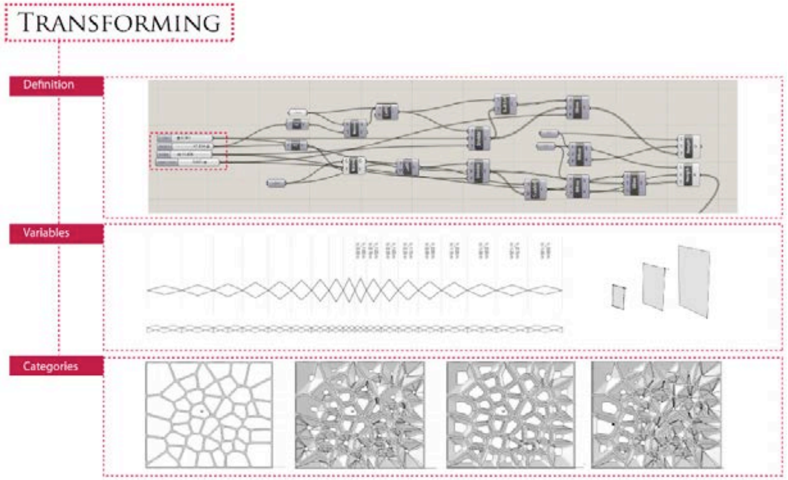

Figure 39: Transforming is one of kinetic movements that allows different configuration and shape at the same time as it involved mainly with material proportion. However, these conditions are mainly related to the objective of kinetic design and required design performance. Source: Author

In addition, three types of kinetic patterns with the potential to be developed into macro scale behaviours are:

1. Retracting
2. Folding
3. Sliding

These motions are categorised based on different geometries that are integrated as part of the kinetic facades ability to respond to daylight. The parametric definition is flexible and can be altered to accommodate different variables, which are represented in sliders. The alteration of variables will propagate changes in the model and suggest different configurations of particular motions. The simulations of these three types of motion are shown in Figure 40 to Figure 42.

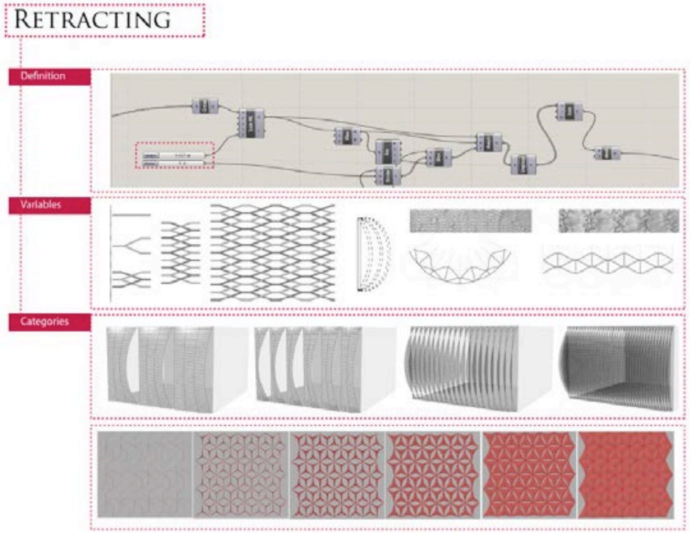

Figure 40: Retracting, one of the kinetic pattern configurations that mainly involved transformation of structure and surface at the same time. The motion required consistent of movement as the component are interrelated. Scissors structures are one of the dynamic structures among many that has been used to produce this type of kinetic motion. This kinetic structure has been adopted for implementation of kinetic facade and has been explored throughout this research. Source: Author.

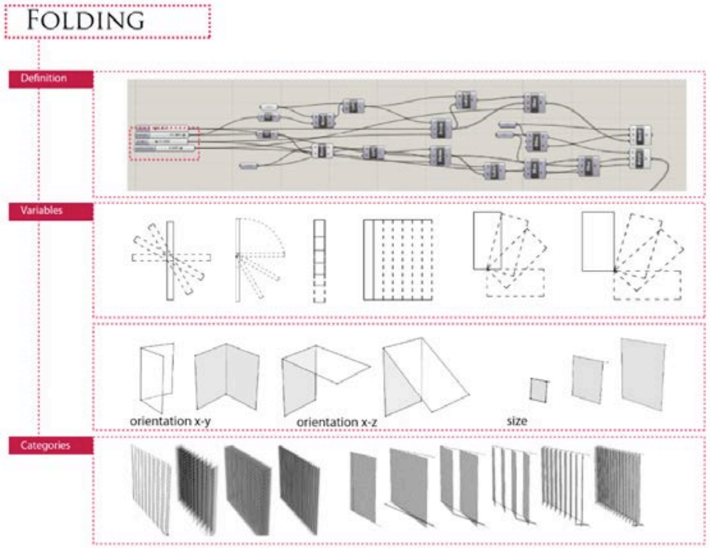

Figure 41: Folding is one of the kinetic movement that widely adopted in kinetic facades in the building practices. This is due to the kinetic system involved is straight-forward and well known in dynamic facades application. The understanding of fundamental kinetic movement such as folding, help designers to explore different kinetic design configuration and pattern that are effectively respond to changes of environmental condition. The basic understanding of kinetic movement will allow the designers to dealing with complex kinetic design configuration. Source: Author.

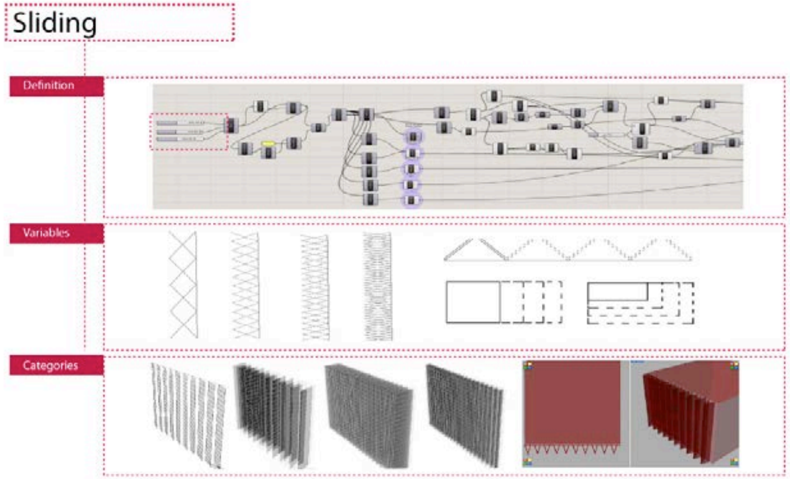

Figure 42: Sliding, one of the kinetic configurations and mechanisms, which mainly involved rail track to move and creating transformation. One of the advantages of sliding movement in kinetic facades application that have the ability to create different types of transformation which able to be designed to move vertically or horizontally. This type of movement is widely applied in kinetic facades such as facade design by AEDAS, Al-Bahr. Source: Author.

Parametric models are used as a way to isolate and apply the most suitable geometric parameters to a kinetic facade. Further evaluation was conducted on physical testing on one type of kinetic pattern that will be discuss in more detail in the next section (Section 4.5), to outline the potential of these motions to work as an appropriate response to daylight conditions.

The integration of parametric design definitions and environmental software can simulate different kinds of constraints, parameters and strategies, which provides and range of options and variables to help designers for making effective decisions and identify critical problems in the early stage of design. This research identified a methodology that is clearly understood and can inform the design and construction of new kinetic facades, so that they are more efficient in response to environmental conditions.

To create kinetic facades that respond to changes in environmental conditions the need for effective simulation tools in the early stages of design are necessary. One of the challenges for effective simulation tools is not only in their ability to evaluate the design more accurately, as well as to also accelerate and simplify the processes used by the tool for evaluating kinetic facades This is necessary as it affects the overall performance and design of a kinetic facade. (Sharaidin, 2012). Further evaluation of selected kinetic motion is tested on physical testing in the next section. The selected kinetic motion shows possibility to be developed in creating effective kinetic facades design (Figure 44).

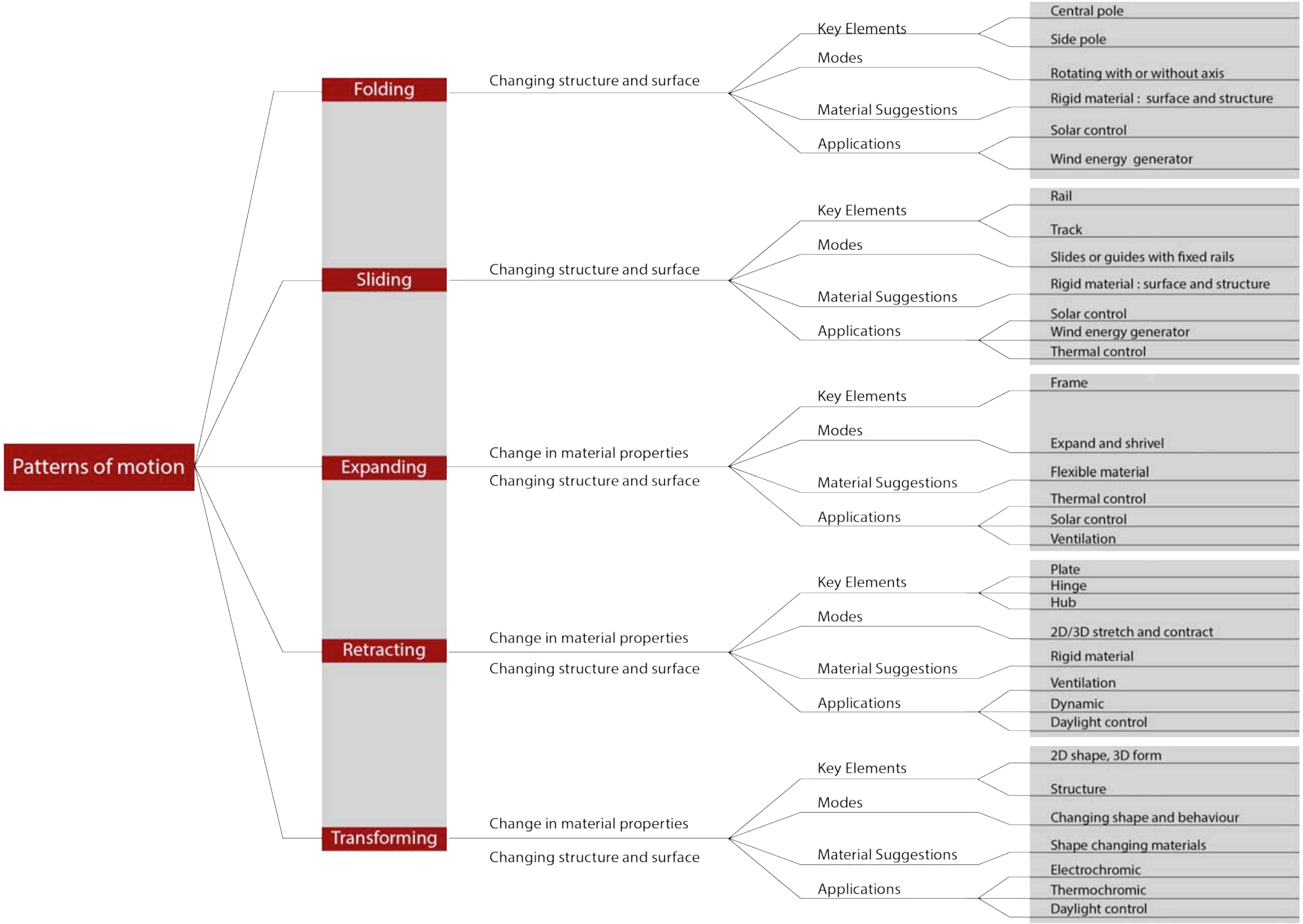

Figure 43: The diagram summarise the kinetic motion and their attributes that are potentially adopted in designing kinetic facades, which respond to environmental performance. These types of motions are mainly influenced by the application of kinetic structures and material properties to response and create the transformation. These motions are identified and evaluated throughout this research to observe their responsiveness and effectiveness of the kinetic facade application for environmental control. From the investigations, I would be able to understand and discover potential and challenges dealing with this motions and configurations. Source:Author

4.5 Physical Testing: Thermal reticulation

Further studies in one type of motions that likely to be developed based on the outcomes from the investigations in the previous sections and Investigation One, particularly, the motion that is associated with sliding, expanding and contracting which form folding and unfolding behaviour, are further investigated. This is because it has the potential to be further developed given their lightweight attributes and a robust structural pattern that can form a building facade. These motions are tested in the context of Smart Geometry 2013[49] (SG13) under the cluster of Thermal Reticulation[50].

It is a challenging task to successfully simulate a buildings' performance. It often requires the art of selection: the right type of virtual experiments with the right models and tools (Leighton, 2010). The ability for designers to simulate different aspects of a building's performance, such as thermal heat and lighting, through Computer-Aided Design (CAD) and Engineering tools (Fernandez et al., 2013), which allows designers to evaluate the dynamic behaviours of kinetic facade systems.

Although facades are designed to respond to a range of different environmental scenarios, they are static systems. However, their functionality often requires that they be designed with the intention of performing contradictory functions. For instance, allowing solar heat and light to enter the interior space as much as possible whilst regulating the glare and heat at the particular period of time during the day. However, while facades are sometimes required to perform such functions, it is necessary to be able to simulate the kinetic performance using a physical model with the aid of digital simulation in order to evaluate the active mechanism and responsive

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[49] http://smartgeometry.org/

[50] Thermal reticulation is one of the workshop clusters in Smart Geometry 2013 led by Alexander Pena, Jane Burry, Kamil Sharaidin, Flora Salim, Mani Williams and Stig Neilson (http://smartgeometry.org/)

elements of kinetic facade systems. As a result, this process requires an investigation into new ways of designing kinetic facades through evaluating their performance in order to properly assess whether the kinetic facade adequately fulfils its functional requirements.

Experiments Setup

In 2013, as part of the Smart Geometry workshop, the physical testing setup to evaluate the facades performance was investigated. A number of experiments were designed and developed investigated two different strategies. The first part of the investigation was aimed at exploring the designing of kinetic facades prototypes. The second is to understand and replicate the real world boundary conditions as much as possible to test the facades performance. During the physical testing setup, various tools and softwares are explored and tested to get better outcome from these experiments (Figure 44). The objective of this physical testing is to observe and evaluate the facades performance without consuming large amount of time to setup the simulation and gaining the outcome. Thus, it is aims to improve the facades design based on the instant outcome gained from the testing conducted. This process informed the possible problems or difficulties in constructing the facades through engaging with the physical material as apposed to evaluate a singular criteria (such form performance) in digital simulation.

Figure 44: Physical testing experimentation setups are conducted in Smart Geometry workshop in 2013. Source: Author.

Frequently, physical simulations must be performed in a series of steps. For instance, first simulating the opening and closing behaviour, another steps by improving different design configuration such as perforated skin for the prototypes. This will allows an observation of different design performance at the real-time. From this, the data gather from this testing, can then be combined to produce a predictive model that can be used to define the operating parameters for the design of kinetic facades (Zarzycki, 2013). However, prior to the data evaluation, proper setup and accuracy of the physical testing need to be established in order for the data to be usable for the performance evaluation.

In order to configure appropriate geometry and pattern, prior to prototyping and fabrication of the kinetic facade, the prototypes were tested through digital model simulation using integrated software of *Grasshopper*, *Ecotect* and *Galapagos*. The testing was carried out appropriately configure the geometry and pattern of the kinetic facades so that it can effectively control the amount of daylight during the day throughout the year (Sharaidin, 2012). The results from the simulations are further reflected and evaluated using physical models.

Physical Testing setup: Daylight experiments

The setup of the experiment includes five halogen lamps with 500W electrical power in a planar arrangement. For special use, the lamp can be rotated in different angles. These particular experiments are conducted for two different states involving 75-degree angle in summer, and 29-degree angle in winter. Different angles are setup one at a time to measure the effect of the kinetic facade in each case. The halogen lamps are positioned 1.5 meters from the facades and the experimental box, and this is to ensure the facades get optimal light distribution using the five-halogen lamps. In this simulation, dimmers are used to control the light level. The three light sensors are embedded in the 500mm x 500mm x 1000mm box to determine the opening and closing of the facade system (Figure 45). The sensors were attached to the actuators using *Arduino*, which allows the sensors to determine the facades performance. In this simulation, thermal heat spring, *SMA spring* is used as an actuator.

These materials have been of interest in numerous research projects on kinetic facade systems, and the application is still at an experimental stage. Ordinary mechanical actuators, for example, motors and gears, could also potentially substitute this actuator. In this simulation, the smart memory spring was located at the end of a scissor structure on top of the facades. The *SMA springs* were attached to the 12V battery to heat the actuator when the light sensor sent the output via *Arduino* to the actuator to create compressive behaviour. When the light was turned on, the smart memory spring would go back to the original state, which created the closing behaviour for the facades. Four actuators were used in this experiment to control different modes of opening depending on the light level (Lux) in the box. The facades can be programmed in different states of opening during the simulation.

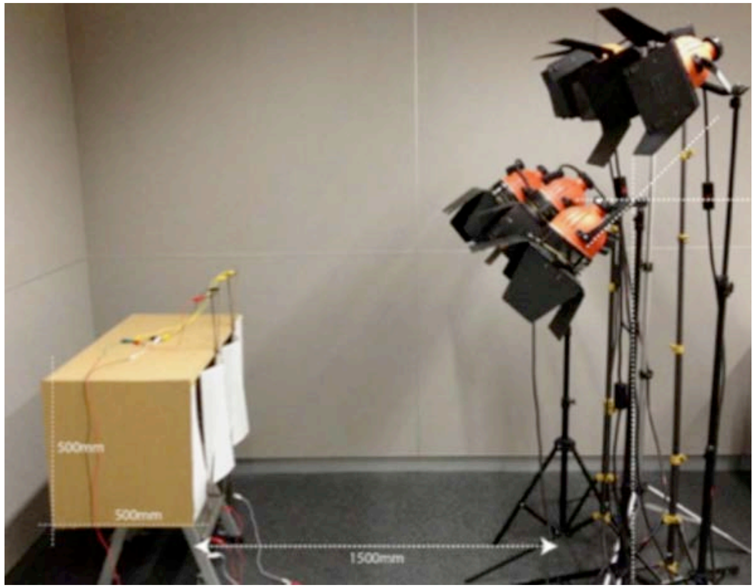

Figure 45: Daylight simulation setup is conducted in indoor environment to test different type of kinetic configuration that responds to the light. The physical setup and testing will be more effective if the curvy light source are imposed during this testing as it will create more comprehensive sources toward the kinetic panels. Source: Author.

The main objective of this simulation is to test and to observe the behaviour of the kinetic facade system (Figure 46). This is to identify and evaluate the effectiveness of the mechanism in responding to the daylight performance and in controlling the light in the space. During this investigation, certain problems are highlighted so that, designers able to understand how the system works and what needs to be improved.

Figure 46: Dimmer and three light sensors are integrated into the simulation to control the facades opening and closing behaviour of the panel. This testing allows to observe the responsiveness of the sensor and actuator to be adjusted to different lighting condition. In this testing, I observed that the sensitivity of the light sensors determined the responsiveness of the panels to create transformation. Source: Author.

The daylight and kinetic performance of the facades are clearly shown during physical simulation of the kinetic facade systems. By comparison, mechanical problems are hardly visible at early design stage in digital simulations. Hence, this highlights the importance of the process of conducting physical experiments to understand, evaluate the environmental performance in developing the design of the kinetic facades.

During this simulation, the frictions of the mechanism are identified so that design improvements can be suggested during this stage. Improving the mechanism of the system concurrently affecting kinetic behaviour and facades performance to respond to environmental changes. The iterative process of testing and modifying the kinetic design through engagement with the physicality of the subject demonstrate strong outcome and issue in making the system operate and function accordingly.

Thermal heat simulation setup

The simulation model is a virtual image of real physical phenomena; as a result the simplification of reality is an inherent feature of models. In other words, the building has to be simplified in a suitable way in order to obtain a simulation model. In the case of a large building with many similar rooms, for example, representation can be made via selection of a small number of rooms. An examination regarding the possible overheating of a large building requires analysis of the internal and external heat gains of the different rooms to identify those that are potentially critical. These are selected for modelling and appropriate boundary conditions defined. In this simulation, the boundary conditions are simplified to understand how heat behaves in this particular area and surface. Similar investigations are conducted in the thermal heat simulation. This experiment is part of experimentation setup during the Thermal Reticulations[51] cluster workshop in Smart Geometry 2013[52]. The cluster investigated heat transfer phenomena from one point to another on the building facades. The simulation is conducted to inform the designers of the performance of kinetic facade design in the early design stage.

The experimental environment for thermal heat simulation was reduced to a 300mm x 300mm x 400mm box. This strategy also helps to reduce the complexity of the simulation setup and the number of pieces of equipment involved. The setup applied two different strategies. The first of the boxes was integrated with infrared imaging cameras located at the back of the box and in front of the box. This setup is to see how heat transfers from one surface to another. A second box was set up using 27 digital temperature sensors (as shown in Figure 47) located as a grid inside the box to visualise how the heat transfers into the space and how well the facades perform in regulating the thermal behaviour of the space (Figure47)

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[51] Thermal Reticulation is cluster lead by Alexander Pena, Jane Burry, Kamil Shraidin, Flora Salim, Mani William, Mark Burry and Stig Anton Nielsen. The cluster are investigating on a way, which we can measure the gap between the prediction of performance and the measurement of reality for facades design.

[52] https://smartgeometry.org

Figure 47: Setup for thermal heat simulation using thirty heat sensors (left) and two thermal imaging cameras. The original idea for this setup is to identify the discrepancy between the digital simulation and physical testing in analysing difference facades configuration. The testing is setup based on replication between digital simulation and physical configuration. The results from both simulations are compared to see the gap between this two simulation tools. However, to setup a physical testing a complex task as it has to dealt with dynamic boundary condition such room temperature and humidity. To replicate the digital simulation is difficult. Through this process of designing and testing different configuration of the facades, it demonstrated that the digital simulation and physical testing served different benefits and complementing to each other. However, in the process of designing and evaluating the kinetic facades, physical testing resulted more favourable outcome and information that will inform the designer on the kinetic design and facades performance. Source: Author.

The sample facade system that was installed on the first box were analysed and evaluated based on how the heat was transferred across the surface into the interior space. This simulation was conducted using two thermal heat infrared cameras in order to observe how heat transfers from one surface to another. In this simulation, folded perforated kinetic facades were tested in order to see how well the facade performs in protecting the space from the artificial heat. A halogen lamp was used as a heat source for this simulation. The halogen lamp is positioned at a 90-degree angle to get uniform distribution of heat on the surface. The halogen lamp was turned on for 15 minutes in every simulation. The images from the thermal camera were captured every 200 seconds to record the heat behaviour changes on the surface of the facades. The images were recorded from in front (Figure 49) and inside the box (Figure 50).

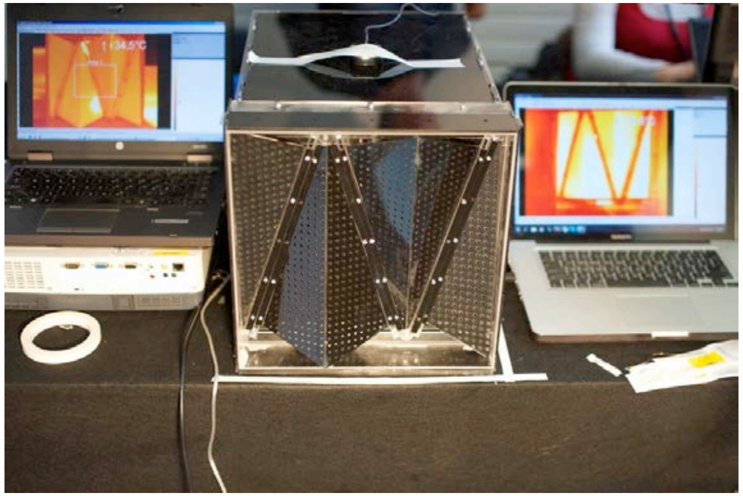

Figure 48: Thermal heat infrared camera is located in front and inside the box to visualise how quick the material observing the heat. This testing involved different material properties and colour. Source: Author.

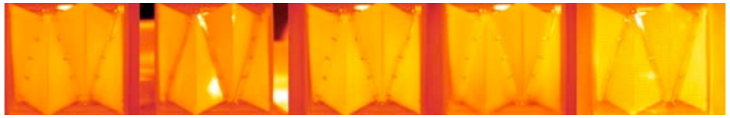

Figure 49: Images of thermal heat infrared camera located in front of the facades and the lamp heat are located in the same distance with the facades. Source: Author.

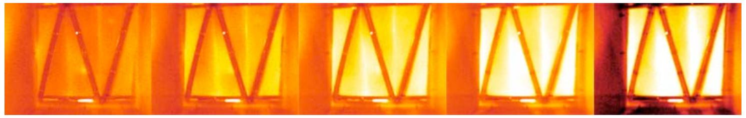

Figure 50: Images of thermal hear infrared camera from inside of the box. Source: Author.

The observation from this testing demonstrated the edge of the surface of the facade heated up very quickly, and the folded facades were not creating a uniform response to surface heat. In the second simulation, the folded kinetic facade was tested with the aim of analysing its effectiveness in responding to the external heat and protects the space. Three states of facade conditions were tested in this simulation (Figure 51).

Two moveable facades were installed as adjustable louvers in this simulation in order to create closing and opening behaviour. As this simulation is an early attempt to simulate a kinetic facade performance using heat sensors, the interactive system is not integrated with the facade behaviour and the output from the sensors. Future investigations are planned to explore the interactive systems.

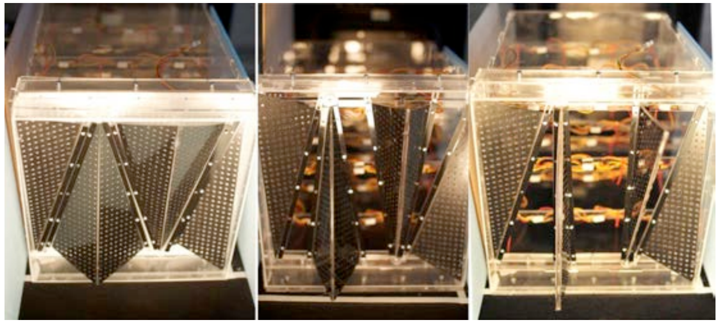

Figure 51: Three different state of the facades are tested during this simulation. The result and observation gained from the testing resulting a few changes on the material properties and kinetic mechanism. Source: Author.

The behaviours of the facade toward the thermal heat are visualised through *Matlab* software (see Figure 52). The flux of the data from the 27 sensors, which were located in a grid, were observed and monitored through this visualisation. During the early observation, we can see the convection of hot air was transferred towards the back of the box very quickly. After the facades had fully opened, the facades were then quickly closed to measure how long the facade was able to store heat. These exercises are effective to visualise the facade performance, enables many design and test iterations in a short period of time to improve the facade performance.

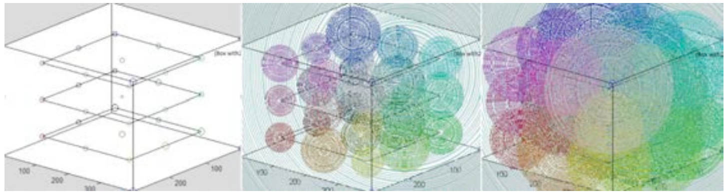

Figure 52: The outcome from the heat sensors are visualised through Matlab software, which demonstrated, by sphere shape. The bigger the sphere the warmer to the heat presence in the space. From the left the facade are from closed to total open. Source: Author.

The simulation setup could be improved in terms of accuracy as some additional parameters can be taken into further consideration. For example, the temperatures inside before and after the simulation can be measured and controlled to ensure constant baseline. Cooler spray can be used to lower the temperature inside the box in order to get the optimum result. In these experiments, the surrounding temperature outside the box might be effecting the measurement of the simulation. Conducting this simulation in a thermal chamber would be more effective in maintaining constant external boundary conditions and produce more accurate results.

Outcome from observation and physical testing

It was evident in the early phase of design that these investigations highlight the importance of physical simulation as a significant method to evaluate the kinetic facade. Furthermore, the feedback obtained through the physical simulations in the early stage of design is crucial for designers as it provide significant information that informed the designer decision through the design development process. The main issues such friction; kinetic forces and durability of the actuator are barely visible during the digital simulation investigation. These variables need to be established at the early stage of the physical setup in order to improve and measuring the kinetic performance during the design development.

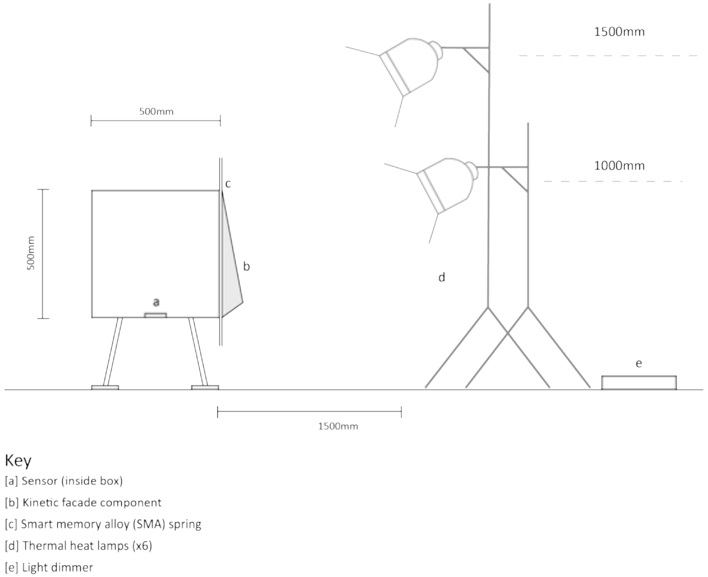

Figure 53: Overview of physical testing setup. The physical testing is designed to evaluate facades sensitivity to respond to different lighting level. Source: Author.

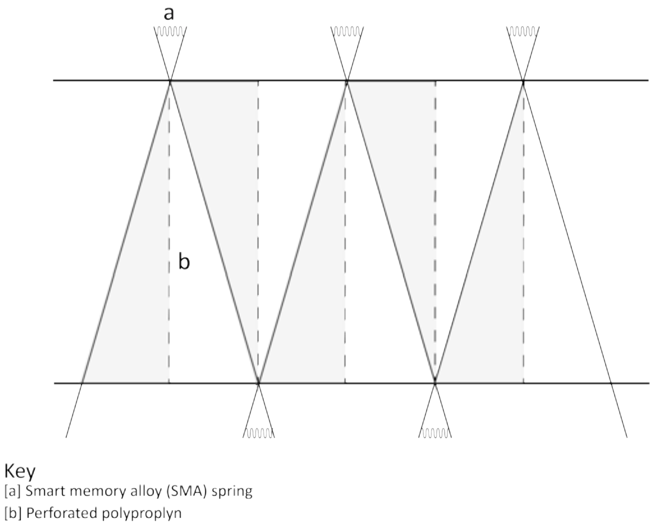

Figure 54: The folded and sliding motion of the facade. Six panels of kinetic facades are tested during this investigation. Smart memory alloy are used as an actuator to trigger the facades to opened and closed. Source: Author.

During the development of these investigations, the accuracy and technical setup could be improved by considering certain aspects in detail design, such as surrounding temperature, material properties used for the facade, insulation of the box and thermal sensor sensitivity. However, physical testing enables the facade performance to be evaluated in early stage of design, given its ability to highlight potential design issues that may not be identified or visible during digital simulation. The process of tuning the physical setup so that it can serve as reliable platform for the testing are crucial important. The calibration of the actuator and sensor are one example of the process of tuning the physical setup in order for the simulation and testing can be conducted effectively. This process for instance involved, try and error of different type of sensor and data reading. Ultimately, the physical setup and testing of kinetic facades provides the designer with more understanding on the performance and behaviour of kinetic facade. As a result that they are able to make important decisions in the early stages of the design process to ensure that the kinetic facade responds adequately towards the environmental conditions.

4.6 Summary, Chapter 4

Creating-making is a formative constant in the ways design thinking translates into the built environment. Creating-making transcends the division between technology and handmade products or, more recently, between analogue and digital modes of production. At the same time, technology and tools affect the ways we produce and conceive the architecture. For instance, during the Renaissance, ideas were expressed in drawings, and sketches were tested with large-scale physical model prototypes, similarly to methods of today where we continuously shift between physical and digital modes of thought and production. However, a significant difference at present lies in a tightly integrated dialogue between the physical and the digital in designing and evaluating the kinetic facade performance.

Furthermore, the digital model and simulation is no longer only used to represent the actual physical (proposed) design, nor is the physical a mere realisation of the digital creativity, fabricated from scale-less and context-less digital models. The digital-physical design dialogue is more intricate and bidirectional, involving simulations, performance analysis, and component optimisation. By connecting digital prototyping with physical prototypes and testing, materials and kinetic elements have become an important variable. Therefore, yet another consideration in the otherwise parametrically has driven the design process. Kinetic elements and materials act as yet another feedback loop that informs the design and provides a set of constraints to guide the designers.

Furthermore, today's generation of designers often have a better grasp of digital than of physical tools. Therefore, the requirement to manually construct designs is even more important than it was in the past. Since the architectural profession ultimately deals with physically constructed buildings, there is a need for designers to understand the translation process of their ideas from the digital to the physical. There appears to be a perception among many students that once a design is modelled in a three-dimensional virtual environment, it is fully resolved. If it exists in a three-dimensional model, it also has the right to exist in a physical setting and evaluated using the actual material.

At present, computational tools solve some of the aforementioned issues but still leave many of them unresolved. Specifically, material properties, physical behaviour, and constructability continue to remain unaccounted or undressed for in most software packages. While the approach discussed above points to ways of addressing the issues of material properties and physical behaviour, physical mock-ups prove to be an effective learning environment. By constructing kinetic designs or pneumatic structures, designers experience the intricacies of mechanical assemblies and material limitations. In contrast criteria such as dealing with dynamic design behaviour are not feasible or taken for granted with existing software simulation packages which, becomes a major issue when manually constructing kinetic designs. For example the criteria dealing with design of kinetic such as deciding the optimal centre of gravity and points of rotation are important factors in the effective operation of kinetic assemblies. Even though these criteria can be simulated in the digital simulation software, it does not demonstrate the actual condition of the kinetic behaviour, as a few significant parameters are not included during the simulation. This is due to the aspect that details and accurate simulation required details scientific tools and consumed more time and experience in order to evaluate the kinetic design which is the constraint of early phase of design.

In addition, the process of building and rebuilding mock-ups, discovering imprecision in produced work, facilitates the discussion such as on the types of loads (concentric versus eccentric) and moments and parameters associated with the kinetic design for building facades. Designers' first-hand experience are essential to design kinetic and develop understanding in making informed decision based on the environmental performance in order to form effective kinetic elements as part of integration building facades components. Therefore, further exploration on physical one to one prototyping and testing with aided of digital model and simulation technique will be discussed in the next chapter.

5 FULL-SCALE PROTOTYPING OF KINETIC FACADES

5.1 Introduction

> "*Prototyping is the pivotal activity that encapsulates innovation, collaboration, and activity in design. Prototypes embody design hypotheses and enable designers to test them*" (Bjorn et al., 2006, p. 1).

As a result of the research conducted through digital simulation and physical testing in the previous chapter, which demonstrates alternative methods and protocols for modelling and testing the kinetic movement and configuration, from this understanding and lesson learnt, further investigations are conducted with an inquiry of full-scale prototyping and testing affecting the kinetic facades performance in response to the actual context. This enquiry was investigated by selecting one of the kinetic patterns that has the potential to work effectively in a large integration of kinetic component and system. In this case, sliding and folded movement are selected to be scaled up for a further investigation called the *Un-fold*.

Un-fold is a part of design development and testing from Chapter Four, which was also explored through physical testing in *Smart Geometry 2013* under the cluster name *Thermal Reticulation* in London. The outcome from this investigation was informed as the design development and evaluation of *Un-fold.* The final version of this project will be constructed and installed on the buildings as part of the design investigation process.

As designers engage in a variety of tools and techniques for postulating the facades of a building before they are built (Yanni, 2012), the e exploration of design was conducted through one to one scale prototyping and supported by digital tools. Even though the process of engaging with physical kinetic in one to one scale aims to provide alternative techniques for evaluating the design of kinetic facade in response to environmental conditions, this chapter does not promote the abandonment of digital evaluation techniques in designing kinetic facades. It is to relatively reinforce that engaging the materiality and physicality of kinetic movements during the exploration process in the early stage of design is for a deeper understanding of the real challenge when dealing with kinetic facades' performance, and further information could be gained through digital model and simulation evaluation.

5.2 Performance based design through full-scale model

In the previous chapter, kinetic design in response to environmental performance of *Un-fold* has been analysed through small-scale prototyping with a few integrated kinetic components. However, this investigation does not demonstrate the actual performance of kinetic design and kinetic mechanism, as the design for construct-ability and durability are mostly visible when the kinetic system and mechanism are executed in the real building environment. In addition, this process of physical prototyping in one to one scale is intended to not only evaluate if the design will be physically possible, but also to find alternative methods of improving the kinetic design for building facades. Therefore, through this research and process, a few alterations to the kinetic design and mechanism are made to ensure the facades are working effectively with larger integration of kinetic components. From this method, it creates a salient and observable change in the design process occurring around the process of design and physical changes of kinetic design through time. As designers are typically concerned with an object's static presence (Amanda, 2008), kinetic and transformation which involved design that changes state, opened up new channels of thinking and design consideration, both in designing the process of development, and the responsive movement of the design object.

Designing kinetic facades through physical prototyping - will be developed and changed based on the information and experience gained through the process of making and designing the kinetic form and mechanism to ensure that it can be effectively responsive to the environmental condition. Therefore, the objective of this investigation is not to get absorbed with designing the kinetic as a static object or simulate it as single parameters, but rather to convey that the exploration are interrelated with changing of information and feedbacks from the process gained in developing kinetic form and mechanism.

The idea of working with full-scale physical models provides the ability for the designer to develop and interact with the facade and kinetic mechanism with the purpose of designing the facade that fits with kinetic configuration and performance to be effectively respond to environmental condition. This approach serves as an alternative design process during the early stage, when designers are able to think and as well as improvise physically and temporarily, bringing to light the emergence of static-dynamic as a possible design approach (Fumar, 2011). Ultimately, working directly with materiality supports intuitive and simultaneous manipulation, mobilising designer's tacit knowledge and enabling participation (Gupta et al., 1997).

Furthermore, physical full-scale modelling is an integral part of a broader process in the design of kinetic facades and requires the ability to comprehend the relationship between the designed object (the facades) and their materialisation in a particular scale and material (Milena, 2013). Methods and techniques of scale modelling allow the designer to assess, correct and implement a project from its earliest stage (the original study of form, motion and mechanical behaviours) to the conceptualisation and materialisation of the kinetic facade. Different stages of the design process of kinetic facades can all be identified through different approaches to building scale models. This is because they provide a view of each of those phases and offer a three dimensional spatial preview.

According to Milena, (2013) the primary benefit of using scale models is the ability to preview and identify a tangible form in material space. The material representations of the form allow designers to interact with it directly (Bjorn et al., 2006). In the case of designing the kinetic facades, the idea of designing through scale models provides great insight to the designer not only due to the challenges in making it effectively functional, but also the effort in making the design as practical as possible and doable as kinetic facade system. Challenges as mention previously, such as friction or mechanical problems of kinetic facades system can be avoided at the early design phase. For example, in the case of designing through actual scale of physical model compared to a computer generated drawing, or digital model is that, it is built within the exploration of material construction during the dynamic working process which involved designing and testing. This process brings together all segments of the project, placing them in perspective, which is used to predict the functioning and behaviour of the kinetic facades presented by the actual scale models and if necessary leads to corrections and improvements. For example, Kinetic movement involving the folding movement which were developed further in this project are be able to be understood clearly through physical exploration as engaging through testing the opening and closing behaviour using physical material and mechanism, provides a simple and intuitive way to explore not only the shape, but also the potential joints and hinges assisting the final decision making of whether the design could be implemented or eliminated from the end product. This is a result from the exploration of design that involves joints and hinges are hardly visualised and experienced through digital modelling and simulation. Even though this subject can be explored through scientific digital simulation tool such as through *Matlab* application *(physic* based simulation software), it requires more time and exceptional skill in accurately setting up of the software, which will be a constraint for some of designers in the early stage of exploration.

5.3 Environmental impact

Several recent projects have attempted to develop full-scale kinetic facades prototypes as a method of exploration with the integration of sensor and actuators to evaluate the performance of the facades toward environmental conditions. The project of aerodynamic tower by Maria Annunziata for instance, demonstrates the use of scaled physical modelling and rapid prototyping technique to verify the facade performance in response to the wind. This project is embedded with wind sensor devices to evaluate the aerodynamics of the facade and structure of the scale tower. This project also involved a rapid prototyping process and physical building model at different levels of detail that allowed the development of the laboratory test. Ultimately, these results led to the evaluation of the buildings' behaviour. In this project, an exploration into small-scale models still represents the most affordable way to predict the performance of quantities of interest as wind velocities and pressure coefficient in a complex shape (Maria, 2013).

Another project collaboratively developed by Arup engineers was a bio-reactive facade prototype, which laminates green algae between two layers of glass. Exposing the panels to the sun was done in order to absorb heat but yet preventing it from entering the building, ultimately generating enough harvestable biomass products that can be used as a way of producing electricity. In this investigation, a one-to-one scale prototype module was built as a way to test and observe the performance of the facades before they are installed as part of the actual building (Charles, 2013).

In addition, one of the latest examples demonstrating an exploration through full-scale physical prototyping is the Los Angeles architect Doris Sung's, *Bloom*[53]. Bloom was installed in early 2012 at the material use gallery in Los Angeles and it is a radical, yet simple example of an investigation that explored physical prototyping and material based exploration, which aims to improve building performance. The prototype are opened and closed solely on heat from direct sunlight. Bloom consisted of 14,000 laser cut pieces of thermo-bimetal in 414 hyperbolic parabolic-shaped stacked panels arranged in the self–supporting manner of shell structure. The structural strength of this prototype is gained from the hyperbolic paraboloid or hyper shaped panels that bend in two directions within the overall organisation grid. Sung and her structural engineer undertook much digital analysis and old fashioned model building to understand how the aluminium frame and the varying size of the

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[53] *Bloom* is a prototype that uses bio-metal as a main material in creating a structure and surface that response to thermal heat. The material are bending once it get warm (in this case because of solar radiation) and return to original state when it cool down.

infill panels could be optimised to increase power. A couple of scaled model prototypes, a part from the final one to one scale prototype, were also built to ensure the construct-ability and the performance of the skin was able to respond well to the thermal heat of local condition. Even though the project is not part of buildings' facade, Sung tries to differentiate her works from becoming art projects or pure engineering, and instead focus on how this prototype can lead to commercial feasible facades system (Chalers, 2013).

The three projects mentioned above demonstrate integration of physical prototyping as a way to verify the structure and skin of the facades. It is apparent from these projects that there are extensive possibilities exist to evaluate the performance of kinetic facades further in regards to the daylight or heat condition of buildings through full scale and scaled down models. The feedback loop process between physical prototyping and digital simulation demonstrated through the design process mentioned in those projects can be considered as an early example of alternative way to evaluate the kinetic facade design performance during the design process. In addition, physical prototyping is a significant activity to enhance the creativity and innovation of design (Bjorn et al., 2006). This process allows designers to obtain more detailed information about kinetic performance and thus enables them to test the performance (Bjorn et al., 2006). However, the physical testing in this project is conducted towards the later stage of the design, and there is minimum information which demonstrates on how the design of kinetic facades can be evaluated using physical testing in the early design stage in response to daylight performance or thermal heat condition in this research context.

By reflecting on the result and outcomes of the previous two investigations, it showed that there is necessity to integrate the full-scale prototype to be integrated with a sensor and actuator apart from kinetic design and mechanism in response to outdoors daylight or heat conditions during design development and evaluation stages. This investigation explored a focused area of research that involved sensitivity to daylight and thermal condition as well as consideration to the leverage of the mechanical system - an approach that was established and reflected in the early of this investigation. In this chapter, new possibilities were investigated in order to evaluate the performance of kinetic facades through one to one physical installation with the integration of kinetic mechanism and physical computing. The results from the previous investigations were analysed and adapted through the reflecting and testing activity, which became a central concern during design development in prototyping *Un-fold*. This project focuses on contributing to two main area:

a) Alternative tools to explore the design and evaluate the kinetic facades in the early design stage.

b) Establish design exploration of kinetic facades by emphasising digital to physical translation and using materiality as a feedback mechanism to inform digital tools.

Un-fold is a kinetic facade prototype that serves as a responsive intervention to control the lighting condition in the 4 x 4 x 2.5m living room in Parkville, Melbourne Australia. Previously, the development of *Un-fold* involved a computational design process and physical testing. The evaluation of *Un-fold* through investigating one to one scale installation allows physical testing as part of the physical testing process, along with information gained from previous investigations in developing kinetic facades in the early design stage. This installation intends to evoke alternative design processes in evaluating the kinetic facades performance towards controlling the daylight luminance in internal space. ***Figure 55*** demonstrates example of the internal condition of space at three different periods of time during the day, which were taken at 9am, 12pm and 3pm in November 2012.

Figure 55: Location for final project installation. Located on the level three apartments in Melbourne, Australia facing southwest sun orientation. Source: Author.

The space functions as a living room on level three of a residential apartment building, with northwest orientation. The room is integrated with huge glass window, which creates a problem of excessive sunlight and solar heat from southwest sun orientation. As a result the space are heated up during the afternoon and becomes critical during the summer season as the temperature rises. Although the canvas roller blinds are available to block out the daylight as an alternative solution to control the light in the space, there are two shortcomings of this approach. First, by lowering the canvas roller blind, the space becomes darker, creating a below than optimal daylight level which is 150 lux[54] for a working or living space. Second, as the blind is located inside the room, the afternoon sun, which penetrates through window glass already heats up and increase the temperature in the space. Therefore, the use of a shading device located outside the glass window is more effective to overcome this problem as this approach can block ninety per cent of the heat transferred into the building and regulate daylight requirement. (Tzempeliko&Athienitis, 2006). As the daylight performance in the building is a dynamic situation as it depends on the external daylight condition, environmental design needs to be integrated simultaneously with interacting factors to secure acceptable climatic condition (Falk, Buelow, & Kirkegaard, 2012). This strategy will allow the facades to be effectively reacting and responding to different changes of light and thermal heat condition.

The graphs (Figure 56) indicate recorded data for the daylight conditions on the 25th November 2013 on the site from 9.00am in the morning until 7.00pm in the evening. The conditions after 3.00pm indicate the highest lux level in the space corresponding to a clear sky condition. This record suggests that the room without blind has higher lighting levels during the day. The used of blind during the day can reduce the excessive daylighbut light level are reduced to 72 lux. This data demonstrates another shortcoming of the chosen site,

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[54] Refer table at http://www.engineeringtoolbox.com/light-level-rooms-d_708.html

which needs to be improved with effective design solution through the application of shading devices. Based on this data analysis, I perceive an opportunity for designing and installing a kinetic facade intervention as a way to improve the lighting condition of the space.

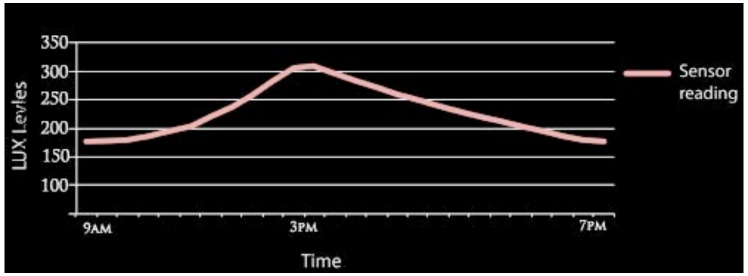

Figure 56: The lighting condition inside the living room without the shading devices or blind during the day from 9am to 7pm. Source: Author

In continuation from the previous investigations undertaken in Smart Geometry as well as the previous two investigations (Chapter 3 and 4), folded surfaces are further developed and applied in this kinetic facade project and consist of a total of 120 folded panels that cover a 3m x 1.5m size full scale window panel. It will function as an adjustable shading device with the aim to overcome the existing shortcoming of the particular environmental conditions through movable kinetic panels embedded with the light sensors. Digital simulations are conducted to evaluate the effective size for every components and appropriate size for the panels to fold to create opened and closed behaviour. Figure 57 and Figure 58 demonstrated the shadow behaviour, which is casted on the panels when the facade is folded, and showing the size of the panels when it has maximum folding pattern. The outcome of simulation are reflected through prototyping of final component, where the size of the panels are determined based on the following consideration: a) avoiding shadow casting of the panels to another panels when it is on the maximum folding state b) selecting effective size for the facades to create a kinetic movement through testing and prototyping the panels with the integration of the kinetic mechanism at the same time.

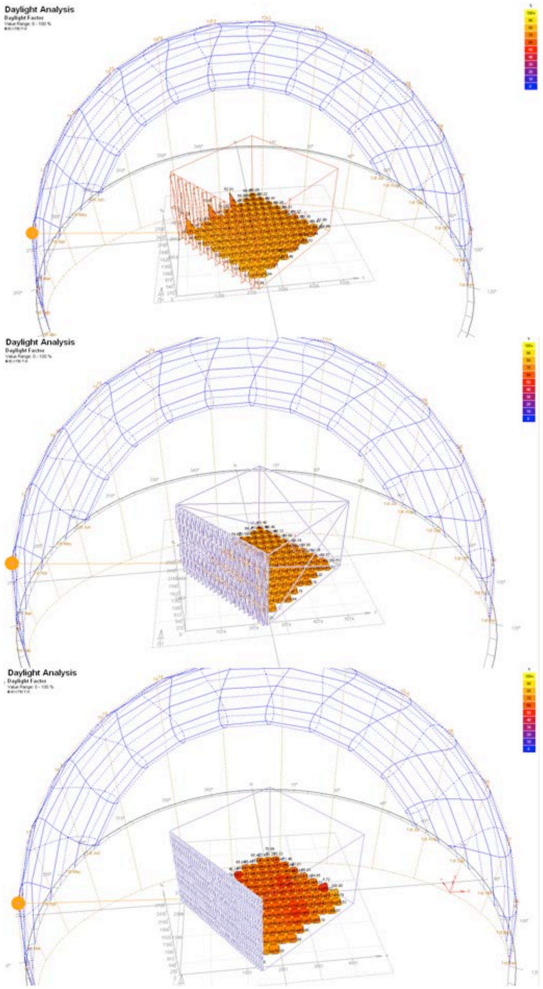

Figure 57: Daylight analysis of Un-fold prototype simulated using Ecotect to see the performance of the facades throughout the year in Melbourne, Australia. Source: Author

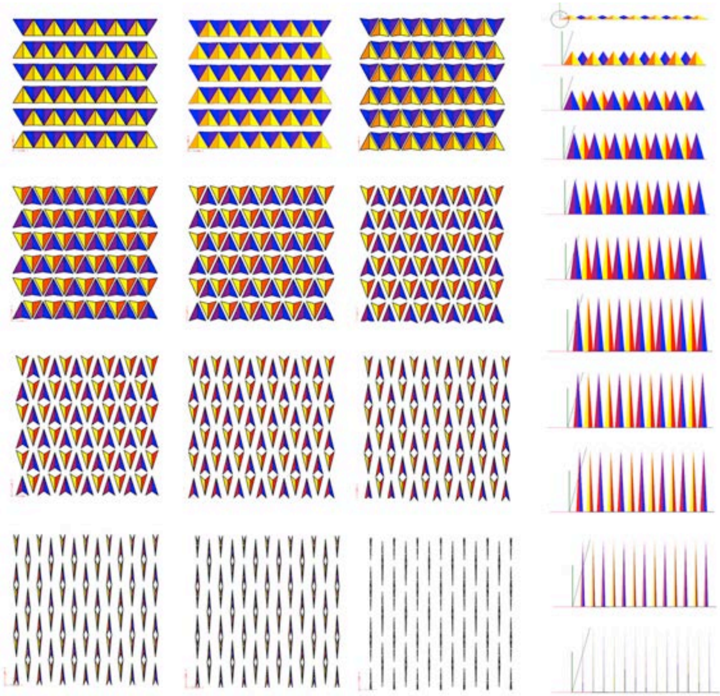

Figure 58: demonstrate the different state of the panels from total open to total close (folded). Source: Author

Furthermore, *Un-fold* responds to numbers of stimuli to control the lighting conditions, which involved three different states, which are total open, half open and total, closed. However, the degrees of the panel are specified based of the specific lighting data from the lighting sensors. Through sensitive kinetic surface capacities, *Un-fold* can function to regulate near optimum light level in the space.

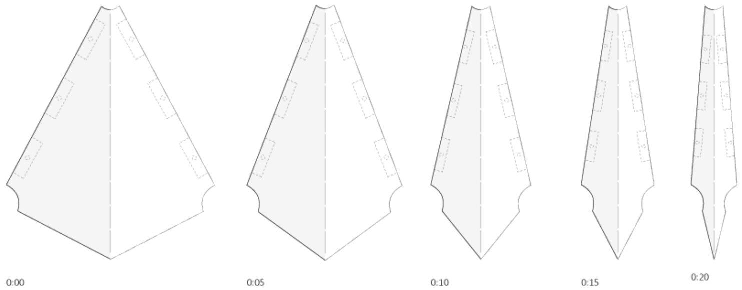

Figure 59: Different state of Un-fold panels are shows in different configuration. Source: Author.

The skin of the facades also allows light to filter in, even in a totally closed state. This strategy encourages the constant optimum lighting condition, even when the panels are open and closed to protect from the excessive daylight condition.

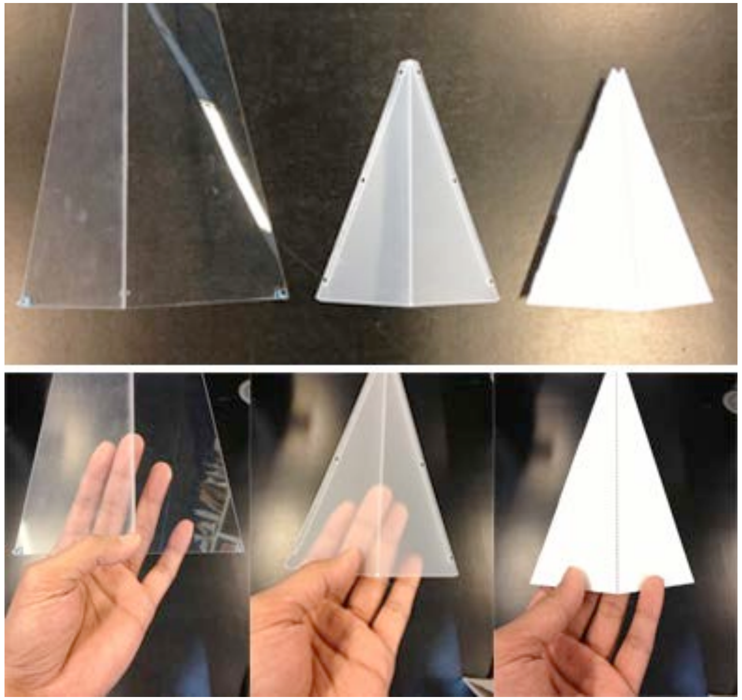

Figure 60: Different transparencies of material are considered for the panels to work effectively in regulating the lighting condition. Source: Author

The following section discusses the detailed design and evaluation based on three stages of design investigation on passive structure, active skin, reaction and design implication on daylight performance. This chapter will reflect on the lessons learned and outcomes from the previous investigation mentioned in this exegesis. These four stages of investigations will go through a critical and systematic, step-by-step process of both digital fabrication techniques and physical prototyping. The evaluation for the performance of kinetic facades will be described throughout the process of investigation. The aim of this process, however, is not to construct the best design for a kinetic facade but to demonstrate the effective design process that can be adopted by designers for use on future designs, during early stages of design. This evaluation provides a deeper understanding in the adoption of kinetic facades for daylight performance.

Prior to designing and constructing this prototype, flexible parametric models are built as a platform to gain feedback on back and forth processes. This involved a feedback 'loop' process using the actual material to validate the construct-ability and the responsiveness of the system in response to the daylight performance. This process integrated with parametric software; *Grasshopper* in *Rhinoceros* was integrated to an *Arduino* and *servomotor* to actuate the movement of the skin via Firefly software. This integration allowed observation of the material behaviour through digital modelling which allowed more information of kinetic performance, which was tested with actual climate data throughout the year gathered from digital simulation activity, while physical material and form give feedback on the responsiveness of the material and effectiveness of the hinges.

Figure 61: Physical model and various material type are used to test the kinetic design and mechanism in constructing digital model that is functional and dynamic to changes for Un-fold prototypes. Source: Author.

In order to make the process of making the changes effective between digital modelling and physical testing, Grasshopper (via Rhino) script that was developed for the prototype is setup to be flexible, dynamic and easy to be tweaked in order to develop an appropriate design for the facades in respond to the context, which allowed me to fabricate and test the design effectively during the process. Therefore, the working's script was divided into five main components, which are kinetic geometry, kinetic mechanism, skin panels, main structure panels and geometry equation and formula. Every single component was integrated with their own parameters called slider[55]. Slider allows the designer to change the dimension; scale and geometry of the facades without rebuilding the digital model again. This will allow a quick process of evaluating and modifying dynamic design that involved constant changing state such as kinetic facade in the early design phase.

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[55] *Slider* is part of Grasshopper and Rhinoceros definition or parameters that connected using *Connection* with the *Slider* as input.

From this Grasshopper definition, Figure 62 shows three-dimensional studies of the kinetic surface that move in space. Prior to this process I developed a physical model to test the panel behaviour and kinetic mechanism. However, there are difficulties of the form and surface to be folded effectively as the hinge and the folding points are not located at the right location. The solutions for this issue are discovered through the observation and evaluation of digital modelling behaviour. As the form emerges from the subtraction of the cone shape it clearly addressed and marked the movement path of the surface when it folding to create opened and closed behaviour. This allows further understanding in developing kinetic mechanism.

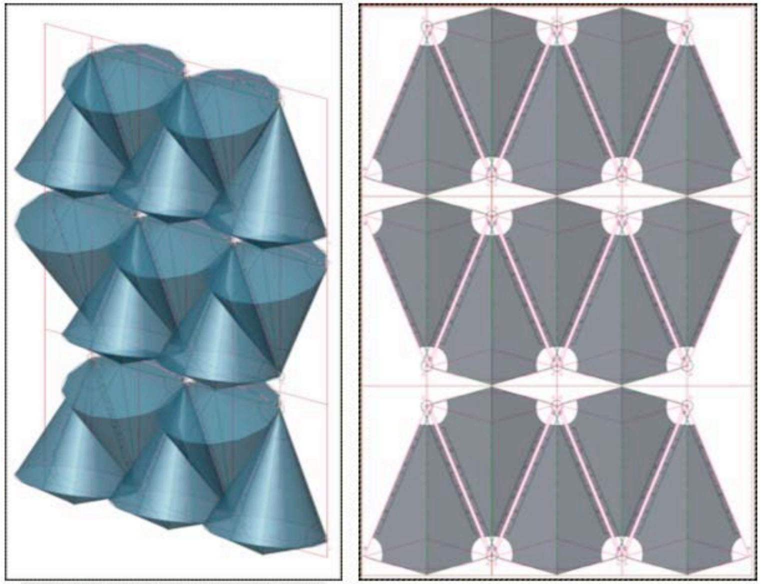

Figure 62: Study of the kinetic movement in space. From this studies, further understanding on the movement of the panels are not moving in the straight line are developed, rather the curvy movement are created which derive from the shape of the hanging cone. This information reflected in developing the kinetic mechanism for Un-Fold. Source: Author.

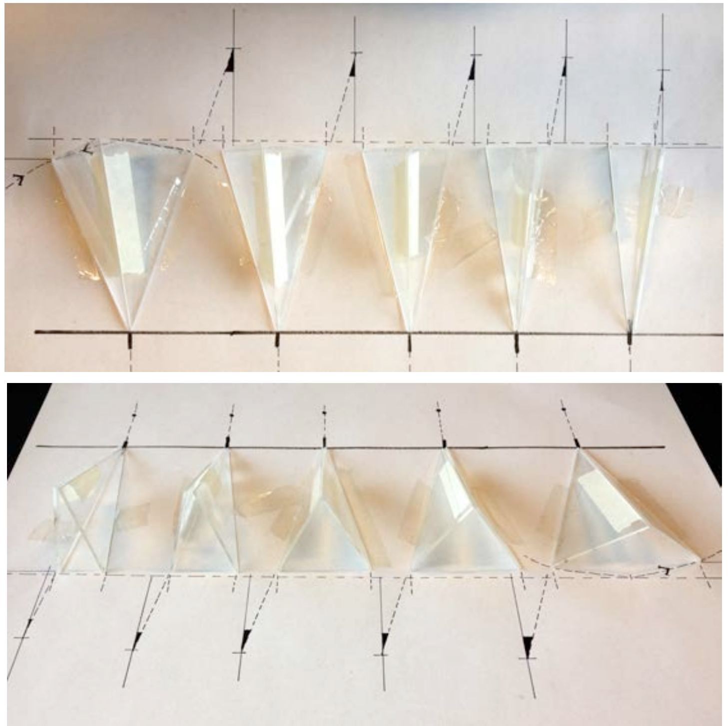

Figure 63: Working model of the folded panels demonstrated the arch shape movement, which derived from the shape of cone. This shape also influenced the shape of the main structure. Source: Author

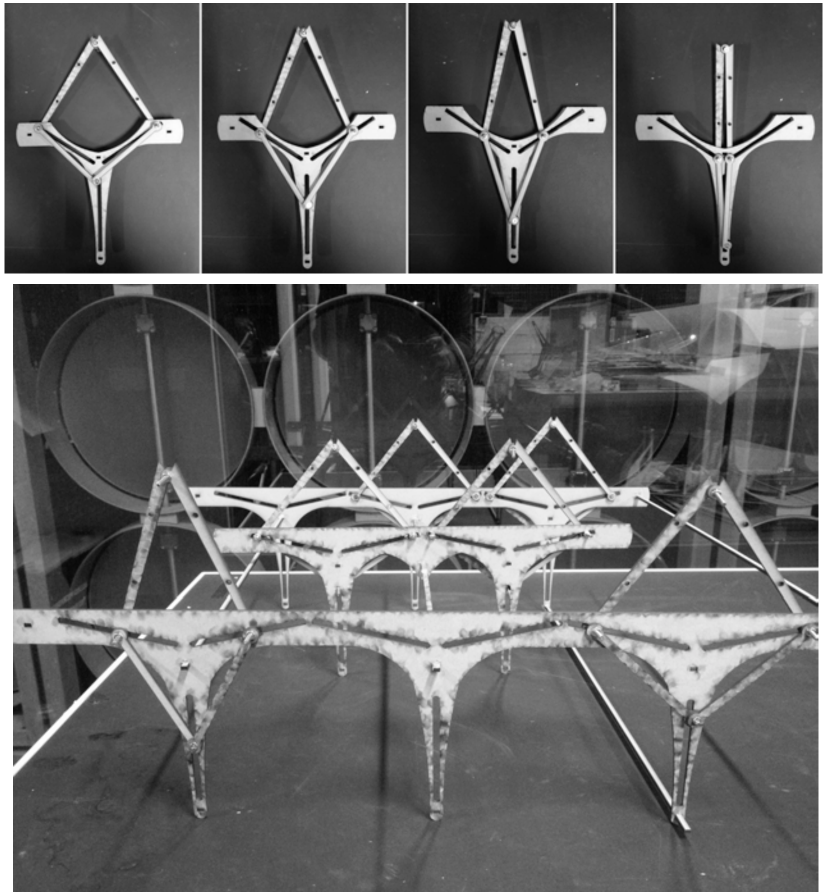

Figure 64: Working models are used to establish an effective kinetic mechanism, which suits with the design intentioned. This process involved couple of testing and re-design number of physical kinetic model. Source: Author

While it is possible to make changes to the dimensions of the components through adjusting the sliders, other components are affected by the changes almost at the real-time. For example, the changes in dimension of the skin area will affect the structure of the facades, which also affects the angle of the movement of the envelope. This process kept the designers aware of the design constraints and possibilities in constructing the facades such as changing form and shapes that affecting the mechanism. Below are descriptions of the function of the slider that is interconnected to form this flexible model of kinetic facades.

Geometry Parameters (Sliders)

Six sliders are used to control the geometry and shape of the prototypes. It is possible to add or subtract a number of panels and to change the scale of the prototype.

Mechanism Parameters (sliders)

These sliders function to control the behaviour of the motion of the kinetic facades. It provided the visual outcomes and exact dimension and angle of the movement of the facades. This will allow the designer to foresee how the movement of the façade panels affect the mechanisms. These sliders are significant components in integration with the environmental simulation software component such *Ecotect* Autodesk or Energy plus. This will allow the designer to conduct simulation of the performance of the facade in response to the daylight throughout the year as discussed earlier in Investigation Two.

Skin Parameters (sliders)

This slider will allow the prototypes to change the dimension of the total area of the skin from the local component to the global components of facades. The details of the size and numbers of hinges of the envelope are determined in this component. This iteration of the prototype was performed during the evaluation of the material, for example, iterations of the hinge, are effective in creating elastic movement for the envelope. Different size and distance are also tested in this process.

Structure Parameters (sliders)

These sliders are divided into two components. It involves the main structure (passive) and the secondary structure (active). Both components of the structures are interconnected. This will speed up the modification to determine the movement of the facades. The secondary structures are a critical part of this component as it involves the active member of the structure that creates the movement of the facades. This slider will also determine the thickness and the size of the structure.

Geometry Equation Parameters (sliders)

This part is important as it determines the degree of folding of the facades and the motion angle of the structure. Setting up the slider to adjust the movement of the kinetic pattern in this prototype allowed more changes prior to determining the effective performance of the facades.

Simulation

The surfaces of *Un-fold* are evaluated through *Ecotect* – Geco – solar access (linking *Grasshopper* to *Ecotect*) to see solar radiation distribution on the surface. These simulations are conducted in a particular time on summer season 21 January, as this is the warmest time around the year in Melbourne, Australia. These facade simulations undergo twelve states of motion from totally opened to totally closed. This simulation also determines the size of the panel when the panels are in a totally open state. The openings of the skin are simulated based on the angle of rotation from the middle point of every panel.

The simulation demonstrates solar access performance are able to be calculated using *Ecotect* simulation software in a feedback loop method (Bedarf, 2012). This investigation is not to demonstrate *Ecotect* as the suggested software or simulation tools, to be used as kinetic design evaluation rather to outline the potential of this software to achieve the objective of setting up appropriate simulation analysis. Furthermore, a single objective, genetic algorithm namely *Galapagos* was used for a proof of concept for optimisation.

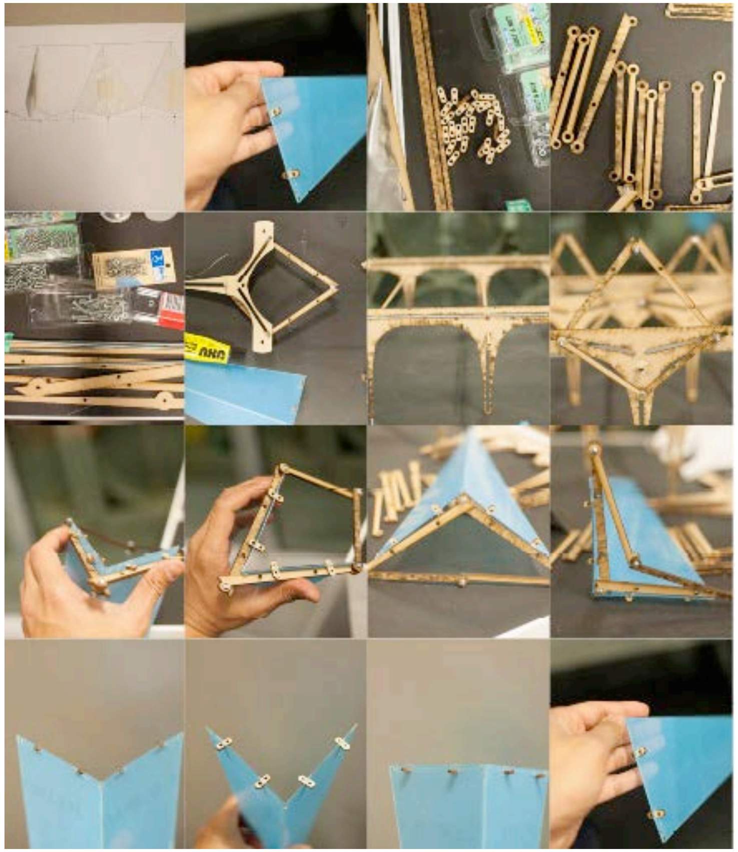

Figure 65: Design developments of Un-Fold prototypes, which include exploration of the kinetic mechanism, joints and hinges, kinetic structure and envelope through fabrication and physical testing.

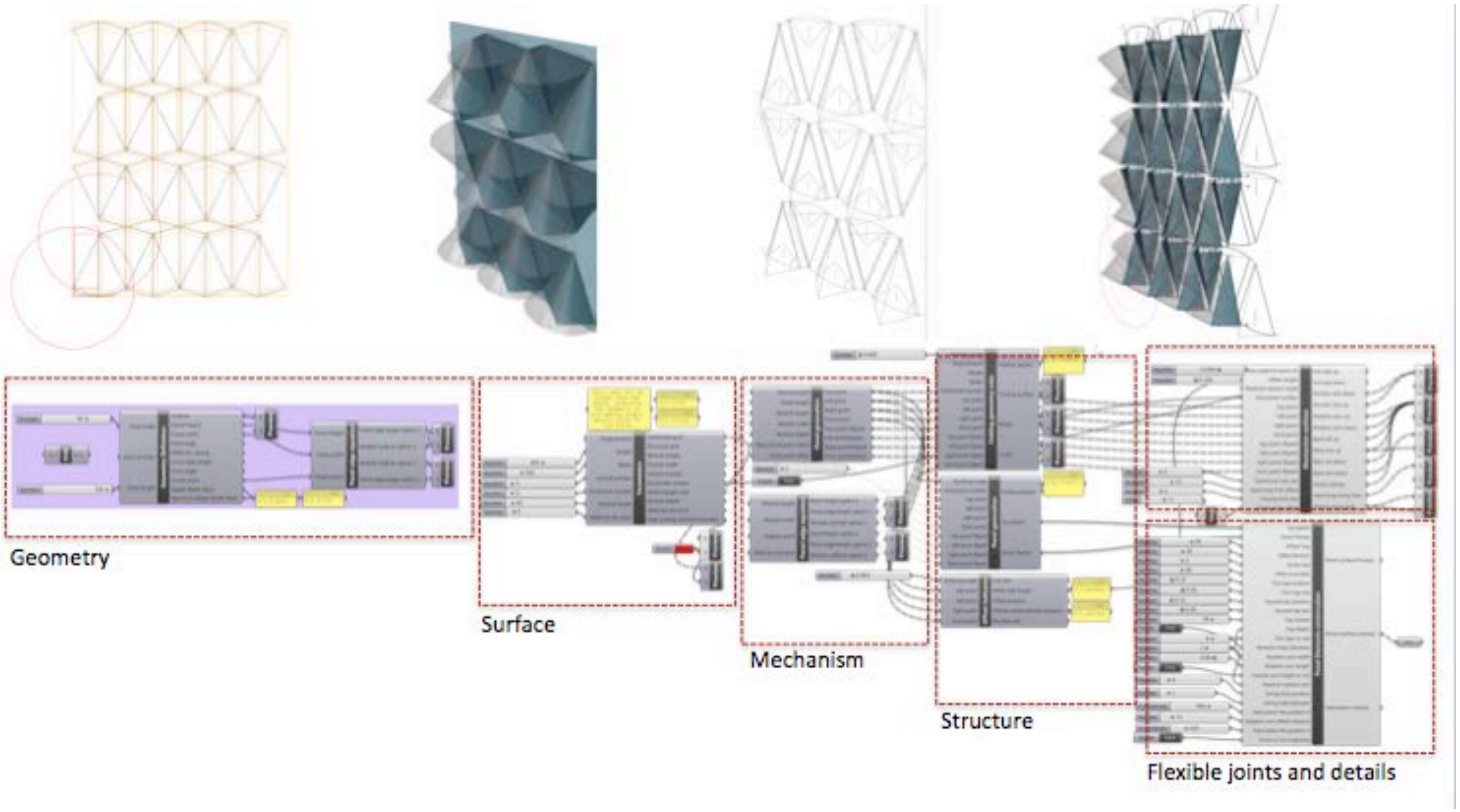

Figure 66: The script which represent the component of the kinetic movement and the facades of the prototype are divided into different parameters and at the same time are interrelated to each other. These parameters are dynamic and adjustable which allows designers to make change to the design of the components instantly and other parameters are affected by the changes at the same time. This allows the designer to visualise the transformation of whole design. This flexible model setup is significant to understand the kinetic mechanism and the movement during early design stage. Source: Author.

5.4 Kinetic Structure

The structure of *Un-fold* serves as the main support, acting as an actuator of the movement of the *Un-fold* facades. The structure of *Un-fold* determines the kinetic movement for overall facade systems. The structure will be actuated by the pulley system and step motor that are derived from the previous exploration of Investigation One. This system was adopted in order to provide a more lightweight and flexible structure with robustness to demonstrate minimum actuation to generate high transformation. There are two types of structure integrated in this system, which are:

a) Main structure or passive components as show in Figure 67.

b) Secondary structure acting as active components (Figure 68).

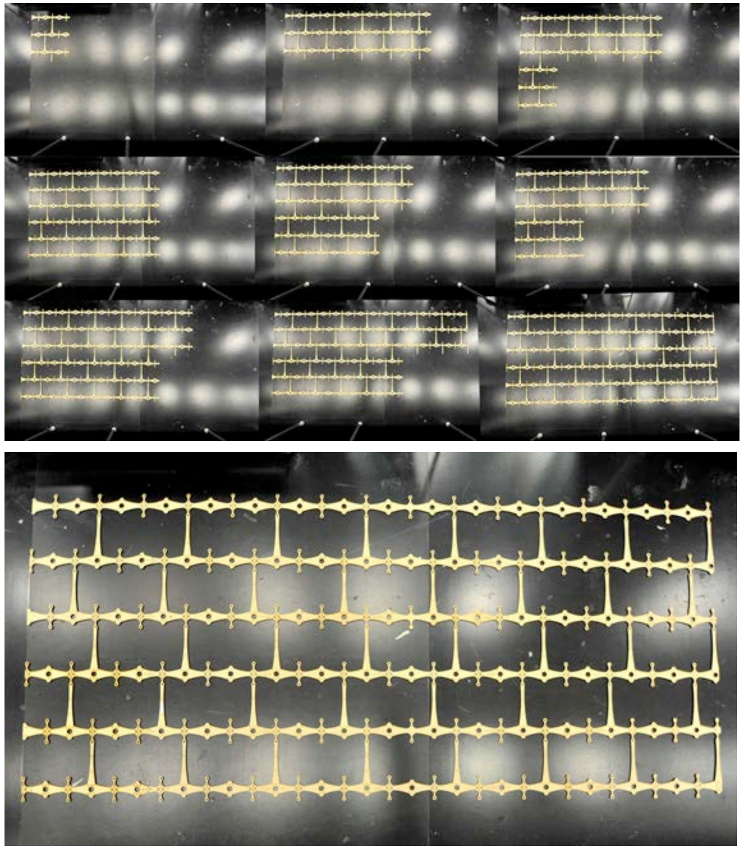

Figure 67: Main structure of the Un-fold. The shapes of the structure are following the curvy kinetic movement. This structure can be divided to small components to be transported to the site for installation. Source: Author.

The structure was integrated with the idea of a pulley system to maximise the transformation of opening and closing of the facades. The pulley system became the main mechanism to actuate the secondary structure in this project. By adopting this mechanism, the movement of the structure can be leveraged, therefore, reducing the mechanical friction between the component structure and the hinges.

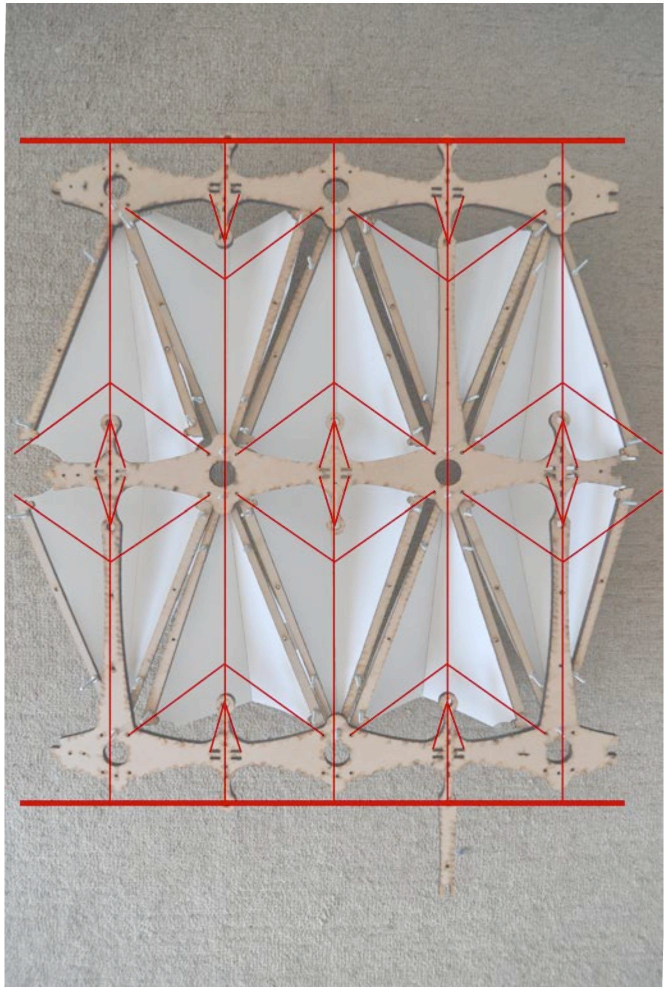

Figure 68: One panel of the structure and the folded panels showing the lines of kinetic mechanism of the Un-fold. Source: Author

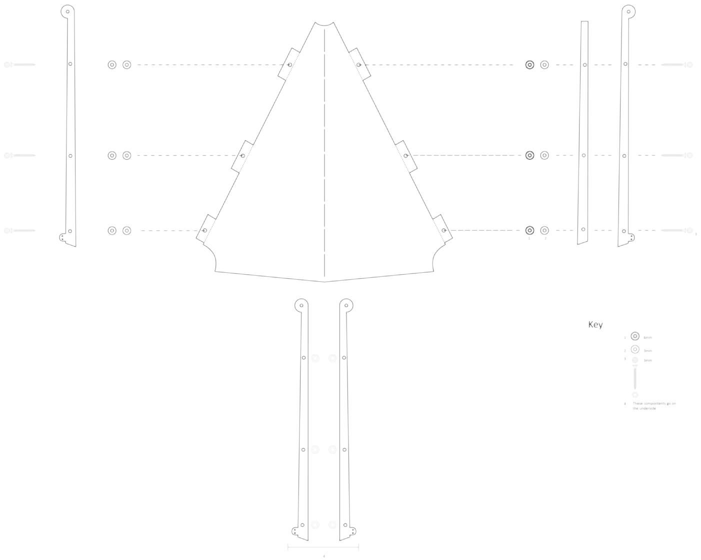

Figure 69: Kinetic structure component and joints diagram of Un-Fold. Source: Author.

Similar to the structural system developed in the end of Investigation Two, the *Un-fold* structure consisted of twelve modular panels that are designed to replicate the movement of the panels – to open and close. The design of the panels took into consideration the aspects of robustness and weight (lightness) to achieve effective mechanism and transformation. The process of designing the whole system as well as the design of this facade were considered and negotiated between the facades' skin and the efficiency of the structural behaviour in order to create responsiveness towards daylight performance.

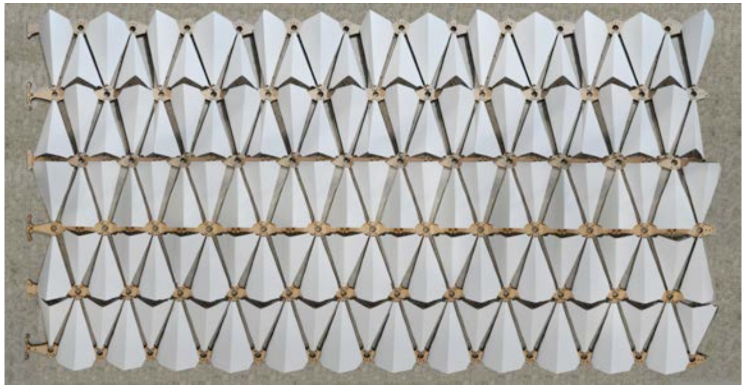

Figure 70: Complete skin of Un-fold in fully closed state. Source: Author

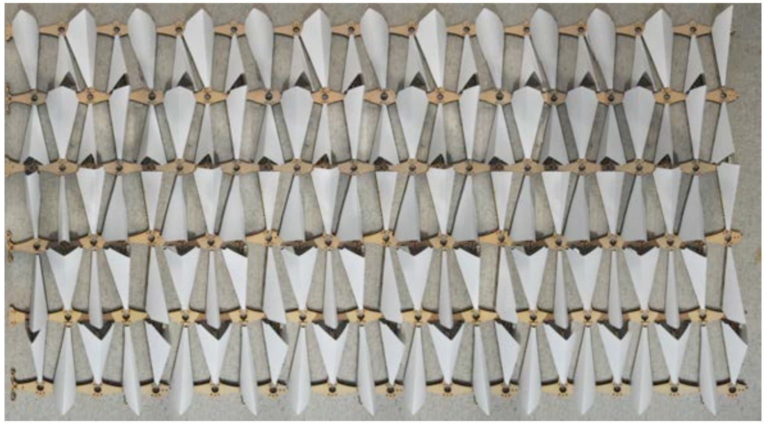

Figure 71: Complete skin of Un-fold in fully open state. Source: Author.

The 12 modules of the main structure were fabricated using *MDF* with 6mm thickness. The secondary structure that acts as an active structure was created using 3mm *MDF* in order to maintain the lightweight structure to achieve flexible movement. This strategy also assisted in improving the effectiveness of the movement for the 120 panels. The main and secondary structures are integrated to create 3000mm x 1500mm kinetic facades, which cover the glass window of the space on the site.
Furthermore, the main structures are created using a module system integrated with the secondary structure. Every module is embedded with an independent mechanism referred to as a local system. Once the structure is put together, each of the local systems will connect, thus transforming into a global system. This technique is important in designing *Un-fold* as the module that needs to be maintained or replaced can be effectively fixed or replaced by the implementation of a new module in the future. The global systems of the mechanism are transformed using an *Arduino* and step motor as a main actuator, triggered by the light sensor.

In developing the structure for this facade, a number of physical models were developed in order to understand the issues and problems in dealing with kinetic pattern. Through flexible digital modelling of the prototype established in the early design exploration, multiple iterations were examined before finalising the prototype.

The crucial part in designing this structure was to understand how the kinetic mechanisms of the panels are to be integrated with structural elements. Different design possibilities and scale were tested, and a couple of alterations were made in the development of the structure and the skin, during the investigation. Back and forth, process, using the physical model as the main reference point during the process of developing the kinetic structure and envelope, provided significant feedback for the digital model.

During the design process, the precise calculation of movement for secondary structure was completed using a three-dimensional model in *Grasshopper* and *Rhinoceros*. Further testing on the kinetic designs was developed by fabricating physical components to test the kinetic movement. Upon testing, significant friction, which prevented the smooth movement between the main and the secondary structure, was observed. This process was crucial as some of the information from the digital modelling was hardly, if at all, visible to inform the kinetic model. The problems of friction of the kinetic mechanism on the secondary kinetic structure are improved by introducing pulley systems mechanism into the kinetic mechanism. The complete version of this prototype with the integration of the system as is showed in Figure 72 are tested through one panels and integrated panels. From this testing, the more the pulley components are integrated the more effective the movement and the lesser problem of friction. Another observation can be seen through this testing is that the amount of forces can be minimised by creating bigger dimension of the roller component in the pulley system and longer distance of pulling mechanism.

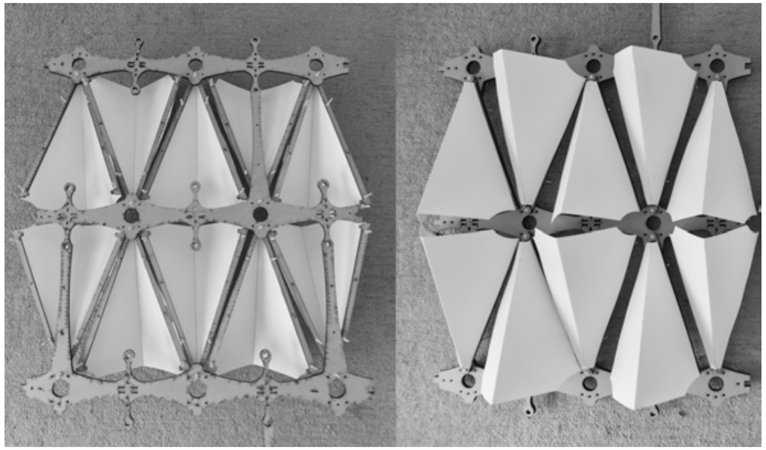

Figure 72: Final prototype: part of the basic panels before other panels are added to create one to one scale installation. This panel can be dissembled for the transportation purposes. Source: Author.

5.5 *Kinetic Skin*

Kinetic skins are active components in kinetic facades. It is one of the components that is significant in determine the effective control of the kinetic system in response to the daylight and thermal radiation from the sun. It is an external layer of the building that determines whether to absorb, reflect or filter the sun (Linn, 2014). In this context of prototyping of *Un-fold*, the envelope design is a building skin that filters and reflects the solar radiation and controls the amount of daylight that infiltrates the building. The materials used for the surface of the facades are determined by the ability to control and reflect the daylight condition. Prior to this installation, this material has been tested and used in the previous project in Chapter Three (*Tringular*) and Four. As the previous project demonstrated the potential of this material in terms of elasticity, this project adopted similar material to be developed in the *Un-Fold* project as it has the potential in terms of filtering and controlling the daylight conditions. In this research, different types of transparency are considered for achieving the design goal of *Un-fold*. I decided to use the white polypropylene as it has more potential to filter and reflect the daylight (Synnefa, Santamouris, & Akbari, 2007). As a white surface is likely to reflect the daylight from the facade skin, these materials are able to reduce solar heat gain and creating diffuse light when the facades are in total closed state (Figure 73). In addition, one of the significant abilities of this material is its capacity to filter the amount of daylight and create a diffuse light that can help to control the amount of light allowed into the space. From the experiment of the material on the site where the prototype is going to be installed, during the clear sky day the daylight luminance levels indoors are around 1200 lux. However, using this material to block the sun under those conditions can reduce this level to 160 lux. It is important to mention in this discussion, that the optimum light luminance level indoors is between 160 and 240 lux for activities that involve reading or doing computer work in relation to the light level standards for Australia (Interior and workspace lighting).

Furthermore, polypropylene is used in this project because it has elastic attributes that aid the movement of the facade. The characteristics of polypropylene suit this application due to its ability to achieve the purpose of folding and unfolding in response to the external environmental conditions. This material is easy to fold and robust to go through thousands of opening and closing cycles. However this material needs to go through proper scientific testing in regards to the life cycle process in determining its exact durability in response to daylight exposure and excessive solar radiation.

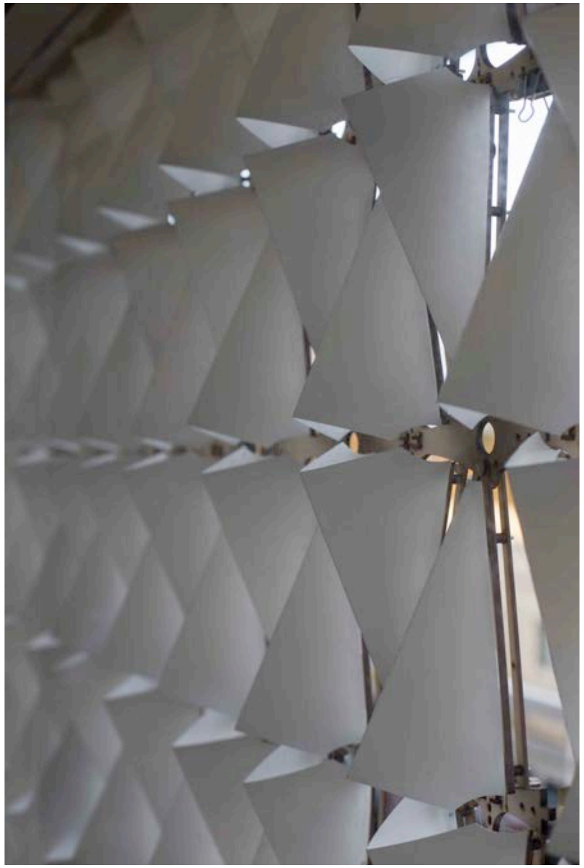

Figure 73: Material properties of polypropylene allowing the minimum light (diffuse light) even the envelope is in total closed condition. This strategy allows minimum lighting condition into the space. Source: Author

5.6 *Folding as structural elements and modular components*

The folding elements and structure can be seen as utilisation and generalisation of classical origami. The use of folding an element is not only limited to the usage as seen in the concept of origami. The application of folding surface for building facades are currently in active area of research (Jaksch & Sedlak, 2011; Kilian et al., 2008; Tachi, 2010). In the area of architecture and structural engineering the stiffening property of folds are actively leveraged as they enable high actuation capabilities in lightweight surface materials for building facades. Recently, self-supporting rigid and kinematic folding structures were developed at full-scale. However, there are great potential to extend this investigation into the area of design for kinetic facades. Potentially, this may lead to improving the design of kinetic facades that are both robust and light-structured in response to environmental conditions.

Logically, the kinetic building envelope panels can change to three periodic patterns related to concave, convex, and flat. For example, the concave allows envelopes to concentrate more solar radiation towards an indoor environment; the convex allows easier heat loss from envelopes from the inside to outside (i.e. during a summer night or rainy day). Lastly, the flat allows the buildings' envelope to minimise the area and slow down the heat transfer (Wang, Li, & Chen, 2010).

Furthermore, the ability for a surface to fold is a practical means of transport and to compact constructional parts. Foldable constructions offer unique challenges for the design of hinges to join microform elements. The prototypes are designed as modular system, which, allow flexibility to fit with different facades or window sizes (Figure 74). This modular system is not solely designed for the structure but also considered through the kinetic mechanism and the kinetic configuration. This strategy will allow the component to be transportable and also creating plug and play kinetic mechanism after being installed with flexibility of different sizes.

Figure 74: Modular panels of Un-Fold before it composed into one kinetic system. Source: Author

5.7 Leveraging the kinetic system

The leverage systems of *Un-fold* kinetic mechanism are developed through the process of applying pulley component into the kinetic system. This strategy aim to reduce the amount of forces applied on the moving component. This will also allow the facades to use minimum energy in modulating the kinetic movement for the facades to respond. In addition, the pulley system is applied mostly in the engineering area (Bhavikatti & Rajashekarappa, 1994). However, the idea of a kinetic system using a pulley system in still new in architecture field, especially in the application of a kinetic facade system. Based on lessons learned and experience from previous kinetic application on leveraging the system, similar applications are applied in the *Un-fold* project, in the real site conditions, which involved actual scale facade and kinetic mechanism. This system has potential to be leveraged in creating high actuation and low mechanical friction as shown in Figure 75 and Figure 76. By actuating small movement, the mechanisms are allowed to form larger opening and closing system.

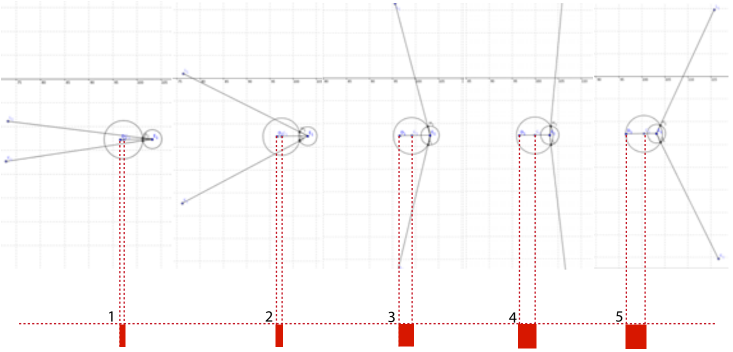

Figure 75: Simulating a small movement to create larger transformation of kinetic structure. Source: Author

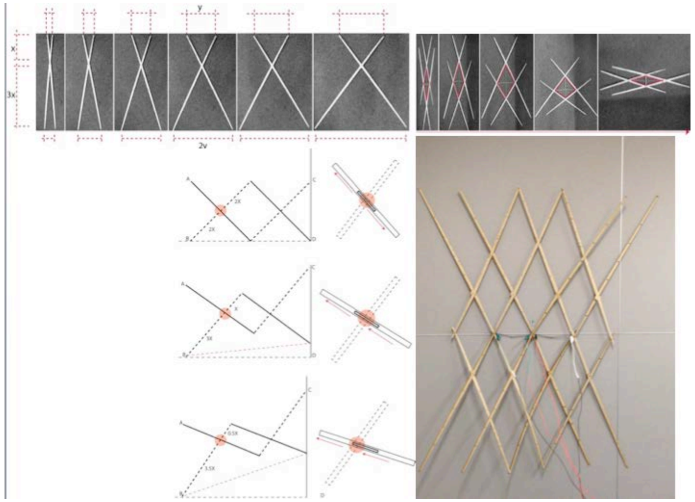

Figure 76: Integration of number of components of kinetic structure in creating kinetic system that able to be actuated using leveraging system. Source: Author

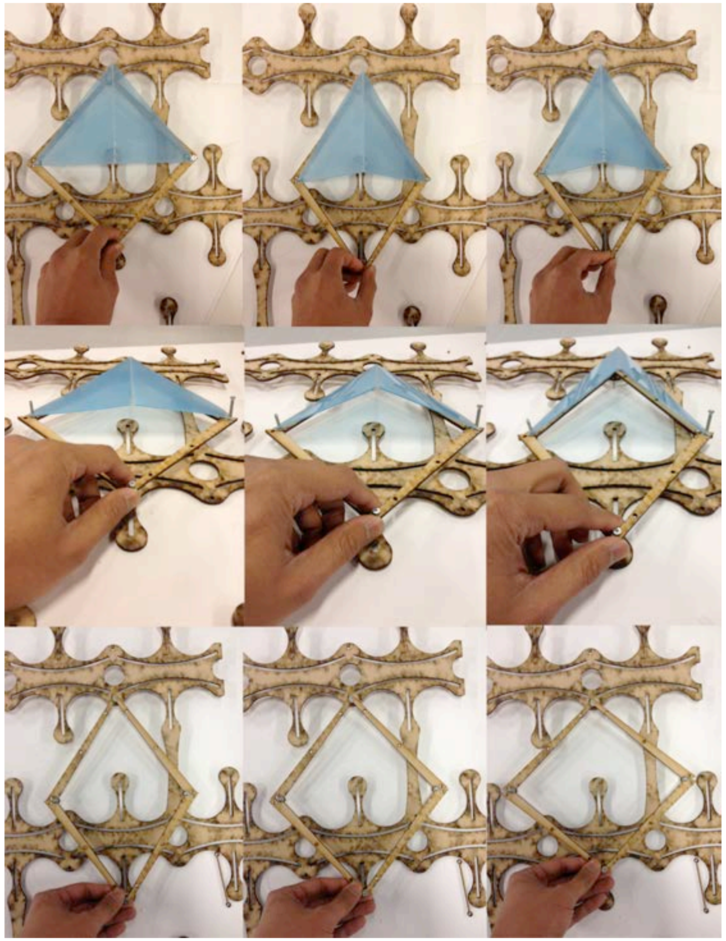

Figure 77: kinetic structure which hold the envelope are tested to observe the behaviour of the mechanism before further development of kinetic design are conducted. Source: Author

The secondary structure, which also function as an active structure will attach to the vertical on the main structure. This pulley system is connected via five panels, which shared the same behaviour when actuated; the vertical components are also attached to the horizontal structure that acts as the main actuator for the whole kinetic system. By moving the horizontal structure from the central point, it will create open and close activity for the facade system. The kinetic mechanism can be attached to different numbers of panels and adjusted depending on the requirement of the lighting condition required. The kinetic mechanism is also allowed to be customised based on the designer's preference to create different variations of kinetic behaviour. In other words, the kinetic mechanism proposed allows the designers to customise this system according to the local context and client requirement.

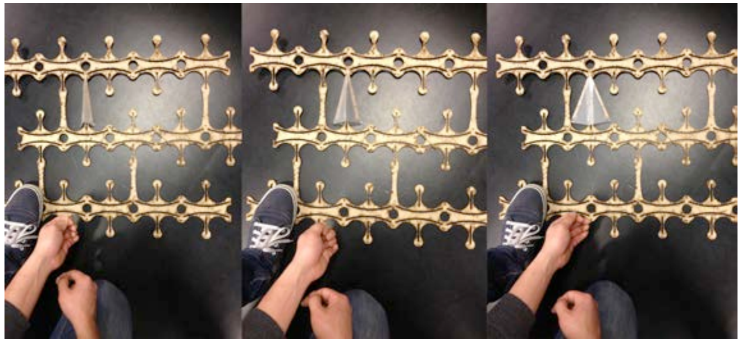

Figure 78: One of the kinetic panels tested using pulley system. Translucent wires are used as part of this system. Accurate measurements on the wire length are marked during this investigation in order to create effective leveraging system. Source: Author

This strategy helps to create effective facades that regulate daylight and thermal heat with flexible requirements from different local context. Hence the digital modelling that have been set up earlier allow further assessment on the local condition and reflected upon suggested panel sizing and numbers. Figure 79 and Figure 81 shows the application of a pulley system in actuating the skin of the facade. The design intention of the pulley system in *Un-fold* is to leverage the actuation to create larger transformation of the facades. This will perhaps reduce the actuation used in designing the system. This strategy contributes to minimising the amount of maintenance, energy used for the system, and cost. Even though this aspect is not the focus of this research; this idea can be further addressed in the future development of this system.

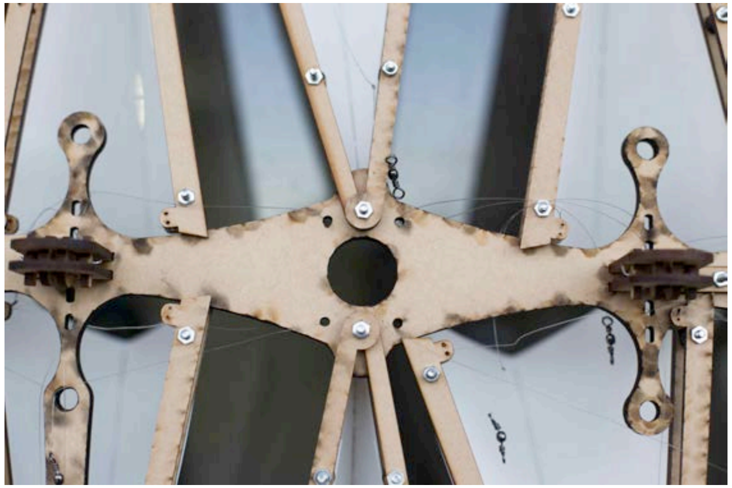

Figure 79: The structures are divided into two categories, which involved main (static) and secondary structure (active). Both of these structures are interconnected using bolt and nuts, and hinges as an active point for the panel to move. Source: Author

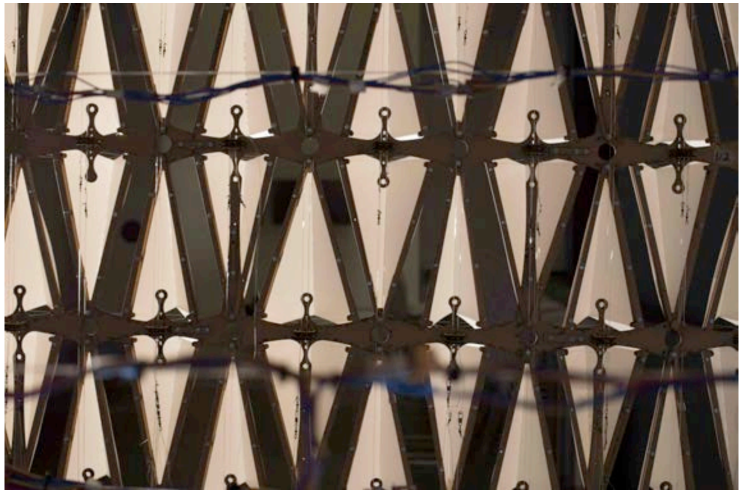

Figure 80: Kinetic mechanism and kinetic structure are demonstrated as integrated system that allowed the system to work appropriately. Source: Author

Un-Fold are integrated with 30 servomotors to modulate the movements of 150 kinetic panels. These servomotors are located at the bottom row of the prototypes, which activate the kinetic mechanism horizontally by pulling and releasing the translucent wire. In controlling 30 servomotors at the same time, *Numato* micro-controllers are used in this prototype as it is designed specifically to control servomotor in larger quantities. One of the issues raised during the testing and experimenting with the 30 servomotor to be operated at the same time is the voltage and power issues. Early testing of this servomotor, lead to damages to 15 servomotors when the current and voltage are observed based on manufacturer specifications, as it is overloaded when forces are applied in pulling and realising the kinetic mechanism and power supply cannot be regulated. Even though the voltage and current are supplied to the servomotor are based on what have been suggested by the manufacturer and electrical technician, the issue of current and voltage needed to forces the mechanism are barely invisible or notified until the 30 servomotors are tested together at the same time. However, the solution to this issue is by introducing power regulator that allows the current to be only regulated and supplied when it required. This step prevented the servomotor to be overheated and damaging the entire servomotors when it operated at the same time. This strategy successfully allowed the servomotor to work effectively without any further issues with the power supply.

The servomotors are divided into 6 panels of actuators (Figure 81), which consist of 5 servomotors. Prior to the installation, every servomotor and panels are tested individually to ensure every servo is setup to the zero angles. This is to make sure the actuator are moving at the same direction and angle when it operated. This process of calibration involved the used of *Numato's* software. Through this process, the number of defected servomotors are identified which involved failure to do full 180 degree rotational. This process of calibration prevented further issues when the prototype is fully operated.

Figure 81: one of the panels of the actuator are tested before it is installed into the whole structure. This panel actuator carried five servomotors. Source: Author

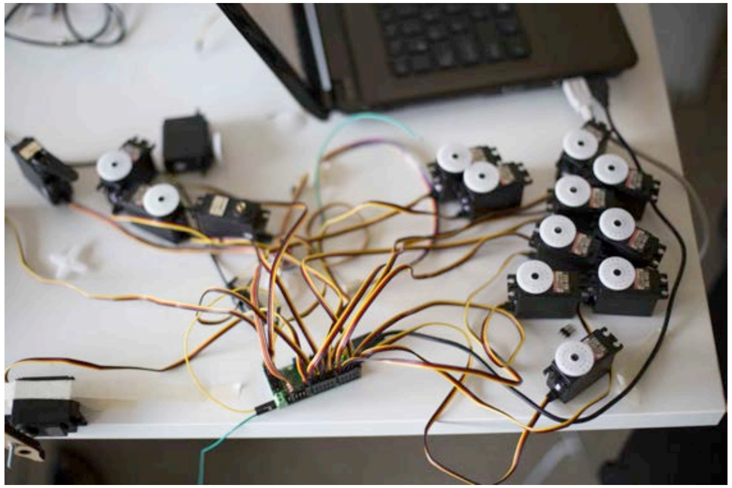

Figure 82: Servomotors are connected with microcontroller called Numato, which allow the servomotor to be controlled individually or in group. Source: Author

In addition, the testing allowed further understanding on the current and voltage usage as well as servomotor behaviour when it is integrated in large number at the same time. As the process of tuning and calibrating one servomotor and 30 servomotors at the same time are totally different and crucial. For example, the processes of selecting the appropriate controller that communicate effectively with the larger number of servomotor at the same time are crucial. Different micro-controller such as

Arduino, *Maestro* and *Numato* are parts of the micro-controller that have been tested during this investigation.

Figure 83: Power Regulators are used to regulate an appropriate current used by the servomotors. These devices prevent from overload current into the servomotor which many cases will harm or heated the servomotor. Source: Author

5.8 Responsiveness

In order for the prototype to be responsive, sensors and actuators are integrated as part of the kinetic system. In order for the system to respond to different light level, light sensors[56] are used. The sensors are programmed to detect different lighting conditions based on the lux measurement. The data output from the sensors let the panels respond to fully open, semi open and fully closed. This strategy allows the facades to react based on appropriate lighting conditions available in the space. Therefore, autonomous kinetic system allows continuous protection of the indoor space from excessive solar radiation throughout the day, especially during the summer season.

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[56] The light sensor (TSL2561) also known as Luminosity sensor has the ability to sense different spectra of visible light and react based on those measurements. These sensors are used during this investigation as the sensors have the capacity to detect accurate lighting level in the space.

In order for the kinetic system to be able to communicate between sensors and servomotor, microcontroller *Arduino* are used in developing this prototype (Figure 84). *Arduino Mega* is used in this prototyping as it allowed integration larger number of sensors that required in this project. Normal type of *Arduino* such as *Duemilanove Arduino* only allow maximum 8 connections of analogue and digital sensors at a time which this project required integration of 30 temperature sensors and 30 light sensors.

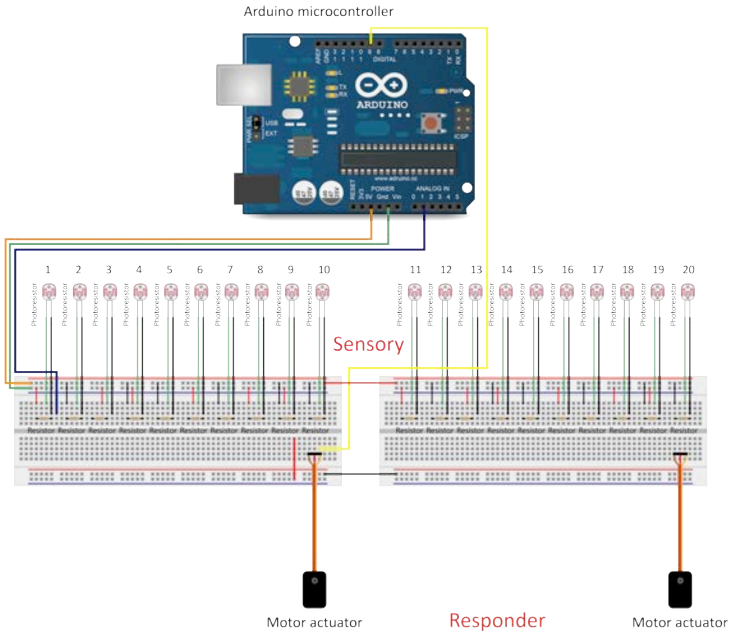

Figure 84: Arduino setup demonstrated the connection between thirty temperature sensors and actuators (servomotor) of Un-fold. Source: Author.

```
#include <OneWire.h>
#include <DallasTemperature.h>

// Data wire is plugged into pin 2 on the Arduino
#define ONE_WIRE_BUS 2

// Setup a oneWire instance to communicate with any OneWire devices
// (not just Maxim/Dallas temperature ICs)
OneWire oneWire(ONE_WIRE_BUS);

// Pass our oneWire reference to Dallas Temperature.
DallasTemperature sensors(&oneWire);

void setup(void)
{
  // start serial port
  Serial.begin(9600);
  Serial.println("Dallas Temperature IC Control Library Demo");

  // Start up the library
  sensors.begin();
}


void loop(void)
{
  // call sensors.requestTemperatures() to issue a global temperature
  // request to all devices on the bus
  Serial.print(" Requesting temperatures...");
  sensors.requestTemperatures(); // Send the command to get temperatures
  Serial.println("DONE");

  Serial.print("Temperature for Device 1 is: ");
  Serial.print(sensors.getTempCByIndex(0)); // Why "byIndex"?
    // You can have more than one IC on the same bus.
    // 0 refers to the first IC on the wire

}
```

Figure 85: Arduino code used for one wire temperature sensors configuration during this investigation. Source: Author

The systems were setup based on two configurations which involved the sensors (temperature and light) which allow the kinetic system to communicate (Figure 86 and Figure 87 with the servomotor and trigger the panel of the facades to respond and second system is setup based on the integration of manually controlled the servomotors through the wireless network application called *TouchOSC* (Figure 88). This application using wireless network to communicate with the servomotor, which allowed the servomotor to be operated as singular component or integrated at the same time. The application allows the designers to custom and assigns their own panels of configuration within the software. In addition this two systems are designed to be responsive, based on the current site condition or it can be overwritten to the manual configurations, if different preferences are required, allowing flexibility to the user to change according to specific local condition. Hence through application of Touch OSC, permits it as part of testing tool in designed and evaluated kinetic component and mechanism. For example the length of the pulley system need to be adjusted accurately so when the actuator pulling the translucent wire using servo rotation between horizontal and vertical state are tense enough to perform maximum strength to open and closed the folded panels. By using the TouchOSC the servomotor and the length of the translucent wire can be appropriately determine by actuating the servomotor and testing the mechanism at same time (Figure 89)

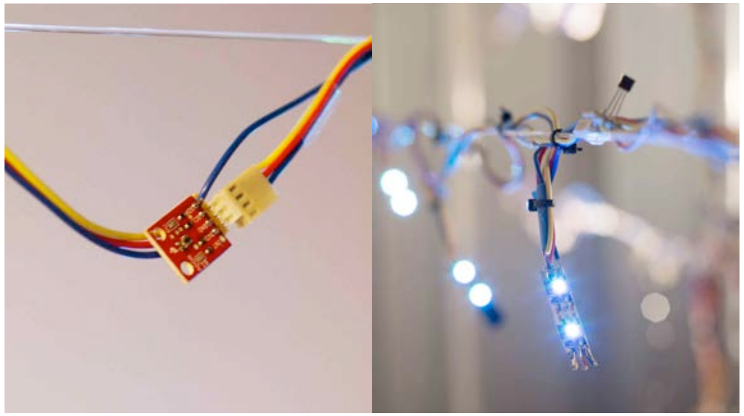

Figure 86:Light sensor (left) and temperature sensor connected to RGB led light to visualise the temperature condition based on RGB colour indicator, from blue (cold) to warm (red). Source: Author

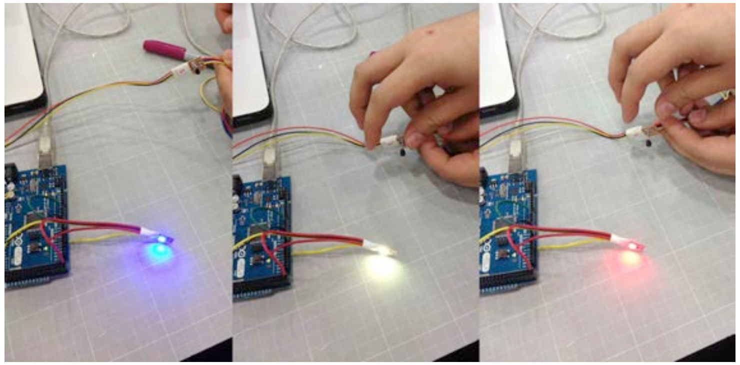

Figure 87: Example of different level of temperature visualised through RGB LED colour. This setup is created as an alternative platform to visualise the thermal heat behaviour during the physical testing. This strategy will allow designer to do quick alteration of the kinetic facades design.

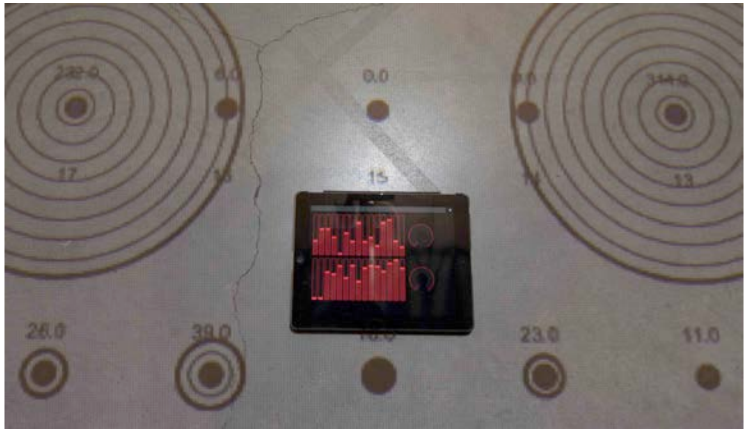

Figure 88: Touch OSC application is used to control the servomotor of the prototype. The designs of the slider panel are customised using Ipad which allow the facades to be controlled through wireless network. Source: Author

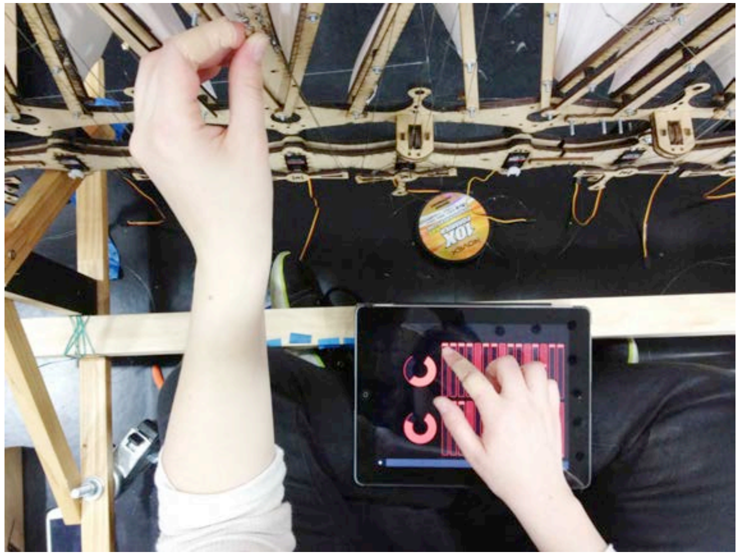

Figure 89 .The processes to determine the length of pulley system aided by TouchOSC application setup. These applications are used as remote control to the actuator in the process of calibrations of the length of the translucent wire. They are also used to synchronise thirty actuators to be working at the same angle position.

5.9 *Simulation and Design Implications*

Furthermore, as facades are crucial mediators between indoor and environmental contexts, development of kinetic facades always involves fine-tuning to get the best performance to respond to the environmental control. Design of kinetic facades sets different objective agenda for designers for environmental control in compared to static design.

The feedbacks from the kinetic behaviour in the early design stage are crucial to identify the facade performance. The *Un-fold* prototype, embedded with kinetic structure and responsive envelope, can adapt to changing conditions of daylight control through the modification of physical configurations. Therefore, the integration of the prototypes with sensors, actuator and microcontroller allows the design to be sensitive to respond to the site condition.

As discussed earlier, the space functions as a living room, which consists of different activities that need constant minimum luminance, level. The activities such as reading, writing or using the computer are activities that require a certain light level. As I mention in previous discussions, the lux level that is required for these activities is recommended around 160 lux, according to this light level standard for Australia. This is significant factor to ensure the comfort to the occupants and productivity is achieved. The outcome from this installation demonstrates the possibilities of *Un-fold* to control the daylight and thermal heat from solar radiation.

The strategy demonstrates qualities, like real-time interaction, self-initiated motion and proactivity. As the investigation is conducted on site with an actual scale prototype, there are a number of significant outcomes that can be identified through this process. The setup of the platform using a flexible digital model to inform the physical prototype during the early design process contributes to the effective decision making process. This process aimed to eliminate uncertainty and ensure constructability of *Un-fold* in the early design investigation.

Figure 90: The prototypes are installed and tested in the real boundaries condition. Couple of design iteration are made during this installation, involving the kinetic mechanism to ensure the facades works effectively. Number of solution discovered in this process for example the used of small roller as the pulling and releasing mechanism. Source: Author

The environmental feedback from daylight and heat play a crucial role in this design investigation. The effective processes to get the feedback from using digital and physical exploration are crucial. The temperature in Melbourne which can vary extensively where on occasions, although rare, can reach as high as 46 degrees in summer and as low as 4.4 degrees in the winter,[57] are crucial to the context for the *Un-fold* investigation.

The figures below display the result of two graphs showing the total opening and closing states of the facades. The closing state shows a fifty per cent reduction of luminance in the space. In this condition, lux level on the mid-day clear sky that show 1221 lux can be filtered to 172 lux, which almost creates an optimal light level for this type of space and activities.

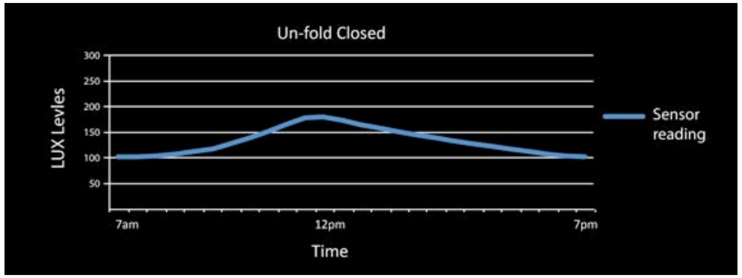

Figure 91: LUX levels during the day when the Un-Fold kinetic facade is closed. Results showed the average of data collected from three light sensors.

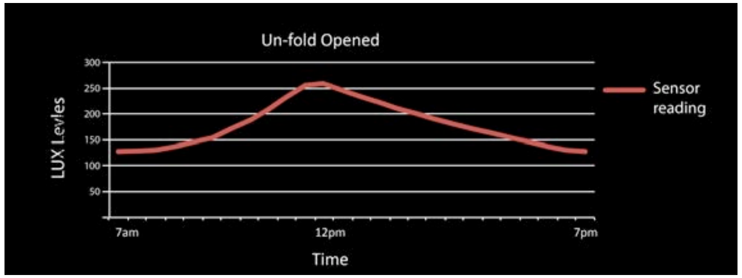

Figure 92: LUX levels during the day when the Un-Fold kinetic facade is opened. Results showed the average of data collected from three light sensors.

Application of *Un-fold* demonstrates the effective design application and evaluation through step-by-step consideration through exploring the potential of kinetic pattern that responds to environmental control. The strategies for exploring the design of kinetic facades through the exploitation of kinetic facades embarks on

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[57] Climate data statistics for Australian locations

new possibilities in designing kinetic facades that are effective in responding to changes in environmental conditions.

Figure 93: Three light sensors are used to measure the lighting condition taken throughout the day. The sensors are located on the floor parallel to each other, which have 1-meter distance to each other and 1-meter from the window. Source: Author.

5.10 Summary, Chapter 5

The construction of *Un-fold* through evaluation of kinetic pattern to control the daylight and solar heat gives insight into how kinetic facades can be designed for environmental performance. The method of investigation provides information in the early design phase helped to identify the problems of dealing with the kinetic pattern.

As the design progress, it has led to countless design outcomes that can be applied to future designs of kinetic facades that respond to environmental conditions. The design approach and the outcome of *Un-fold*, applies the collective results gained from previous investigations, which demonstrate alternative design tools and evaluation for kinetic facades. The approach of integrating physical and digital testing to gain performance feedback during the early design stage can lead to kinetic facades designs that are able to adapt to environmental changes with kinetic mechanical components and sensing features.

The outcome and design process shown in the investigation of *Un-fold* provides a platform to the designer for exploring the design of kinetic facades in the early design stage. This ensures the possibilities in realising the design of the kinetic facades that effectively respond to the environment. Far from suggesting this is the ultimate tool to design kinetic facades, the outcome from this investigation shows some positive outcomes that can inform designers in investigating this concept and development of future research.

6 DISCUSSION

At the centre of this research, the idea of conducting an evaluation of kinetic patterns through digital and physical testing empowers the designer with a new set of tools and technologies. This is with the intention of allowing them to make a more informed and better design analysis of designing kinetic facades in the early design stage. This exegesis has documented my approach in exploring this proposition. The primary investigation based on project-based research and the principle contribution is identifying how the critical parameters underpinning this endeavour – physical engagement and better feedback for responsive design that could support design through an integral computation-based approach. Furthermore, this method employs and identifies five main kinetic patterns that have potential to be developed for environmental control.

In Chapter One, I summarise the outcomes and findings of my applied research work, discuss the tools, responsive feedback from the kinetic pattern, research limitation and potential area for further research. I present the background of my research motivation, which led to a general theoretical background and framework. This framework and background research includes the inspiration, aim, research question, methodology, and exegesis structure.

Chapter Two explained the related literature review on the design elements of kinetic patterns, environmental response and application of digital and physical testing in designing kinetic facades for daylight and thermal heat performance. The summaries of this review suggest the five types of kinetic pattern that can adapt in response to environmental stimuli.

Chapter Three outlined and presented a method of evaluation and presented a platform for the evaluation of kinetic patterns. These methods are presented to evaluate the performance of kinetic in respond to the daylight and thermal heat condition. This method is tested in the design investigation from Chapter Three to Five with reflection of critical review in Chapter Two.

Three types of design investigations are explored through Chapters Three to Five. The first design investigations in Chapter Three evaluates the five types of kinetic patterns that can be applied in response to environmental conditions. The processes of investigation are conducted through scale model prototyping with the support of digital tools. In the following investigation in Chapter Four, the types of kinetic patterns are further developed to observe the performance of the kinetic pattern in response to environmental conditions. These investigations are crucial for evaluating the performance of kinetic facades toward environmental stimuli. Furthermore, I also discuss the current technologies and the challenge in conducting the evaluation on kinetic patterns for the facades.

The outcomes from Chapters Three to Chapter Five inform the last investigation. This chapter demonstrated working prototypes constructed as a proven concept that show kinetic facades are able to respond effectively to environmental conditions by considering the appropriate kinetic patterns and mechanisms. This investigation led to significant findings about kinetic facades, the strategies used to evaluate and integrate them in buildings as part of adaptive strategies. This series of design investigations provided more evidence that supports the research argument as well as augmenting existing knowledge than could involve an exploration through the text alone. At the core of this research is the acquisition of primary results and the demonstration of appropriate outcomes.

Among the final chapters of this exegesis, Chapter Six and Chapter Seven present concise discussions and conclusions. These chapters address the research again in the context of the aim and research question. Additionally, this chapter will discuss in particular, the area of architectural simulation, kinetic performance, technology and environments

Chapter Seven concludes and presents future research directions that could be investigated in the area of responsive kinetic facades.

6.1 Design Implication and outcome

This PhD is conducted by project. The projects designed and developed act as the practical driver of my exploration. These explorations develop a dialogue between existing literature and the design project that has been taken across numerous scales and evaluation techniques. I have decided to elaborate further on the following areas as it related to the primary result of my research.

Performance visibility

Current designers have not visualised building performance in the design process in designing the facades (Morello & Piga, 2013, p109-116). The literature review demonstrates that a limited range of vision during the design process often leads to low performance in design process. For example, high levels of inefficiency found in the building envelope of the performing art centre in Abu Dhabi when compared with a hypothetical building of the same dimensions led to the belief, this understanding is true (Morello & Piga, 2013). Ultimately this investigation encourages designers to approach the early design stage with an expanded range of vision (Morello & Piga, 2013) in order to take advantage of digital tools and physical testing to contemplate environmental performance.

These limitations are crucial as the tools or the approach in evaluating responsive design, which includes kinetic facades, are significant in response to the environmental impact. As I discussed in the introduction, there is a modern interest growing in regard to the development of kinetic facades. However, the designers are keen to create the components (Moloney, 2007) rather than looking into their potential in responding to the environment.

The results of the investigations in Chapters Three to Five demonstrate a different medium and scale involved in the process of investigation of kinetic pattern. This suggests design implications that contribute to the responsive architectural facades. As the process evolves through the process of action research, it demonstrates the outcomes and various strategies that can be used in order to achieve the objective in designing kinetic facades.

In Chapter Three, I discussed how analogue prototypes could expand the range of vision of the potential of kinetic pattern in response to the daylight and thermal heat. This approach has an underlying principle behind performance-based design, but significant limitations encountered thus far in the computationally expensive nature of high-resolution design analysis, and the time taken for the result to emerge (Kolarevic & Malkawi 2005, Nicholas, 2008). During the conceptual phase of kinetic design, the designer's imagination is at work in order to capture different design possibilities. Early design exploration is an essential and speculative process with its own dynamics, which involves spontaneity (Attar et al. 2009). To compliment the potential of kinetic patterns in response to environmental performance, just-in-time feedback from computational analysis and physical testing should ideally be given.

In pursuing this line of thinking, I discovered that the integration of flexible modelling with digital form finding tools with a link to environmental analysis software offers an important clue. The integration of simulation reveals the possibilities of a more dynamic framework and its potential in the early design stage (Attar et al. 2005). Investigation Two demonstrates the engagement of this strategy to explore the potential of kinetic patterns that are effective for environmental control. This investigation was conducted mainly with digital simulation tools for evaluation in order to reflect the performance of the prototype around the year in specific local conditions. The integration of simulation broadens the potential that a more dynamic framework can provide during the early stages of design (Ibid). However, the downside of this investigation in the context of kinetic design is that how the kinetic patterns integrate with the actual materiality is not visible to the designer in this stage.

The ability to interact with and adjust the mechanism in order to integrate it as part of a kinetic facade is significant to ensure that it is 'tuned' to respond to the environmental conditions. From my observation and experience with working on this investigation, I discovered that the interaction of virtual kinetic pattern models, which are interconnected with physical in real-time evaluation, was an effective trade-off for close to reality performance. This demonstrated unforeseen material tendencies and enabled a further exploration of the complex behaviour of kinetic patterns that would otherwise be very difficult if not impossible to identify let alone explore during early design stage.

The qualitative feedback gained through project based design, is crucial in gaining more detailed information about the design of the facade than in comparison to the precise, quantitative feedback, which emerges from the digital simulations. However, while it is acknowledged that physical prototyping is a crucial element in the design process, due to time constraints, digital simulation was able to test the physical prototype to gain insight to its performance throughout the year. I believe that designing the kinetic facade through physical prototyping first in order to identify the effectiveness of kinetic components in response to environmental conditions is a requirement before digital testing. Physical prototyping is an effective process in the design of kinetic facades as it serves as a basic framework for the interactive design and digital simulation. This iterative design and testing process provides valuable information that is often overlooked in preference to digital design and simulations.

Feedback Architecture

Typically, a designer's interaction takes a considerable amount of time due to complexities around information transfer and software interoperability (Piker, 2010) in evaluating the performance of kinetic facades. As I stated in the previous discussion, the visibility of the changes that are envisaged in the design, while making them, will open up a whole new way of working (Piker, 2010) dealing with responsive elements in designing and evaluating the facades.

One of the ways to understand how interactive simulation and evaluation tools can effectively assist and evaluate the responsive design, such as the design that is involved in kinetic facades, is to consider conventional word processing software (Fumar, 2011). Word processing provides real-time feedback to aid with correct grammar and spelling. It is continuously checking for mistakes, which are coloured in order to communicate the type of error that has been made, for example, red for incorrect spelling and green for grammatical errors. The writer can ignore the feedback, fix the mistake manually, or choose from a drop down menu of possible ways around the problem. However, the significant part of this process is to demonstrate, that the writer is aware the problems as they are working through the text. It not only allows the writer to make changes, but it will open up other possibilities to restructure the whole sentence in making it clear and better.

Critical engagement with computational and physical testing allow designers to consider the design involved with kinetic pattern, precedes material feedback, and these two criteria are independent. Consequently I show here that, real time digital support to design notwithstanding; materiality is actively involved in the design process (Weinand & Hudert, 2010).

The project *Un-fold* that is described in Chapter Five, best illustrates this approach. The integration of a digital and material feedback loop that I used during this investigation enabled effective and practical design decisions to be made with respect to the material characteristics and kinetic potential. I discovered this in the process of designing the kinetic facades that involved environmental performance. Instead of focusing on the aesthetics of the design, I began to explore the design through an understanding of materials and their kinetic potentials – how is a kinetic facade designed primarily with the mechanics in mind, followed by the aesthetic.

From a series of testing and prototyping investigations that were demonstrated early in Chapter Three toward Chapter Five, I found that designing kinetic facades through identifying their role and responsive feedback, gave effective insight into what the potential of kinetic pattern can provide as part of the design of kinetic facades. For instance, to describe this process of designing kinetic facades, I use the analogy of designing a car tyre. Assuming that someone does not know how to design a tyre, the process of designing the design of tyre is not important. Instead, you need to consider the function (i.e. racing, urban, off-road) and the mechanism required of the tyre in order to gain insight as to what form the tyre should take in order for it to be efficient.

In the context of evaluating kinetic facades for environmental performance, I suggest that the design approach should be conducted after a thorough exploration of the requirements of the kinetic pattern and mechanism of the facade in response to the environmental conditions. This is so that a more informed decision can be made in the early stage of design in regards to the requirements for the facade to be made as early possible. This approach involves engaging with the materiality and real-time feedback rather than just the conceptual during the early phase of design. This process opened up unexpected and innovative forms, structural possibilities and material choices in dealing with the state of change in kinetic pattern.

Design Technology

The driver of my investigation for evaluating the kinetic facades was always to explore and identify new and effective technologies and software in order evaluate the performance of the kinetic facades, by giving real time feedback response. However, instead of limiting my investigation method to the current technologies that suited the needs of my investigation, I examined the possibilities to create different approaches for evaluating my research projects. Project-based research provided me with these explorations that identified the potential to be gained from exploring new possibilities of evaluation techniques for kinetic facades.

This exploration is demonstrated in Chapter Three, where I tried to explore different configurations to evaluate the responsive digital models through environmental software analysis and coupled with form finding software that can achieve different configuration states of motion. This approach suggests a new technique to be applied to the evaluation of kinetic facades. Furthermore, these processes are further tested in integrating the digital with analogue feedback in order to effectively evaluate the performance of the kinetic system. The use of physical computing, actuation and sensors provided me with appropriate tools to explore new potential options for evaluating the kinetic facades. In

Scissornet I used the microcontroller with the sensors and actuators to create autonomous behaviour in respond to the light. This process was further integrated in the last investigation though three physical testing prototypes, in response to light. Further exploration is made in the *Un-Fold* project, through integration of micro-controllers in exploring the surface of the facades. The use of microcontrollers in processing the light level to actuate the prototype is a potential technique to observe the performance of the kinetic facades in the early design stage. This provides the designer with information in order to understand the integration of the kinetic system within the kinetic facade without overlooking other problems that exist.

During this exploration, this technique is discovered and potentially adopted in evaluating the performance of the kinetic facades in response to environmental conditions. This led to a physical testing setup that was demonstrated in investigation four. I propose this technique of investigation to be explored in the early stage of design. This is because; this technique demonstrated an attempt to establish new tools to evaluate the performance of kinetic facades. These strategies are not new in the engineering and building science; the approach is still new in the responsive architecture area. This technique contributes to the existing tools for evaluating specifically kinetic architecture that responds to environmental performance.

Environmental Performance Feedback – Multi-criteria simulation and evaluation

The methods used to evaluate kinetic facades are always tied back to the response to the environment, as it is the first barrier to protect or to modulate the internal environment of the building. To evaluate and replicate the existing environmental conditions, still proves to be a challenging part during the process of realising the kinetic facade. Producing new components for the kinetic facade in response to the environmental conditions does not do the design justice unless the components are working effectively and efficiently in response to the environmental conditions.

During the process of investigation, I integrated a number of digital software to evaluate the design in response to elements of environmental performance, such as light and heat. The suggested integration of flexible 3D software such as *Grasshopper*, and form finding software such as *Galapagos* and *Ecotect* are one among a number of strategies used to evaluate the performance of kinetic facades.

In Chapter Four, I demonstrated how kinetic strategies could respond to the local environmental conditions. By adopting specific local context, weather data can be used to conduct further investigations in the project. Even though using digital simulation tools can identify a number of issues in a facade, and the weather data can be expanded; some of the outcomes of the kinetic design are not visible. This is due to the limitation that digital simulations have in their ability to evaluate the performance of the design in response to the environmental performance without considering other factors such as material forces and kinetic mechanism.

The physical testing setup attempted to fulfil this gap. Even though in this setup, designers cannot simulate the design of kinetic facades with the integration of weather data throughout the year due to the time constraint and cost; it can provide more invisible information for the kinetic facades in terms of it functionality for early design stage evaluation. The physical testing will allow the designer to engage with materiality and kinetic mechanism to respond to the changing environmental stimuli.

This technique for evaluating the kinetic facades through physical testing will contribute to the existing tools available that simulate responsive design. The components used to setup the physical experiment have become affordable in recent years. This provides the designer with the ability to undertake more 'do it yourself' (DIY) experimentation and investigations in evaluating the performance of the facades. This will serve as an interactive tool for the designers to explore beyond traditional simulation techniques.

6.2 Limitations

Post Occupancy Evaluation

As energy becomes a main motivation for the application of kinetic facades as discussed earlier in the exegesis, the evaluation of kinetic facades design should be extended towards building applications in order to evaluate the efficiency of energy use of the building. Post occupancy evaluations are the key in identifying the performance of the kinetic facades in evaluating the contribution toward energy performance.

Even though design considerations are required when creating kinetic facades, the kinetic facades also need to be effective in responding to environmental conditions and contribute to other building strategies. Further evaluations, post-installation on the effectiveness of facades are and will be effective not only ensuring that the kinetic facades are working properly in response to environmental conditions, but also learning why they may not be. These activities will further inform the designers of the current facades' performance and the possibilities for the kinetic facades to be improved in the future.

Building Cost

Evaluating the costs involved for developing kinetic facades is a significant aspect when designing for response to environmental conditions with regards to building costs in the long term. Even though this aspect is one of the important elements to consider during the creation of *Un-Fold*, by integrating the leveraging system, it was evident that there is a need to conduct further research on establishing a novel approach in this issue. Furthermore, the cost considerations of kinetic facades are based on a few factors; mainly involving maintenance and life cycle costs. There is very little evidence on how kinetic facades can contribute to reduced maintenance and life cycle costs by integrating the kinetics in the facades. It is more likely to increase these costs but the question remains whether this is more than offset by potential energy savings in the building.

Exploring self-sustainable and energy efficiency of responsive facades for buildings is one of the potential areas of enquiry for this area. The application of solar power technology can be integrated into creating the facades to be responsively kinetic. Furthermore, the potential of this technology to be integrated into the design of kinetic facades, could overcome the issues of sustainability and energy efficiency of kinetic facades.

Scalability

The final installations of the prototype, *Unfold* are conceived in full-scale, which present the potential of kinetic facade design through physical prototyping supported by digital simulation. Even though the full scale prototypes are constructed in actual scale, the challenge lies on how well the actuator and sensor working for particular duration of time. Different actuator, sensors and material properties will be slightly different when applied or manufactured in larger quantitates as this will involve more facades panels and kinetic mechanism which adding up to the complexity of the kinetic system at the same time. This is crucial as evaluating singular panel of kinetic facades is different to evaluating it with group of panels and a kinetic system. Different problems and challenges will start to be visible when the kinetic system are integrated. The problem appears during the installation of the kinetic facades. Simplifying the kinetic mechanism and reducing the amount of friction of the kinetic mechanism in the early stage of design will be a great advantage at this stage as the small issues appearing from the singular panel will create a strong impact to the integrated kinetic mechanism and system.

Instead of being the obstacle, the scalability can be the opportunity for further research, exploring the kinetic facades' design during early design stage by exploiting the technology in identifying the possible mechanisms for effective transformation of kinetic facades through leveraging system – that is, a system using the principal of levers. Even though, during the exploration of Un-fold the leverage systems are introduced, possibilities remain to explore other mechanisms in creating similar outcomes.

7 REFLECTIONS AND CONCLUSION

The fascination designers have had with designing kinetic facades to be aesthetically pleasing has been apparent for a very long time. A literature review of existing buildings demonstrates that there is considerable interest in realising kinetic facades as an environmental mediator between indoor and outdoor conditions. Even though it is evident in the literature and publications that the ability of kinetic facades to respond to environmental conditions exists, there is no clear evidence showing that the claim is either based on the evaluation in the early design stage nor in the post occupant evaluation.

The critiques of the Institute Monde Arabe facade have been published and discussed extensively within literature, and there is research showing that the facade did not function to modulate the daylight and heat as it claimed to, even in the beginning. Even though this building became an example of interest for the both designers and researchers, the focus should be on the issues of effectiveness of the design of kinetic facades that utilise technology and production of its components (Fox, 2001; Loonen, 2010; Moloney, 2007). Furthermore, the issue of ineffective responsiveness is evident through a number of similar uses and strategies, which are shown from the buildings in the 1960's, such as Fuller's American Pavilion to more recent designs such as the Institut Monde de Arabe.

Through the investigations and exploration of the research that I have undertaken, I am satisfied that in order to realise kinetic facades which respond to changes in environmental conditions, the facades require the designer to identify and evaluate the kinetic patterns and mechanisms in the early design phase. Identifying and evaluating the kinetic patterns is done in order to provide the designer with detailed information so that they are able to make more informed decisions with regards to what decisions will provide better performance in response to changes in environmental conditions, in the early design phase.

Throughout my projects, I have demonstrated how the process of identifying and evaluating appropriate kinetic patterns and processes were specifically made possible through developing a series of interactive physical prototypes, testing and evaluating with the support of digital media. My research has evolved via three main investigations. Although the investigations varied in the media that was utilised, the insights gained from each investigation has contributed to my overall understanding of how physical prototyping and testing and evaluation can provide feedback to the designer in identifying the appropriate kinetic patterns, that can be used as part of the facade that deals with the environmental conditions that it is targeting.

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The action research methodology I applied throughout the investigation process is in parallel with the cultural and philosophical elements of my work. Instead of using a predetermined series of methods for evaluating kinetic facades, each investigation was planned and carried out in an iterative fashion that was informed by prior practical work and complimentary theoretical explorations. This approach acted as a driver to investigate my hypothesis and ideas, towards unexpected findings that addressed the inquiry in a more comprehensive manner.

From the start, my assumptions and motivations were based on my experience and engagement of the literature in regard to evaluating the design of kinetic facades in their response to changes in environmental conditions. As a result, I pursued this notion during Investigation One. My action-based investigations revealed that engaging with materiality provided more feedback to develop the understanding of the kinetic system and how the motions work. From this, I adopted five types of kinetic patterns that were tested in response to the environmental conditions. Furthermore, these motions are part of an ongoing investigation developed by Jules Moloney (2011) who investigates kinetic facades for architectural use. Moloney's (2011) work provided a significant platform for the subject of kinetics that examine art and aesthetics as a foundation to identify the most suitable motion to be further tested using animation.

Moloney's (2011) work in identifying the types of kinetic patterns was conducted through a series of animation investigations without associating any environmental response. The method of investigation through animation that was carried out previously provided a strong basis for inquiry into how the kinetic patterns could be identified without presenting considerations of materiality. However, since kinetic patterns mainly involved intrinsic or extrinsic control that employss the use of the mechanical components, it leads to the idea of identifying the form and materials for kinetic facades.

Reflecting on my experience and through the review of the literature, I found that approaching physical prototyping and digital computation in a significant manner prompted considerations that kinetic patterns and mechanisms should precede the performance of designing environmentally responsive kinetic facades. I proposed physical tests – in particular those capable of better bridging between virtual and performance dimensions in the context of designing the facade. This perspective facilitated a significant shift away from visually driven methods, used only for the development of kinetic facades with an approach to designing a system in which physical testing and computing are actively involved in the design process (Weinand & Hudert 2010, p107).

My initial engagement for exploring different typologies of kinetic facades, involved areas of rotation, sliding, retraction, elastic and folding in response to environmental conditions. Using the aforementioned strategies, it provided information to make a more informed decision by identifying the effectiveness of the motion in response to environment conditions. Through this evaluation process and method of investigation, the outcomes of this evaluation resulted in selecting one of the kinetic patterns in order to develop an effective response to the daylight and thermal performance. These types of kinetic patterns are evaluated through physical testing and propose strategies of digital simulation prior to installing and testing in real boundary conditions. This evaluation serves as a process for the designer to adopt as part of their design and strategy and framework in using kinetic facades as a response to environmental control.

I pursued three investigations through exploring the behaviours of kinetic patterns that informed the kinetic mechanism. From this investigation I found, the main driver for designing kinetic systems lies with applying effective mechanisms that respond to the light or thermal heat performance, prior to the design of the skin. This informed my understanding on how kinetic pattern can be leverage in the early design stage to ensure the design can function effectively after it has been constructed.

I demonstrated how physical and digital interaction, material considerations, simulation, and evaluation of the environment could improve the decision of material and understanding by providing meaningful feedback in regards to the behaviour of complex kinetic patterns and mechanisms. Ultimately, rather than only providing a means for the kinetic pattern to respond to the environment, and thus directly integrating it as part of the design and production, physical testing can offer greater and perhaps more enduring opportunities to the designers. This is done by strengthening the relationship with kinetic patterns for facades that interact with the environment. As a result, this notion can assist the designer in three important ways:

a) Facilitate dynamic modes of testing with direct interaction with the motions and mechanisms that serve as the main ingredient in realising the kinetic facades.

b) It will allow the designer to gain quick, practical knowledge through early and close engagement with materials and manufacturing process.

c) It will support informed digital-material feedback loops that serve to calibrate results from generative computational modelling and analysis to improve the mechanism and kinetic pattern understanding and guide further exploration.

My research demonstrates that the exploration of kinetic facades as early as possible through physical prototyping and physical testing, in the early design phases, can provide designers with an accelerated feedback loop between design synthesis and design analysis. As the design of kinetic facades involved interactive components and mechanisms, it provided the ability to quickly simulate, evaluate and calibrate the mechanism and material behaviour to enable a more informed and effective integrated design to inform and enhance the design response.

A mutual platform informed the digital and physical feedback loops making it effective in gaining the result and deploying different possibilities of kinetic facade design. This approach provided a stronger bond between the design intent and the built result, through a more detailed and precise setup design, from the early design stage to the production process. Furthermore, this process enables the discovery of potential mechanisms for kinetic pattern that effectively responds to changes in environmental conditions. It will further help to influence the design with integrated aspects of the kinetic facade components.

Lastly, I identified how the transition toward materiality-informed design - catalyses the potential for kinetic pattern in environmental performance. This fundamental change in understanding the design philosophy of interactive design such as dealing with kinetic pattern and mechanisms can be characterised as 'static relation, form-matter, and tends to fade into the background in favour of a dynamic relation, material forces' (Deleuze and Guattari, 1980, p 364). Related to this thinking architectural form is not the expression of one individual creative genius, but rather must be gained through the interacting with physical objects, as a way of negotiating between intrinsic material properties and extrinsic factors.

My investigations that are presented in this exegesis, not only serve as a driver to support this discovery, they also provide evidence for this claim, and form a significant investigation that identifies the potential of kinetic facades through the use of kinetic patterns that are effective in response to environmental conditions.

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Appendix

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A3.Sample of publication
A4.Images of Exhibition
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A1. Publications

1. Sharaidin, K., Salim, F. D. (2011). Affordable, Performative, And Responsive: Designing Affordable Responsive Architectural Prototypes Through Physical And Digital Modeling. Computer-Aided Architectural Design Research in Asia (CAADRIA) 2011, Newcastle, Australia.

2. Sharaidin, K., Salim, F. D. (2011). Affordable, Performative and Responsive. Adaptive Architecture 2011 Conference, London, United Kingdom.

3. Sharaidin, K., Salim, F. (2012). Design Considerations for Adopting Kinetic Facades in Building Practice. In Digital Physicality and Physical Digitality:(eCAADe 2012) (pp. 619-628). Czech Technical University in Prague, Faculty of Architecture.

4. Rafael A, Salim F.D William M, Sharaidin, M.K, Pneumosense Project: A Flexible Kinetic Windbreak ACADIA 2013)

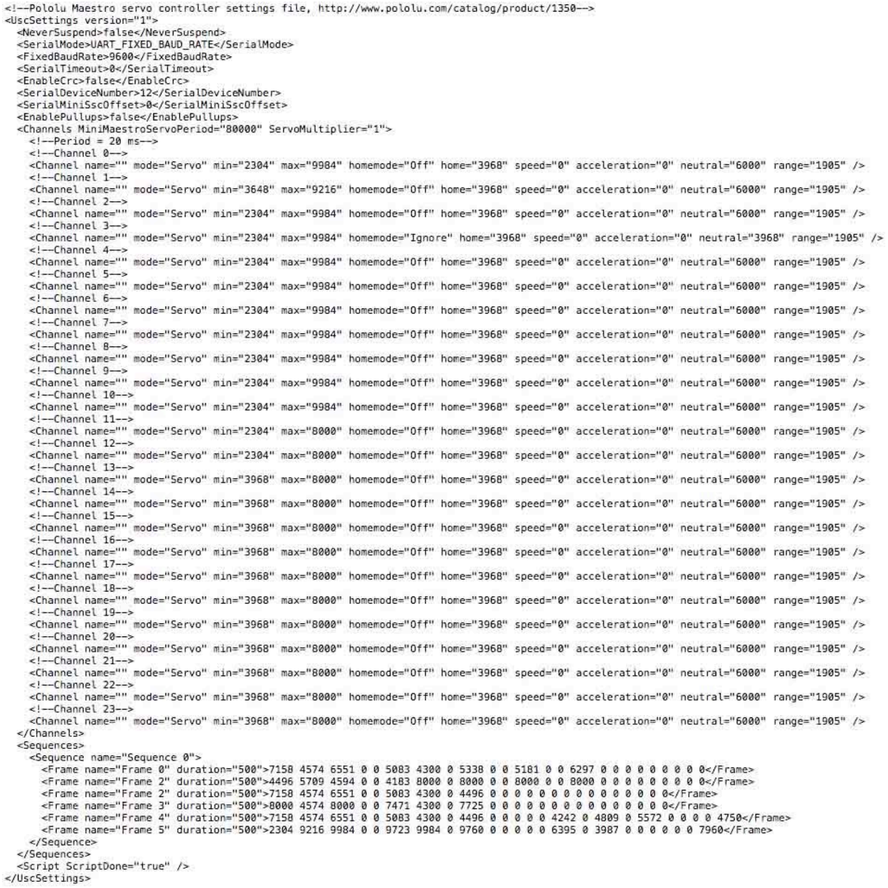
5. Sharaidin, M.K, (2013) Kinetic Facades: Leveraging Kinetic structure for daylight performance, Education and research in computer Aided Architectural Design

6. Sharaidin, M, Pallett, J and Salim, F 2012, Integration of digital simulation tools with parametric designs to evaluate kinetic façades for daylight performance, in Achten, Henri; Pavlicek, Jiri; Hulin, Jaroslav; Matejdan, Dana (ed.) Proceedings of the 30th International Conference on Education and research in Computer Aided Architectural Design in Europe (eCAADe 2012), Prague, Czech Republic, 12 - 14 September, 2012, pp. 691-700.

7. Pallett, J, Salim, F, Williams, M, Pena De Leon, A, Sharaidin, K, Burry, M and Nielsen, S 2013, Understanding heat transfer performance for designing better façades, in Philip Beesley, Omar Khan,and Michael Stacey (ed.) *ACADIA 13: Adaptive Architecture Proceedings of the 33rd Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)*,Delaware, United States, 24-26 October 2013, pp. 71-78.

8. Sharaidin, K, 'Using Physical Models in Design to Evaluate the Acclimatization of Kinetic Facades for Daylight and Thermal Performance'. *ACADIA 14: Design Agency.Proceedings of the 34rd Annual Conference of the Association for Computer Aided Design in Architecture*

A2. Script Example



```
<!--Pololu Maestro servo controller settings file, http://www.pololu.com/catalog/product/1350-->
<UscSettings version="1">
  <NeverSuspend>false</NeverSuspend>
  <SerialMode>UART_FIXED_BAUD_RATE</SerialMode>
  <FixedBaudRate>9600</FixedBaudRate>
  <SerialTimeout>0</SerialTimeout>
  <EnableCrc>false</EnableCrc>
  <SerialDeviceNumber>12</SerialDeviceNumber>
  <SerialMiniSscOffset>0</SerialMiniSscOffset>
  <EnablePullups>false</EnablePullups>
  <Channels MiniMaestroServoPeriod="80000" ServoMultiplier="1">
    <!--Period = 20 ms-->
    <!--Channel 0-->
    <Channel name="" mode="Servo" min="2304" max="9984" homemode="Off" home="3968" speed="0" acceleration="0" neutral="6000" range="1905" />
    <!--Channel 1-->
    <Channel name="" mode="Servo" min="3648" max="9216" homemode="Off" home="3968" speed="0" acceleration="0" neutral="6000" range="1905" />
    <!--Channel 2-->
    <Channel name="" mode="Servo" min="2304" max="9984" homemode="Off" home="3968" speed="0" acceleration="0" neutral="6000" range="1905" />
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    <Channel name="" mode="Servo" min="2304" max="9984" homemode="Off" home="3968" speed="0" acceleration="0" neutral="6000" range="1905" />
    <!--Channel 5-->
    <Channel name="" mode="Servo" min="2304" max="9984" homemode="Off" home="3968" speed="0" acceleration="0" neutral="6000" range="1905" />
    <!--Channel 6-->
    <Channel name="" mode="Servo" min="2304" max="9984" homemode="Off" home="3968" speed="0" acceleration="0" neutral="6000" range="1905" />
    <!--Channel 7-->
    <Channel name="" mode="Servo" min="2304" max="9984" homemode="Off" home="3968" speed="0" acceleration="0" neutral="6000" range="1905" />
    <!--Channel 8-->
    <Channel name="" mode="Servo" min="2304" max="9984" homemode="Off" home="3968" speed="0" acceleration="0" neutral="6000" range="1905" />
    <!--Channel 9-->
    <Channel name="" mode="Servo" min="2304" max="9984" homemode="Off" home="3968" speed="0" acceleration="0" neutral="6000" range="1905" />
    <!--Channel 10-->
    <Channel name="" mode="Servo" min="2304" max="9984" homemode="Off" home="3968" speed="0" acceleration="0" neutral="6000" range="1905" />
    <!--Channel 11-->
    <Channel name="" mode="Servo" min="2304" max="8000" homemode="Off" home="3968" speed="0" acceleration="0" neutral="6000" range="1905" />
    <!--Channel 12-->
    <Channel name="" mode="Servo" min="2304" max="8000" homemode="Off" home="3968" speed="0" acceleration="0" neutral="6000" range="1905" />
    <!--Channel 13-->
    <Channel name="" mode="Servo" min="3968" max="8000" homemode="Off" home="3968" speed="0" acceleration="0" neutral="6000" range="1905" />
    <!--Channel 14-->
    <Channel name="" mode="Servo" min="3968" max="8000" homemode="Off" home="3968" speed="0" acceleration="0" neutral="6000" range="1905" />
    <!--Channel 15-->
    <Channel name="" mode="Servo" min="3968" max="8000" homemode="Off" home="3968" speed="0" acceleration="0" neutral="6000" range="1905" />
    <!--Channel 16-->
    <Channel name="" mode="Servo" min="3968" max="8000" homemode="Off" home="3968" speed="0" acceleration="0" neutral="6000" range="1905" />
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    <!--Channel 19-->
    <Channel name="" mode="Servo" min="3968" max="8000" homemode="Off" home="3968" speed="0" acceleration="0" neutral="6000" range="1905" />
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    <Channel name="" mode="Servo" min="3968" max="8000" homemode="Off" home="3968" speed="0" acceleration="0" neutral="6000" range="1905" />
    <!--Channel 22-->
    <Channel name="" mode="Servo" min="3968" max="8000" homemode="Off" home="3968" speed="0" acceleration="0" neutral="6000" range="1905" />
    <!--Channel 23-->
    <Channel name="" mode="Servo" min="3968" max="8000" homemode="Off" home="3968" speed="0" acceleration="0" neutral="6000" range="1905" />
  </Channels>
  <Sequences>
    <Sequence name="Sequence 0">
      <Frame name="Frame 0" duration="500">7158 4574 6551 0 0 5083 4300 0 5338 0 0 5181 0 0 6297 0 0 0 0 0 0 0 0 0</Frame>
      <Frame name="Frame 2" duration="500">4496 5709 4594 0 0 4183 8000 0 8000 0 0 8000 0 0 8000 0 0 0 0 0 0 0 0 0</Frame>
      <Frame name="Frame 2" duration="500">7158 4574 6551 0 0 5083 4300 0 4496 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0</Frame>
      <Frame name="Frame 3" duration="500">8000 4574 8000 0 0 7471 4300 0 7725 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0</Frame>
      <Frame name="Frame 4" duration="500">7158 4574 6551 0 0 5083 4300 0 4496 0 0 0 0 0 4242 0 4809 0 5572 0 0 0 0 4750</Frame>
      <Frame name="Frame 5" duration="500">2304 9216 9984 0 0 9723 9984 0 9760 0 0 0 0 0 6395 0 3987 0 0 0 0 0 0 7960</Frame>
    </Sequence>
  </Sequences>
  <Script ScriptDone="true" />
</UscSettings>
```
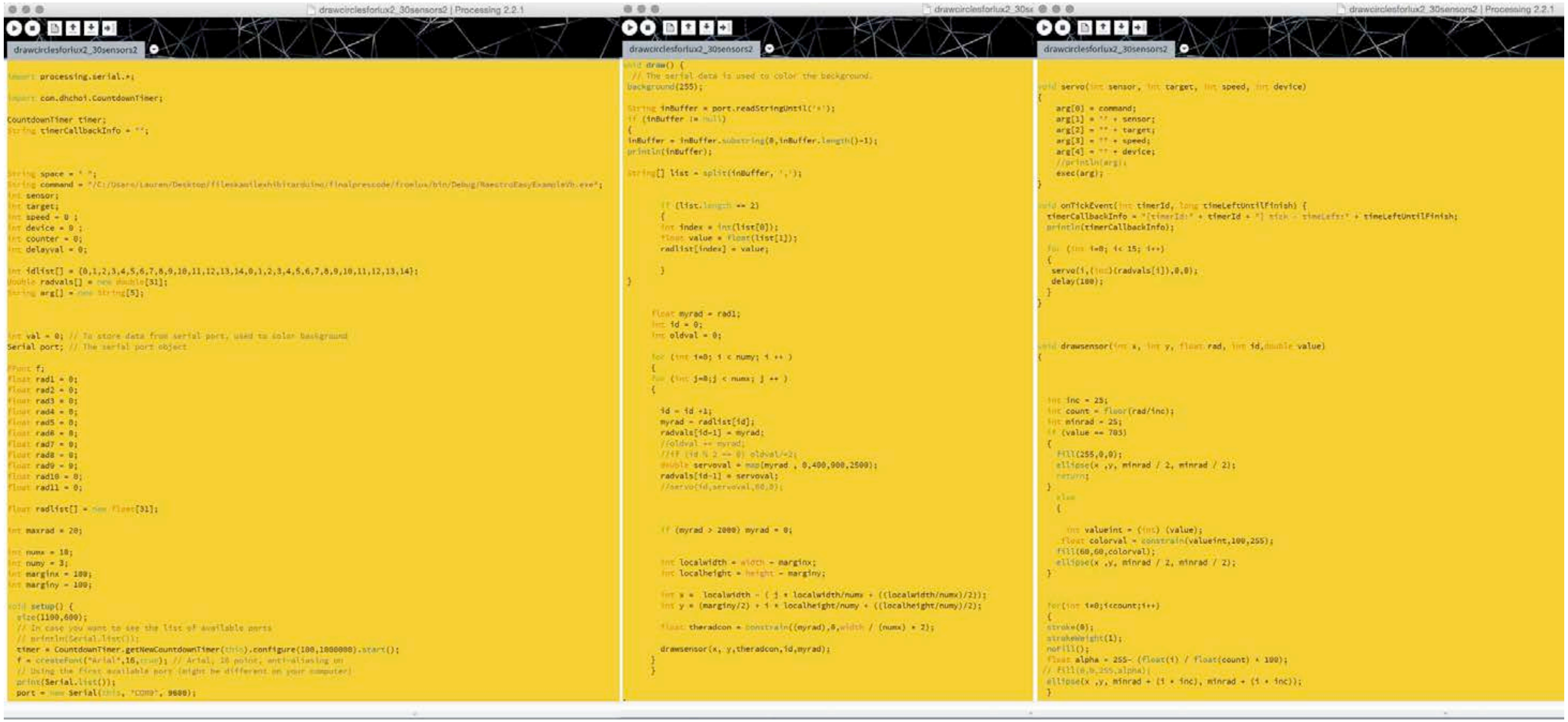

Appendix 1: Micro-controller, Maestro code controlling 30 servomotors

```
from OSC import OSCServer,OSCClient, OSCMessage
from time import sleep
import types
import serial
import msvcrt

#serPort = serial.Serial("COM3", 115200, timeout=1)
serPort = serial.Serial("COM3", 9600, timeout=1)
server = OSCServer(("0.0.0.0", 8000))

val1 = 0
val2 = 0
val3 = 0

def push1_callback(path, tags, args, source):
    #print(str(path))
    val = int(args[0] * 180)
    global val1
    val1 = val

    #print("val:" + str(val))
    #serPort.write("<"+str(val1)+">" + "<" +str(val2)+">")
    val1str = str(val).zfill(3)
    val2str = str(val2).zfill(3)
    serialmsg = val1str + val2str
    print(serialmsg)
    serPort.write(serialmsg)
    #print(str(args[0]))


def push1_callback2(path, tags, args, source):
    #print(str(path))
    val = int(args[0] * 180)
    global val2
    val2 = val
    #print("val:" + str(val))
    val3str = str(val1).zfill(3)
    val4str = str(val).zfill(3)
    #print("f:" + val3str)
    #print("s:" + val4str)
    serialmsg = val3str + val4str
    print(serialmsg)
    serPort.write(serialmsg)
    #print(str(args[0]))


def handle_error(self,request,client_address):
    pass

server.addMsgHandler( "/1/volume1",push1_callback)
server.addMsgHandler( "/1/volume2",push1_callback2)

server.handle_error = types.MethodType(handle_error, server)

count = 0
while True:
    count = count +1
    server.handle_request()
    if count > 1000:
        count = 0
        #serPort.flushInput()
        #serPort.flushOutput()

server.close()
```

Appendix 2 : TouchOSC script

```
#include "TSL2561.h"

// Example for demonstrating the TSL2561 library - public domain!

// connect SCL to analog 5
// connect SDA to analog 4
// connect VDD to 3.3V DC
// connect GROUND to common ground
// ADDR can be connected to ground, or vdd or left floating to change the i2c address

// The address will be different depending on whether you let
// the ADDR pin float (addr 0x39), or tie it to ground or vcc. In those cases
// use TSL2561_ADDR_LOW (0x29) or TSL2561_ADDR_HIGH (0x49) respectively
TSL2561 tsl(TSL2561_ADDR_FLOAT);

void setup(void) {
  Serial.begin(9600);

  if (tsl.begin()) {
    Serial.println("Found sensor");
  } else {
    Serial.println("No sensor?");
    while (1);
  }

  // You can change the gain on the fly, to adapt to brighter/dimmer light situations
  //tsl.setGain(TSL2561_GAIN_0X);         // set no gain (for bright situtations)
  tsl.setGain(TSL2561_GAIN_16X);      // set 16x gain (for dim situations)

  // Changing the integration time gives you a longer time over which to sense light
  // longer timelines are slower, but are good in very low light situtations!
  tsl.setTiming(TSL2561_INTEGRATIONTIME_13MS);  // shortest integration time (bright light)
  //tsl.setTiming(TSL2561_INTEGRATIONTIME_101MS);  // medium integration time (medium light)
  //tsl.setTiming(TSL2561_INTEGRATIONTIME_402MS);  // longest integration time (dim light)

  // Now we're ready to get readings!
}

void loop(void) {
  // Simple data read example. Just read the infrared, fullspecrtrum diode
  // or 'visible' (difference between the two) channels.
  // This can take 13-402 milliseconds! Uncomment whichever of the following you want to read
  uint16_t x = tsl.getLuminosity(TSL2561_VISIBLE);
  //uint16_t x = tsl.getLuminosity(TSL2561_FULLSPECTRUM);
  //uint16_t x = tsl.getLuminosity(TSL2561_INFRARED);

  Serial.println(x, DEC);

  // More advanced data read example. Read 32 bits with top 16 bits IR, bottom 16 bits full spectrum
  // That way you can do whatever math and comparisons you want!
  uint32_t lum = tsl.getFullLuminosity();
  uint16_t ir, full;
  ir = lum >> 16;
  full = lum & 0xFFFF;
  Serial.print("IR: "); Serial.print(ir);   Serial.print("\t\t");
  Serial.print("Full: "); Serial.print(full);   Serial.print("\t");
  Serial.print("Visible: "); Serial.print(full - ir);   Serial.print("\t");

  Serial.print("Lux: "); Serial.println(tsl.calculateLux(full, ir));
```

Appendix 3: Example of script code for light sensor 30 light sensor



```
import processing.serial.*;

import com.dhchoi.CountdownTimer;

CountdownTimer timer;
String timerCallbackInfo = "";



String space = " ";
String command = "/C:/Users/Lauren/Desktop/fileskamilexhibitarduino/finalprescode/fromlux/bin/Debug/MaestroEasyExampleVb.exe";
int sensor;
int target;
int speed = 0 ;
int device = 0 ;
int counter = 0;
int delayval = 0;

int idlist[] = {0,1,2,3,4,5,6,7,8,9,10,11,12,13,14,0,1,2,3,4,5,6,7,8,9,10,11,12,13,14};
double radvals[] = new double[31];
String arg[] = new String[5];



int val = 0; // To store data from serial port, used to color background
Serial port; // The serial port object

PFont f;
float rad1 = 0;
float rad2 = 0;
float rad3 = 0;
float rad4 = 0;
float rad5 = 0;
float rad6 = 0;
float rad7 = 0;
float rad8 = 0;
float rad9 = 0;
float rad10 = 0;
float rad11 = 0;

float radlist[] = new float[31];

int maxrad = 20;

int numx = 10;
int numy = 3;
int marginx = 100;
int marginy = 100;

void setup() {
  size(1100,600);
  // In case you want to see the list of available ports
  // println(Serial.list());
  timer = CountdownTimer.getNewCountdownTimer(this).configure(100,1000000).start();
  f = createFont("Arial",16,true); // Arial, 16 point, anti-aliasing on
  // Using the first available port (might be different on your computer)
  print(Serial.list());
  port = new Serial(this, "COM9", 9600);
```

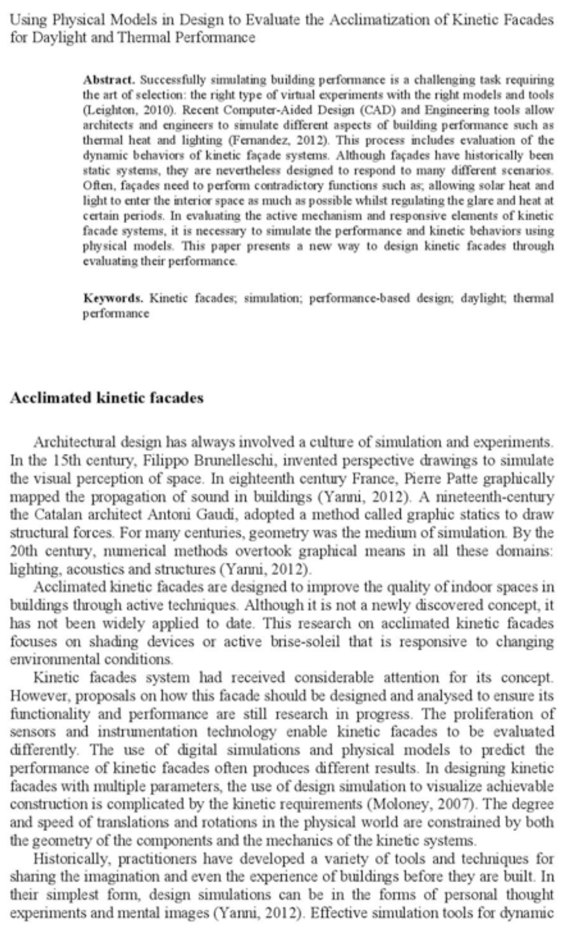
```
void draw() {
 // The serial data is used to color the background.
 background(255);

 String inBuffer = port.readStringUntil('*');
 if (inBuffer != null)
 {
 inBuffer = inBuffer.substring(0,inBuffer.length()-1);
 println(inBuffer);

 String[] list = split(inBuffer, ',');


      if (list.length == 2)
      {
      int index = int(list[0]);
      float value = float(list[1]);
      radlist[index] = value;

      }
 }



     float myrad = rad1;
     int id = 0;
     int oldval = 0;

     for (int i=0; i < numy; i ++ )
     {
     for (int j=0;j < numx; j ++ )
     {

      id = id +1;
      myrad = radlist[id];
      radvals[id-1] = myrad;
      //oldval += myrad;
      //if (id % 2 == 0) oldval/=2;
      double servoval = map(myrad , 0,400,900,2500);
      radvals[id-1] = servoval;
      //servo(id,servoval,60,0);



      if (myrad > 2000) myrad = 0;


      int localwidth = width - marginx;
      int localheight = height - marginy;

      int x =  localwidth - ( j * localwidth/numx + ((localwidth/numx)/2));
      int y = (marginy/2) + i * localheight/numy + ((localheight/numy)/2);

      float theradcon = constrain((myrad),0,width / (numx) * 2);

      drawsensor(x, y,theradcon,id,myrad);
     }
     }
```

```

void servo(int sensor, int target, int speed, int device)
{
   arg[0] = command;
   arg[1] = "" + sensor;
   arg[2] = "" + target;
   arg[3] = "" + speed;
   arg[4] = "" + device;
   //println(arg);
   exec(arg);
}

void onTickEvent(int timerId, long timeLeftUntilFinish) {
 timerCallbackInfo = "[timerId:" + timerId + "] tick - timeLeft:" + timeLeftUntilFinish;
 println(timerCallbackInfo);

 for (int i=0; i< 15; i++)
 {
  servo(i,(int)(radvals[i]),0,0);
  delay(100);
 }
}



void drawsensor(int x, int y, float rad, int id,double value)
{



 int inc = 25;
 int count = floor(rad/inc);
 int minrad = 25;
 if (value == 703)
 {
   fill(255,0,0);
   ellipse(x ,y, minrad / 2, minrad / 2);
   return;
 }
   else
   {

     int valueint = (int) (value);
    float colorval = constrain(valueint,100,255);
   fill(60,60,colorval);
   ellipse(x ,y, minrad / 2, minrad / 2);
 }


 for(int i=0;i<count;i++)
 {
 stroke(0);
 strokeWeight(1);
 noFill();
 float alpha = 255- (float(i) / float(count) * 100);
// fill(0,0,255,alpha);
 ellipse(x ,y, minrad + (i * inc), minrad + (i * inc));
 }
```

Appendix 4: Arduino code for the light sensors using MUX circuit's board.

A3. Published Samples

1.Paper submitted in International Conference, ACADIA 2014



Using Physical Models in Design to Evaluate the Acclimatization of Kinetic Facades for Daylight and Thermal Performance

Abstract. Successfully simulating building performance is a challenging task requiring the art of selection: the right type of virtual experiments with the right models and tools (Leighton, 2010). Recent Computer-Aided Design (CAD) and Engineering tools allow architects and engineers to simulate different aspects of building performance such as thermal heat and lighting (Fernandez, 2012). This process includes evaluation of the dynamic behaviors of kinetic façade systems. Although façades have historically been static systems, they are nevertheless designed to respond to many different scenarios. Often, façades need to perform contradictory functions such as; allowing solar heat and light to enter the interior space as much as possible whilst regulating the glare and heat at certain periods. In evaluating the active mechanism and responsive elements of kinetic facade systems, it is necessary to simulate the performance and kinetic behaviors using physical models. This paper presents a new way to design kinetic facades through evaluating their performance.

Keywords. Kinetic facades; simulation; performance-based design; daylight; thermal performance

Acclimated kinetic facades

Architectural design has always involved a culture of simulation and experiments. In the 15th century, Filippo Brunelleschi, invented perspective drawings to simulate the visual perception of space. In eighteenth century France, Pierre Patte graphically mapped the propagation of sound in buildings (Yanni, 2012). A nineteenth-century the Catalan architect Antoni Gaudi, adopted a method called graphic statics to draw structural forces. For many centuries, geometry was the medium of simulation. By the 20th century, numerical methods overtook graphical means in all these domains: lighting, acoustics and structures (Yanni, 2012).

Acclimated kinetic facades are designed to improve the quality of indoor spaces in buildings through active techniques. Although it is not a newly discovered concept, it has not been widely applied to date. This research on acclimated kinetic facades focuses on shading devices or active brise-soleil that is responsive to changing environmental conditions.

Kinetic facades system had received considerable attention for its concept. However, proposals on how this facade should be designed and analysed to ensure its functionality and performance are still research in progress. The proliferation of sensors and instrumentation technology enable kinetic facades to be evaluated differently. The use of digital simulations and physical models to predict the performance of kinetic facades often produces different results. In designing kinetic facades with multiple parameters, the use of design simulation to visualize achievable construction is complicated by the kinetic requirements (Moloney, 2007). The degree and speed of translations and rotations in the physical world are constrained by both the geometry of the components and the mechanics of the kinetic systems.

Historically, practitioners have developed a variety of tools and techniques for sharing the imagination and even the experience of buildings before they are built. In their simplest form, design simulations can be in the forms of personal thought experiments and mental images (Yanni, 2012). Effective simulation tools for dynamic

design or kinetic façade need to be conducted in the early design phase. This will help the designers to make predictions of the performance of the kinetic systems and assist broader knowledge in decision-making.

In designing kinetic facades which deal with the large-scale transformation of human environment: plan, sections, models, diagrams and other possible design medium, physical simulations are part of the evolving tool-kit that practitioners use to establish a site in which design can be tested before construction. The physical simulations exist between conception and construction, and also between professional groups. However physical simulation can be different for different groups: tools for exploration, verification, reflection or simply communication.

This paper will describe an attempt to perform physical simulation for evaluating the daylight and thermal heat performance for the kinetic facades in the early design phase. In addition, it will describe further what can be gained through physical simulations and the challenges in adopting this type of investigation.

Why physical simulations?

Why do kinetic facades need to use physical simulations to evaluate the environmental performance? Is physical simulation is just another name for physical testing? The short answer is no and they are not similar. While all physical simulation involves physical testing, the key difference is that physical simulation attempts to replicate real-worlds process on a laboratory scale in a way that the data can be used to solve real world problems (Linda, 2002). For example, it is fairly easy to heat the facade surface to nominally uniform temperatures in a furnace, then measure the deformation at a given temperature. This is physical test and when performed properly, it should yield reproducible results.

However, if the architect's goal is to understand the mechanism, microstructure and material behavior on the kinetic facades system, then more information is required. Anyone who has ever observed steel being rolled for an example, will notice that the edges of the surface are darker than the middle of the surface, and the corners, where the edges meet, is darker still (Giuseppina and Maurizio 2013). That is because the edges and corners of the steel surface cool faster than its main body. As a result, the surface is not at a uniform temperature; instead, there are thermal gradients between warmer and cooler portions of the surface. This is an example of the steel being used as a frame or surface for the kinetic facades system. The folding motion may be affected by this kind of phenomenon. Thermal gradients are present in every heating and cooling process and are part of almost every metal fabrication process. Research has clearly shown that thermal gradients affect ductility and workability of material especially in application to kinetic facades system (Giuseppina and Maurizio 2013). Therefore, the architects will have to physically simulate these thermal gradients (and other factors as well) in order to gather meaningful information in the laboratory that can later be applied successfully to the design of kinetic facades.

Frequently, physical simulations must be performed in a series of steps, for example: one test to simulate the opening and closing behavior, another to replicate part of the edge, another to replicate a portion further in. The data can then be linked together to form an accurate predictive model that can be used to set the operating parameters for design of kinetic facades.

Methodology

In this paper, the experiments are set up and investigated in two different strategies. The first part of investigation is aimed to explore the designing of kinetic facades prototypes. The second is to understand and to replicate the real world boundary conditions as much as possible. In this experiment, the time to setup the simulation is considered during the early stage. In this stage, effective decision-making is crucial, as it will affect the design and performance of kinetic facade.

The first strategy is to define the location of the testing. The environmental conditions are defined and the simulations are for these specific conditions. In this investigation, the location proposed was in Melbourne, Australia. Further elaborations of the environmental condition are detailed in the physical simulation setup. The prototypes are designed and improved a couple of times based on the simulation feedbacks.

Experiment setup: Testing under real boundary conditions

Physical models are design tools commonly used in the architectural creative process and reflect most of the aspects of daylight design (figure 1). They play an important role for decision-making throughout the different project development stages from schematic design to architectural project presentation. Architects also use scale models to evaluate the lighting environment within buildings (Schiler, 1987). Scale models are among the primary design tools used for daylight systems before their integration into a real building (Chauvel et al., 1985). Virtual models have recently become a universal design tool for architects and environmental researchers (Scartezzini et al., 1994c and International Energy Agency, 1999); many validations of daylighting simulation programs have been carried out (Love and Navvab, 1991, Fontoynont et al., 1999,Mardaljevic, 1999 and Maamari and Fontoynont, 2003). Daylighting researchers usually require detailed scale and virtual models for the assessment of daylight performance.

Figure 1. Examples of physical simulation to evaluate facades performance. Testing real boundary condition (left) and using artificial light to study the daylight on scale model (Anothai, 2009)

Prior to kinetic facade prototyping and fabrication, the prototypes have been tested through digital model simulation using integrated software of Grasshopper, Ecotect and Galapagos to configure appropriate geometry and pattern for the kinetic facades that can effectively control the daylight during the day throughout the year (Sharaidin, 2012). The results from the simulations are further tested and evaluated using physical models.

Figure 2. Trade off diagrams between daylight, glare and transparency

Daylight, glare and visual transparency are the main parameters that are considered in this simulation (figure2). The triangulated parameters are negotiated to be implemented in response to daylight performance. The integration of computational tools and techniques such as parametric design, real-time simulation with environmental information mapping, using sensing and actuating systems with inbuilt control systems helps to evaluate the kinetic facades performance. Manufacturing physical models has created a strong background to understand kinetic facades design. Further explorations from this simulation are explored using physical models behaviour.

Physical prototype

Physical models are common design tools used in the architectural creative process and reflect most aspects of the daylight design. They play an important role for decision making throughout different project development stages from schematic design to architectural project. A scale model was carefully constructed in the course of this study in order to simulate the daylight environment and properties of the test module. The model was constructed using *mdf* boards, *polypropylene* as the main surface and nuts and bolts used to join. The facades elements were fixed using screw and glue; to avoid parasitic light the joints were sealed with black tape. The surfaces for the facades are designed to be perforated to introduce transparency. The facades are designed to create a concave and convex surface when closed. This strategy might help to trap heat under winter conditions. The color of the surface is tested using white and black, however in this simulation reflective black surfaces of *polypropylene* are used which can reflect heat and absorb heat at the same time. This strategy may be beneficial during winter and summer conditions.

The facades are adjustable and tested in three different states. The behavior of the opening and closing of the facades is based on the sliding motion. Several types of motions have been tested in previous experiments. Based on the observations and experiences of the writer in previous experiments (Sharaidin, 2010), sliding motion has been selected to be tested further, due to the simplicity of the system, which performs well with the intended mechanism of the facades.

Daylight simulation setup

The setup of the experiment includes five halogen lamps with 500W electrical power in a planar arrangement. For special application, the lamp can be rotated in different angles. These particular experiments are conducted for two different states involving 75 degree angle in summer, and 29 degree angle in winter. Different angles are setup one at a time to measure the effect of the kinetic facade in each case. The halogen lamps are positioned 1.5meter from the facades and the experimental box and this is to ensure the facades get optimal light distribution using the five halogen lamps. In this simulation, dimmers are used to control the light level. The three light sensors are embedded in the 500mm x 500mm x 1000mm box to determine the opening and closing of the facades system (figure 3). The sensors were attached to the actuators using Arduino, which allows the sensors to determine the façade's behavior. In this simulation, thermal heat spring, smart memory spring (SMA) is used as the actuator. These materials have been of interest in numerous research projects on kinetic facades systems and the application is still at an experimental stage. This actuator could also potentially be substituted by ordinary mechanical actuators for example motors and gears. In this simulation the SMA spring was located at the end of a scissor structure on top of the facades. The SMA springs were attached to the 12V battery to heat the actuator when the light sensor sent the output via Arduino to the actuator to create compressive behavior. When the light was turned on, the SMA would go back to the original state, which created the closing behavior for the facades. Four actuators were used in this experiment to control different modes of opening depending on the light level (Lux) in the box. The facades can be programmed in different states of opening during the simulation.

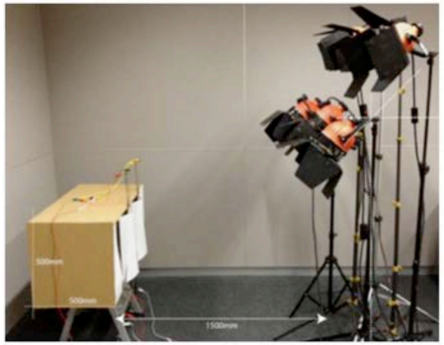


Figure 3. Daylight simulation setup

The main objective of this simulation is to test and to observe the behavior of the kinetic facade system (figure 4). This is to see the effectiveness of the mechanism in responding to the daylight performance and in controlling the light in the space. During this investigation, certain problems are made visible to the designer to understand how the system works and what needs to be improved.

Figure 4. Dimmer and three light sensors are integrated in the simulation to control the facades opening and closing behavior

The daylight and kinetic performance of the facades are clearly shown during physical simulation of the kinetic facades systems. By comparison mechanical problems are hardly visible at early design stage in digital simulations. Hence, the importance of the process of conducting a physical experiment to understand, evaluate the environmental performance and develop the design of the kinetic facades.

During this simulation, problems of friction of the mechanism are being identified that suggest design improvements during this stage. Improving the mechanism of the system might also affect the environmental performance of the facades system.

Thermal heat simulation setup

A simulation model is a virtual image of real physical phenomena and simplification of reality is an inherent feature of models. In other words, a building has to be simplified in a suitable way in order to obtain a simulation model. In the case of a large building with many similar rooms, for example, representation can be made via selection of small number of rooms. An examination regarding the possible overheating of a large building requires analysis of the internal and external heat gains of the different rooms to identify those that are potentially critical. These are selected for modeling and appropriate boundary conditions defined. In this simulation the boundary conditions are simplified to understand how the heat behave in this specific area and surface.

Similar investigations are conducted in the thermal heat simulation. This experiment is part of experimentation setup during the Thermal Reticulations cluster workshop in SmartGeometry 2013. The cluster investigated heat transfer phenomena from one point to another on the building facades. The simulation is conducted to inform the designers of the performance of kinetic facades design in the early design stage.

The experimental environment for thermal heat simulation was reduced to 300mm x 300mm x 400mm box. This strategy also helps to reduce the complexity of the simulation setup and the number of pieces of equipment involved. The setup applies two different strategies. The first of the boxes is integrated with infrared imaging cameras located at the back of the box and in front of the box. This setup is to see how heat transfers from one surface to another. A second box was set up using 27 thermal sensors (as shown in Figure 5) located as a grid inside the box to visualize how the heat transfers into the space and how well the facades perform in regulating the thermal behavior of the space (figure 5)


Figure 5. Setup for thermal heat simulation using heat sensors and thermal imaging camera

The sample façade systems installed on the first box were analyzed and evaluated based on how the heat was transferred across the surface into the interior space. This simulation is conducted using two thermal heat infrared cameras to see how the heat transfers from one surface to another. In this simulation, folded perforated kinetic façades are tested to see how well the façade performs in protecting the space from the artificial heat (figure 6). A halogen lamp is used as a heat source for this simulation. The halogen lamp is positioned at a 90-degree angle to get a uniform distribution of heat on the surface. The halogen lamp was turned on for 15 minutes in every simulation. The images from the thermal camera were captured every 200 seconds to see the heat behavior changes on the surface of the facades. The images were recorded from in front (figure 7) and inside the box (figure 8).

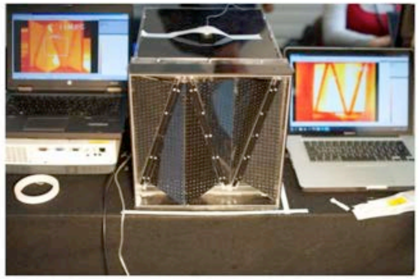


Figure 6. Thermal heat infrared camera is located in front and inside the box

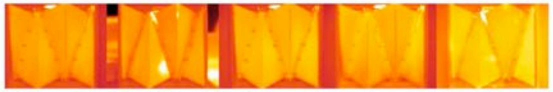


Figure 7. Images of thermal heat infrared camera from the front


Figure 8. Images of thermal hear infrared camera from inside the box

Early observations show that the edge of the surface of the façade gets heated up very quickly and the folded facades are not creating a uniform surface heat response. In the second simulation, the folded kinetic façade was tested to analyze its effectiveness in responding to the external heat and protect the space. Three states of facade conditions were tested in this simulation (figure 9).

Two moveable facades were installed as adjustable louvers in this simulation to create closing and opening behavior. As this simulation is an early attempt to simulate kinetic facade performance using heat sensors, the interactive system are not integrated with the facade behavior and the output from the sensors. There will be further investigation of the interactive systems.

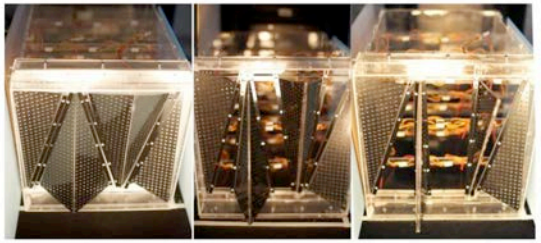


Figure 9. Three different facades condition are tested during this simulation.

The behaviors of the façade toward the thermal heat are visualized through *Matlab* software (figure10). The flux of the data from the 27 sensors, which were located in a grid, were observed and monitored through this visualization. During the early observation, we can see the convection of hot air was transferred towards the back of the box very quickly. After the facades were fully opened, the facades were then quickly closed to measure how long the facade can store heat. These exercises are effective to visualize the façade performance, enables many design and test iterations in a short period of time to improve the façade performance.

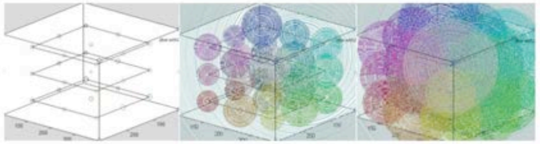


Figure 10. The heat sensors are visualized through Matlab software. From the left the façade are from closed to total open

The simulation setup can be improved in terms of accuracy as some additional parameters can be taken into further consideration. For example, the temperatures inside and after the simulation can be measured and setup as a constant mode. Cooler spray can be used to lower the temperature inside the box in order to get the optimum result. In these experiments, the surrounding temperature outside the box might be effecting the measurement of the simulation, conducting this simulation in thermal chamber will be more effective in maintaining a constant external boundary conditions and produce more accurate results.

Conclusion

In conclusion, physical simulation is a significant method to evaluate the kinetic facade performance in the early design phase. The outputs from the physical simulation in the early design stage are very intuitive for designers to understand the facades behavior and performance in response to the daylight conditions. The attempts to conduct physical simulation are quite successful in terms of evaluating the facades performance in early design phase, as the physical simulation could highlight potential design issues, which may not be visible otherwise.

However, in term of accuracy and technical setup, this simulation can be improved by considering certain aspects in detail, such as surrounding temperature, material properties used for the façade, insulation of the box and thermal sensor sensitivity.

Conducting the physical simulation for the kinetic facades provides more understanding on the performance and behavior of kinetic façade design and assists the architect to make a decision at the early design phase when designing kinetic facades to respond to environmental conditions.

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Integration of Digital Simulation Tools With Parametric Designs to Evaluate Kinetic Façades for Daylight Performance

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Abstract. *This research presents a solution for evaluation of kinetic façades system performance via experiences and lessons learnt from experiments. We bridge between architects and engineers to address limitations associated with incorporating performance criteria in the design of kinetic façades by integrating different simulation tools. The experiments focus on optimization of the daylight performance through the design and motion of kinetic façades using various integrated software. The research is developed using real time data feedback processed through various digital tools from three domains: (1) Architectural design, (2) day-lighting performance and (3) parametric design computation. From the evaluations, the paper demonstrates the analysis of kinetic motion for daylight optimization at the early design stage and suggests possible configurations for daylight performance.*

Keywords. *Kinetic façades; digital simulations; design considerations; early design stage.*

BACKGROUND

Successful simulation of building performance is a challenging task and has been phrased as the art of performing the right type of virtual experiment with the right model and tool (Augenbroe, 2010). Recent computer-aided design and engineering (CAD) tools allow architects and engineers to simulate many different aspects of building performance such as energy and lighting (Leighton, 2010). This process includes evaluation of kinetic façades system, which involve dynamic behaviour. Although façades have historically been static systems, they are nevertheless designed to respond to many different scenarios. Often, façades are needed to perform functions that are contradictory to each other in order to control the indoor environment. For instance, they are used to allow solar heat to enter as much as possible, whilst keeping out the glare and heat at certain periods of time, protecting the building and allowing the building occupant to have a visual connection with the outside environment. They balance different functions throughout the life of the building.

By actuating the façades and making them more dynamically responsive to the environment, they can now better adapt to the different conditions and improve occupant comfort by providing a higher level of building performance. Dynamic actuation reduces the compromises needed in the design of the trade-off process to balance daylight in the space. Hence, one of the minor scopes of this research is to explore the evaluation of this idea using computer simulation and empirical testing of selected kinetic motions that can be adapted for

Figure 1
Traditional simulation method (left) and dynamic performance method.

environmental benefits. These can be compared to each other and recommendations can be proposed from the outcomes.

DESIGN PROBLEM

The problem with existing environmental simulation tools is that they were designed for static building elements. For example, material properties such as thermal conductivity, solar factors or daylight transmission are assumed as a constant in these tools, not a variable. Traditional simulation tools are based on static design, primarily suggesting solutions for peak load estimates. However, in evaluating dynamic building performance, kinetic systems must be analysed under a range of diverse conditions for proper system sizing. (Selkowitz, 2003). Figure 1 shows the differences between traditional façade design and kinetic façade design. The evaluation process for kinetic façades has integrated a few variables, which are simulated together in real-time.

The most promising tools for the simulation at present is called Control Virtual Test Bed, an open source software platform that integrates several building energy and control tools such as *Energy plus, TRNSYS, ESP-r, Radiance, Modelica, Fluent, MATLAB, Eco-Tect* and others. Some of the environmental tools are tested and presented in this paper.

It remains of paramount importance to develop adequate building performance simulation tools as there is a great demand for effective tools and instruments that can be used in the design process of kinetic façades (Loonel, 2010). Some evaluations and observations will be recorded in this paper. The simulation process will allow us to choose the right design among several options; to understand how kinetic façade systems work in relation to the whole building; to explore design possibilities and variations; to identify constraints; to build consensus with other specialists; and to predict the final performance in the early design stage (Fernandaz, 2012). These computational simulation tools are still largely unexplored. This is one of the reasons why responsive building envelopes are not yet a mainstream concept in the building industry.

SIMULATION OBJECTIVE

Simulation projects usually originate from the queries about real world systems evaluation, which in this case is kinetic façade concept design. This is to give some ideas on the performance of kinetic façades in responding to the environment. In this process, before the performance of these objects can be predicted, the systems first need to be translated into conceptual models. A conceptual model is defined as “a non-software specific description of a computer simulation model, describing the objective, inputs, output, content, assumptions and simplification of the model” (Robinson, 2008). Modelling and simulation by definition implies ‘approximation’, introduced in the abstraction process by means of assumptions. Assumptions are ways of incorporating uncertainties and beliefs about the real world into the model (Robinson, 2008). In this way, it deals with randomness and unknowns about the system, conditioning these trials to obtain reliable outcomes. It should be noted here that it is not a model itself, but the model of the model’s results should be close to reality (Leighton, 2000). For this reason conceptual kinetic façades models are presented in critical evaluation with the right level of detail relationships to predict actual behaviour with sufficient accuracy for the early design stage. This result suggests a possible design process for kinetic façades.

However, designers are often unable to leverage simulation tools during the design process due to the difficulties of setting up. Effective simulation tools must be set up to complete a design cycle involving accurate analysis by integrating different variables and running in real time. One of the issues is difficulties in evaluating different variables together in real time interactions. This is important due to the fact that (i) unexpected events can take place, (ii) decisions have to be made in real-time, and (iii) future conditions are highly uncertain which make the control process even more complex. This requires thoughtful control strategies, which take all the interrelated aspects above into account. When one succeeds, it perhaps leads to an elegant conceptual idea for both energy and occupant comfort that the designer can use at the early design stage.

Kinetic façades are inherently complex systems, consisting of interrelated components that are working across various physical domains. All components have to deal with trade-offs and resolve conflictive performance objectives in real-time. For these reasons, traditional design methods are likely deemed inappropriate and it will no longer be effective to rely on past experiences or rules of thumb. In order to obtain adequate kinetic façades design, all the functional requirements need to be considered and satisfied simultaneously. As the requirements are strongly interrelated and sometimes even conflicting, this is not always a simple task (Rivard et al., 1995).

Moreover, another advantage of conducting this simulation is that the software tools create virtual building models which can be used to predict building performance for the following purposes: choose correctly, understand why, explore possibilities, diagnose problems, identify constraints, develop understanding, build consensus, etc (Sokolowski and Banks, 2009).

This paper presents an algorithmic and parametric design process developed in *Rhino/Grasshopper, Galapagos* as form finding tools and *Ecotect* as a daylighting simulation tool. These tools are selected based on the possibilities for integrating them together to run at the same time to get real time feedback. The main objective of the process and algorithm is to evaluate the performance of kinetic façades in integrating different motions and to compose a series of kinetic louvers that actuate in response to dynamic daylighting. Within the framework of this study, Grasshopper as a parametric computational tool allows the integration into a single process of Rhino/Grasshoper as the design space modeller, *Ecotect*, as the dynamic day-lighting tool, and *Galapagos* as the solver. The parametric tool extracts designed geometry from the modelling space and sends the inputs into the Ecotect component to be tested for luminous distribution and daylight penetration depth inside a space. In this process, Galapagos is given a few different variables, for example, maximum size and pattern of geometry. These variables will undergo a process of interrogating fitness where the trade-off between these two variables will be calculated in a loop process in finding an optimal solution. This allows the designer to run numerous iterations during the design stage and select the best possible based on pre-determined criteria.

ENVIRONMENTAL CONDITION AS FIRST LEVEL DESIGN ASSUMPTION

The research presents a methodology and develops tools that focus on performance-based design integration to address designs, simulations and motions of kinetic façades and analysis of the impact on daylight performance to produce intelligent configurations. The research situates itself in the field of kinetic façades and adds to existing solutions a validation of the performance of kinetic façades systems with interdependent louvers of varying tilt angle, with different configurations. It provides a digital evaluation of kinetic façades' response to dynamic lighting conditions. Within the scope of this framework, Grasshopper, Rhino, Galapagos and Ecotect are linked and programmed into one integrated process, facilitating design options to get real time feedback. The paper will conclude with a description of the extensibility of the tools, the future incorporation of physical system interaction and complexity in combination with the digital. The main objective of this study is to investigate:

1. what the effective way of using digital simulations for kinetic façades is as an early predictor of the performance of the façades.

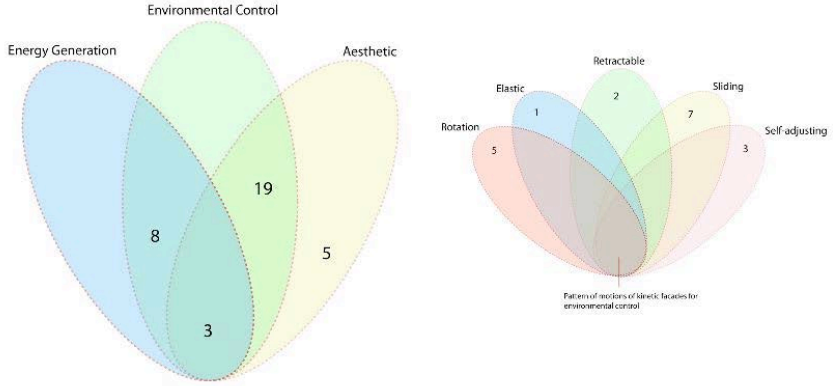

Figure 2
Function of existing kinetic motions (left) and type of existing of kinetic motions: the numbers indicate the numbers of case studies in each category.

2. What the available options and possibilities to improve the performance of kinetic façade designs are using digital simulations at the early design stage.

This study focuses on the climatic and geographical conditions in Melbourne, Australia located at 37.8075°S 144.9700°E, with a monthly av. max. temperature of 26.7 degree Celsius in the hottest month and monthly av. min. temperature of 5.7°C the lowest. The critical surface of north- west façades of the building will be evaluated in this paper. This side of the building is critical due to direct solar radiation which has max. angle of altitude of 75° in summer and 29°at winter solstice. In this paper, numbers of kinetic motions that have potential for environmental control have been identified and tested in this simulation process. Within the design component presented here, three different development stages can be defined, of which the first has already been finalized. The first stage implied a study of the state of the art in kinetic façade design and further definition of the design problem. It involved a wide literature review and analysis of various kinetic façade motions, placing emphasis on solutions of a local nature that respond to local climatic conditions. This process is further developed into case studies which are conducted to identify different kinetic façades patterns or motions which were adapted in the existing buildings around the world specifically in respond to the environmental control. Figure 2 represents existing kinetic façades' function and kinetic

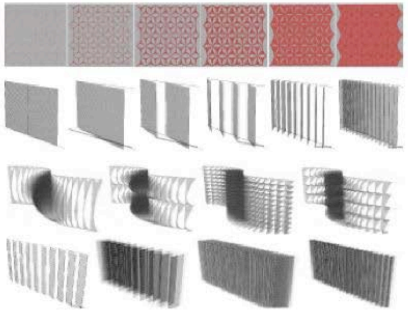

Figure 3
Parametric model of different type of motions.

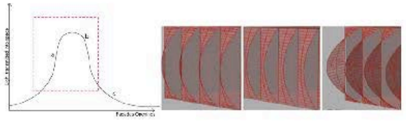

Figure 4
Problem that can be avoided using this simulation in the early design stage: a =, b =, c =

façades' motions in existing buildings for environmental control.

Four out of five kinetic motions are identified for this study: rotation, elastic, retractable, self-adjusting and sliding as show in Figure 2.

The kinetic motion selections are based on the pattern of geometry, kinetic surface behaviour, and the size of the surface. These elements are important to consider in order to obtain accurate results in this analysis to avoid a phenomenon shown in Figure 4. The oversize surface when it is retracted to open and close will overshadow another opening and prevent solar radiation from penetrating the space. The red section in Figure 4 suggests the possibility of optimal size openings for this type of motion. Further evaluation of kinetic motion will be presented using this process.

SIMULATION STRATEGY

The simulation investigates the possibilities of integrating different variables into designing the kinetic system. Evaluating the kinetic geometry and surface in this research is important as they play a vital role in kinetic façade systems' operation. These parameters will affect the behaviour of the kinetics and determine how they respond to daylight during the simulation. In this simulation, appropriate candidate tools met four requirements: 1) kinetic features are present in the conceptual model, 2) the desired performance outcome is at an appropriate level of detail, 3) the way adaptive behaviour is controlled is …, and 4) supports physical kinetic interactions.

The variables are simulated in real time using Melbourne weather data for part of the year. The simulation processes were developed by design-

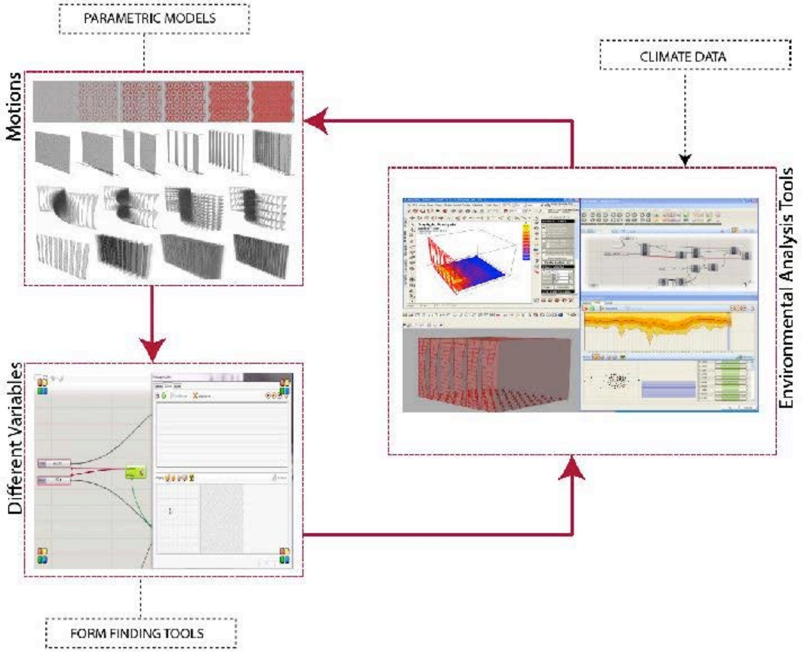

Figure 5
Simulation process.

ing the façade motions which were embedded with 5000mm x 5000mmmm x 3500mm cubic spaces. The real time weather data of Melbourne solar radiation from 21 June to 21 December 2011 were integrated with *Ecotect*. *Galapagos*, integrated with *Ecotect* and *Grasshopper* and used in this simulation to identify the optimal opening and closing patterns of kinetic façades for this period. This design tool adds possible solutions to the current performance-based technology by making a particular contribution to the field of integrated energy performance in the early design phase. The outcome includes finding the best possible skin configuration for better daylighting performance throughout the year.

Based on previous studies, this research further defined the variables field for five types of kinetic motion where patterns of motion and movements were influenced by the geometrical configurations. The design parameters were integrated into three groups i.e. first group responding to general conditions, second group to the structure and surface and third group to defining the potential behaviour of kinetic façades.

Through these simulations, the optimal pattern, size of surface and form of kinetic façades were also identified. Figure 5 explains the process of these simulations to find the optimal configuration of kinetic façades.

The variables were represented by sliders with set minimum and maximum values depending on designers' requirements. The proposed design tool is extensible; it is open to accepting additional parameters and variables, which makes it more complex but with better performance assessment.

The main objective of using *Galapagos* in this study as an algorithmic process is to evaluate the performance of an intelligent façade, which is composed of a series of kinetic louvers that are actuated in response to dynamic daylighting, and incorporates occupants' preferences. It creates an evolutionary generic loop that populates generations of possible solutions with random individuals based on the predefined criteria. The system couples similar possible solutions together and then finds a best '*fit*' solution, which may end up being a locally optimal solution in some cases. *Galapagos* is used in this study to find the best possible tilt angles of the louvers' configuration for certain times of the day. However, *Galapagos* is run using a pre-defined set of parameters, leaving only the calculation for this tool. A genetic algorithm has been incorporated into the definition to enable a search for the best skin configuration at specific dates and times or under different sky conditions. The genetic algorithm works by finding an optimal - although not necessarily the best - solution under certain parameters and conditions. These parameters could range from users desired illumination levels, to externally reflected daylighting components. Changes in any of these parameters trigger the system to run and find an optimal configuration for the skin to maintain the desired luminous environment. It creates an evolutionary loop that populates generations of possible solutions with random individuals based on the previously defined criteria

Through the entire process, the material assigned for the external louvers is high reflectance (90%) in this set up. The parametric tool extracts the designed geometry from the modelling space and inputs it into the *Ecotect* component to be tested for illumination performance, luminous distribution, and daylight penetration depth inside an office space. This allows the designer to run numerous iterations during the design process at early stage and select the best possible one based on pre-defined criteria.

In this simulation, there is some behaviour that is not eligible, for example, evaluation of hybrid motion. This would be possible with a more complex simulation configuration. This motion can be classified as combination of two totally different types of motions, for instance, *elastic* and *sliding*, which creates the need for a more integrated simulation process. In this case, the model behaviour is being simplified and requires more rigorous assumptions or less detailed analysis to ensure that it does not violate the utility of the simulation process. The capabilities of the simulation tool for better solutions for more complex cases may be developed in near future. However as this is a cost and time intensive process, the effort to accommodate complex combined motions might not be justifiable in the routine design development stages.

DESIGN GENERATION AND APPLICATION

As a parametric design tool, *Grasshopper* allows the creation of a kinetic system that can respond to multiple inputs (variables) and outputs through genetic algorithm (*Galapogos*). However, in this context of application, intelligence is represented by variables, mathematical functions and benchmarks. This means that the intelligence system is limited, but flexible enough for the system to implement certain desired tasks for better daylighting performance. As *Ecotect* is a *Rhino/ Grasshopper* plugin, it can easily be integrated into the intelligent part of parametric model definition.

From these simulations, numbers of parameters were identified which can be classified into definitions, variables and design categories. The motion and changing position of the surface defined the positioning and pattern relative to the external environment, resulting in higher or lower levels of solar radiation in the space. For instance, the surface pattern was identified for a retractable kinetic motion, which was flat, singly curved or doubly curved as shown in Figure 5.

The designs were analysed in terms of their performance as a climatic barrier. The evaluations have been realised in different types of motions and the highest performing models have been compared and selected with respect to the best environmental outcomes. After a comparative analysis of 23 possible geometries and patterns of kinetic motion, five models representing different kinetic motions were selected. Self-adjusting and elastic motions are suggested for more dynamic material behaviour with integrated dynamic structure. Both motions in Figure 5 show possible geometry that is effective for particular places and micro level behaviours by integrating with dynamic materials. The suggestion of the geometry and surface can be represented by a value in the simulation, which involves size and dynamic behaviour. For these two motions' configuration, it is important to understand the potential materials that can be associated with self-adjusting and elastic behaviour in order to select the right material in *Ecotect*. The suggested configurations as shown in Figure 6 may perhaps give an understanding to the designer of what kinds of geometry can be considered in designing kinetic façades using these types of kinetic motion.

Another three types of kinetic motions, with the potential to be developed into macro scale behaviour, are rotation, retractable and sliding. These motions are categorised in different possible ge-

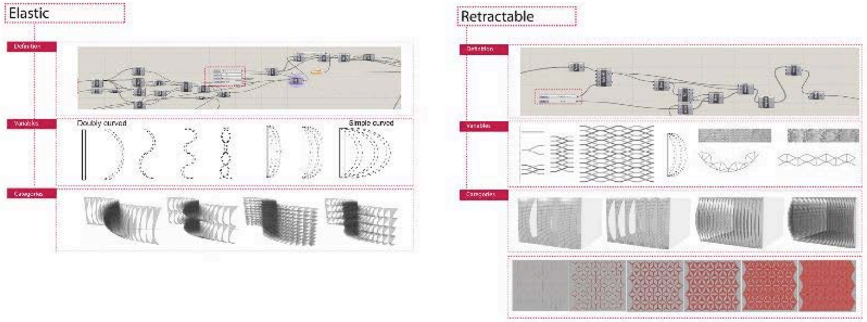

Figure 6
Two type of kinetic motion configuration for dynamic material application.

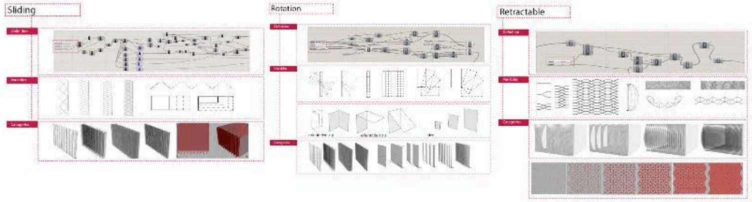

Figure 7
Types of mo
retractable
gested for ki
tions.

ometries in response to daylight conditions and presented in different configurations. The alteration definition is flexible to add different variables, which are represented in sliders. The alteration of the variable will make changes and suggest different configurations of particular motions. For these three types of motion shown in Figure 7, two or more possible variables are integrated in the evaluation. However, different possibilities due to environmental factors, such as wind, can also be integrated, adopting a similar process. These factors may affect the categories of configuration of kinetic pattern. In this particular study, it is suggested to the designer to further evaluate kinetic motions in realising kinetic façades for effective daylight control for the early design stage.

Parametric models are being used to fine tune for the best geometrical attributes to design for a particular case. Further evaluation will be conducted using physical models to know better the possibilities of these motions working as intended.

CONCLUSION

The paper focuses on the integration of parametric design definitions and environmental software, which can assist in the development of kinetic facades' design. The process involved different kinds of constraints, parameters and strategies, which created different options and variables to assist designers to make effective decisions at the early design stage. This is significant as creating digital simulation with different variables simultaneously in real time will surely help to identify and solve the crucial issues at the beginning of the design stages. Moreover, in evaluating kinetic façades in this study, there is already a result that can guide designers towards informed solutions of a problem studied in a wide research context. In addition, the study demonstrated a methodology, which is clearly understood as part of so many other similar examples. It can assist the new construction of kinetic façades to be more efficient in term of digitally driven evaluation

As the ultimate objective is to realise kinetic façades for environmental control, the needs of effective simulation tools are necessary at the early design stage. One of the challenges of an effective simulation tool is not only the ability to evaluate accurately but to speed up and simplify the process used by the tool for such dynamic design evaluation. This is crucial and will affect overall performance of the kinetic façades and design. Further evaluation using physical model analysis will be conducted on selected kinetic motions from this study. This evaluation will be compared and analysed in the context of kinetic performance for environmental control.

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A4. Project Exhibition – UnFOLD (Please visit https://vimeo.com/97520741 to see to video)

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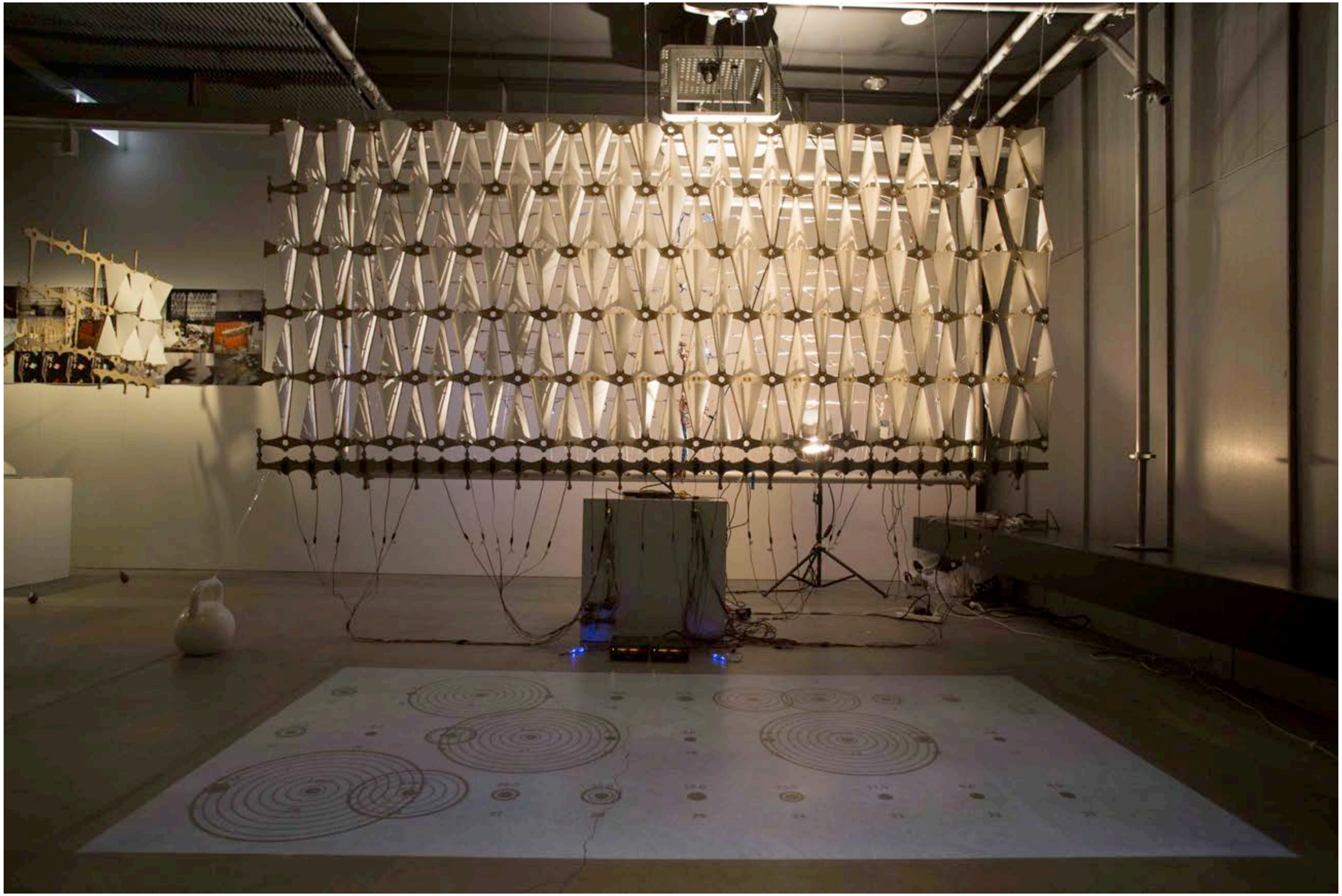
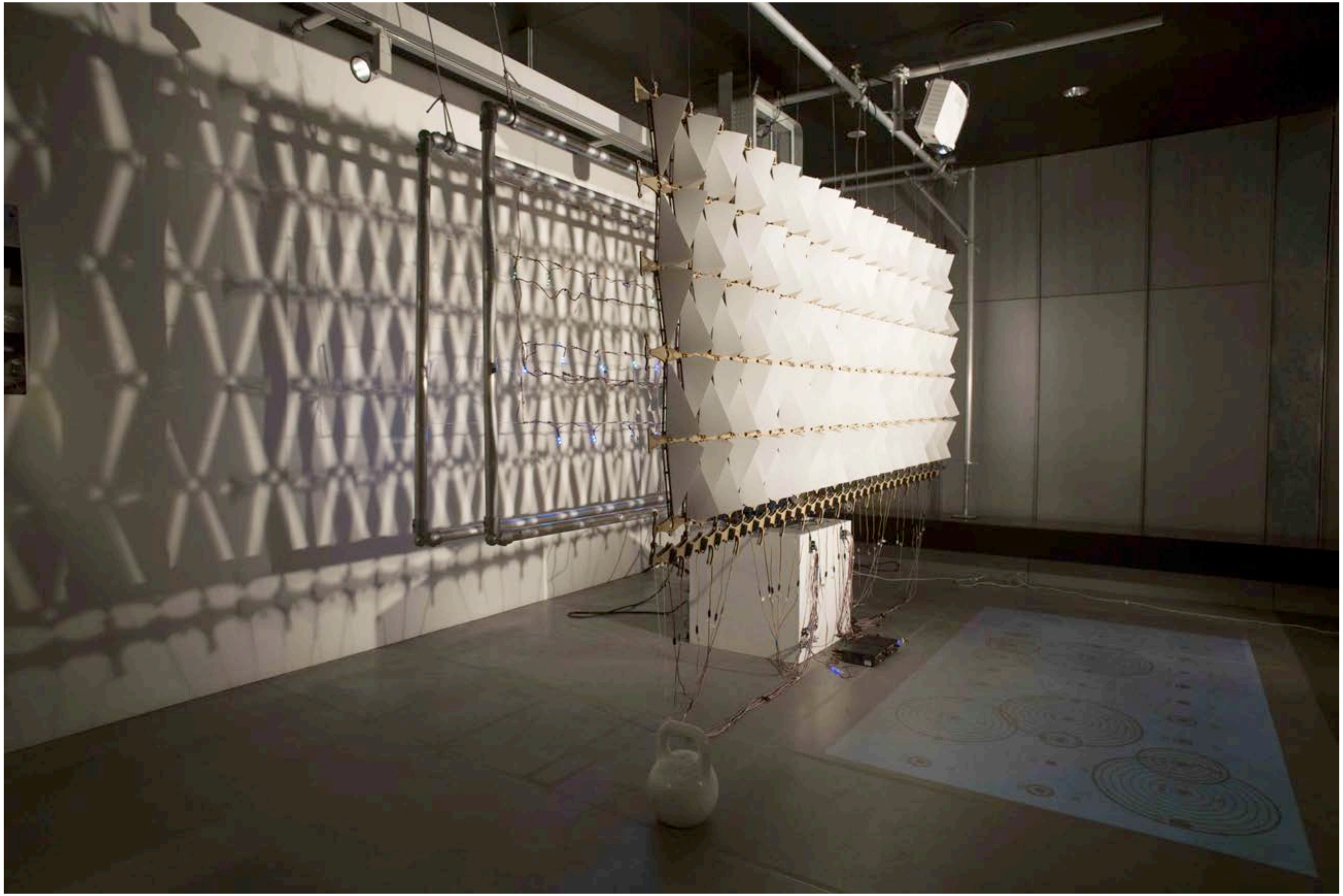
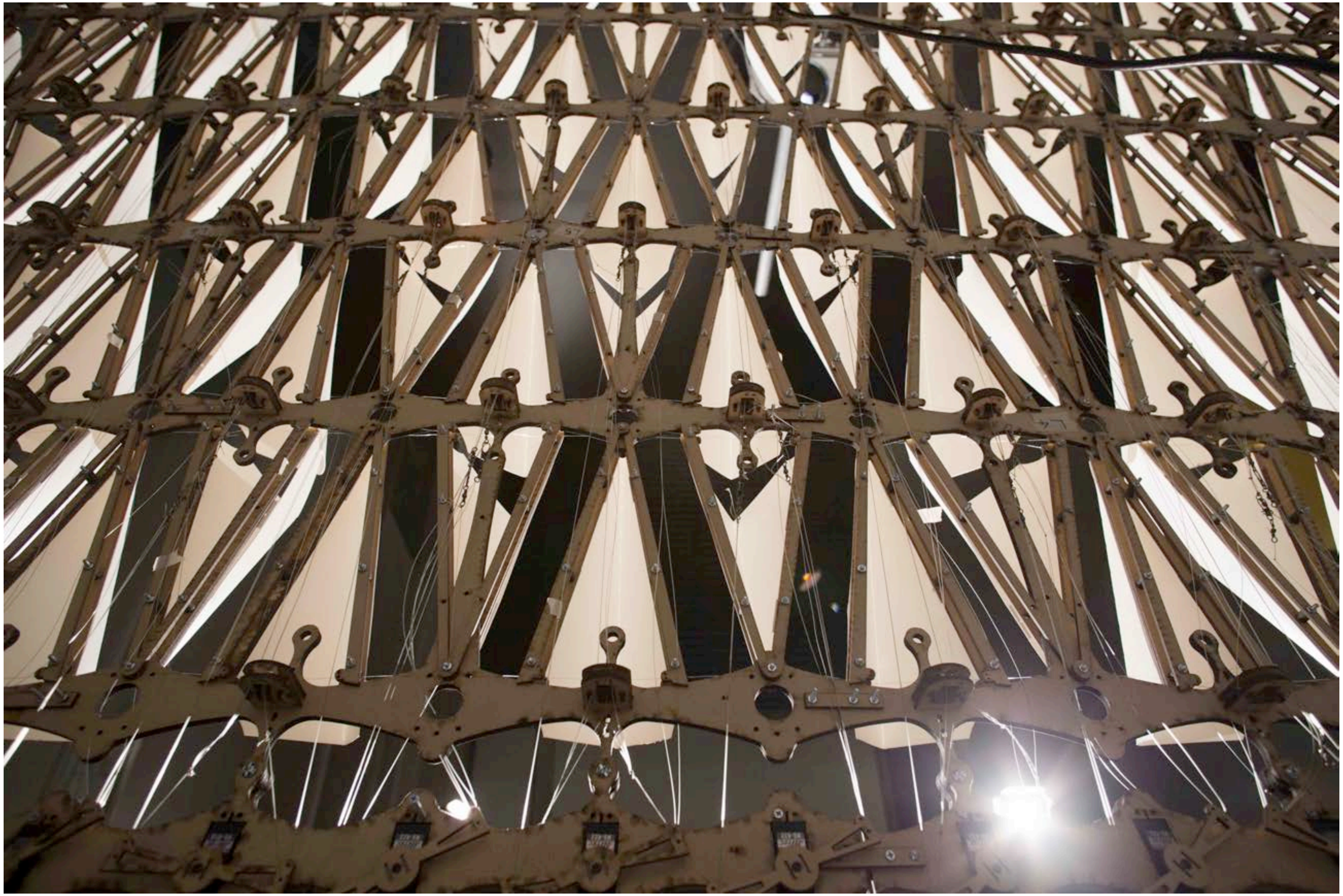
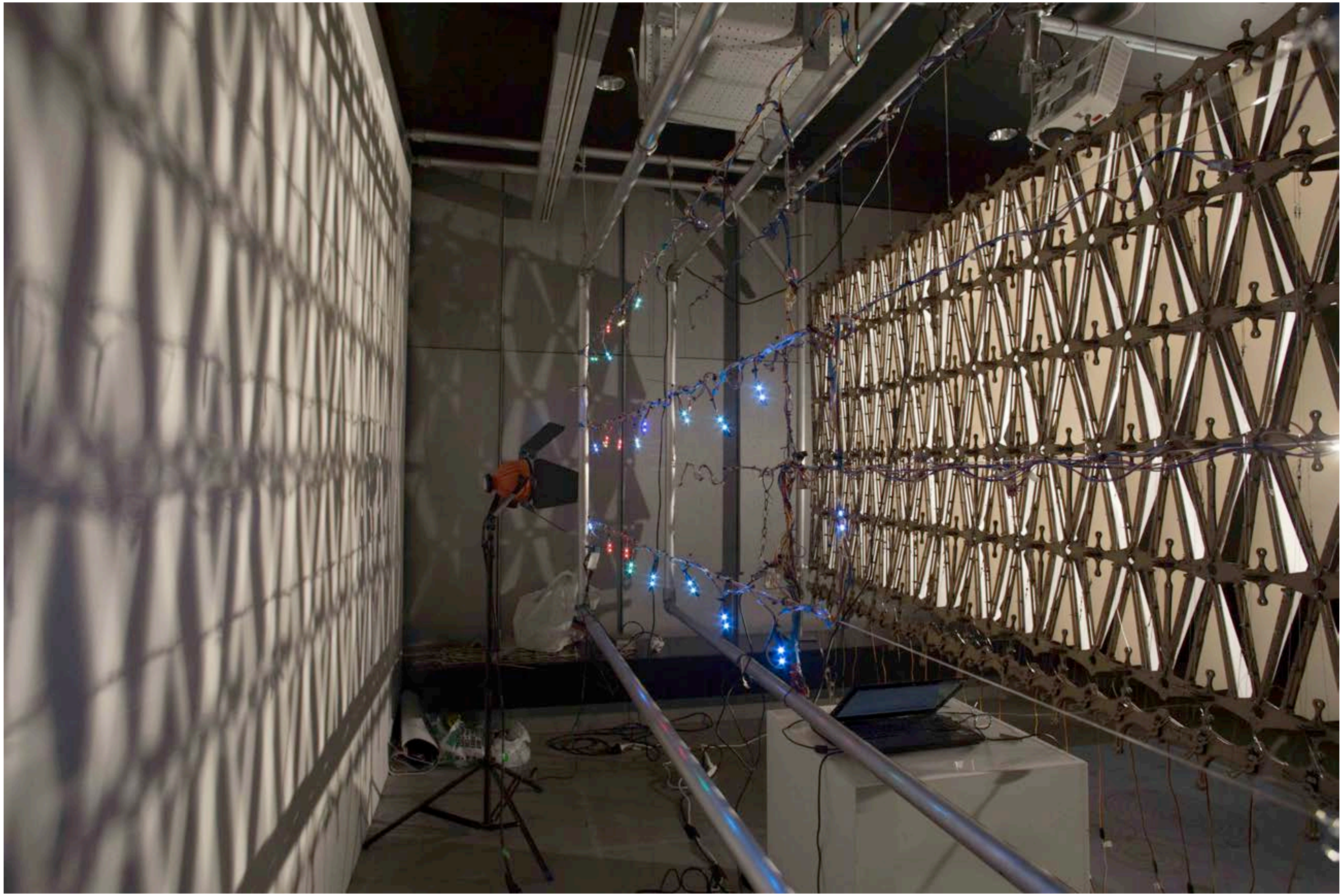
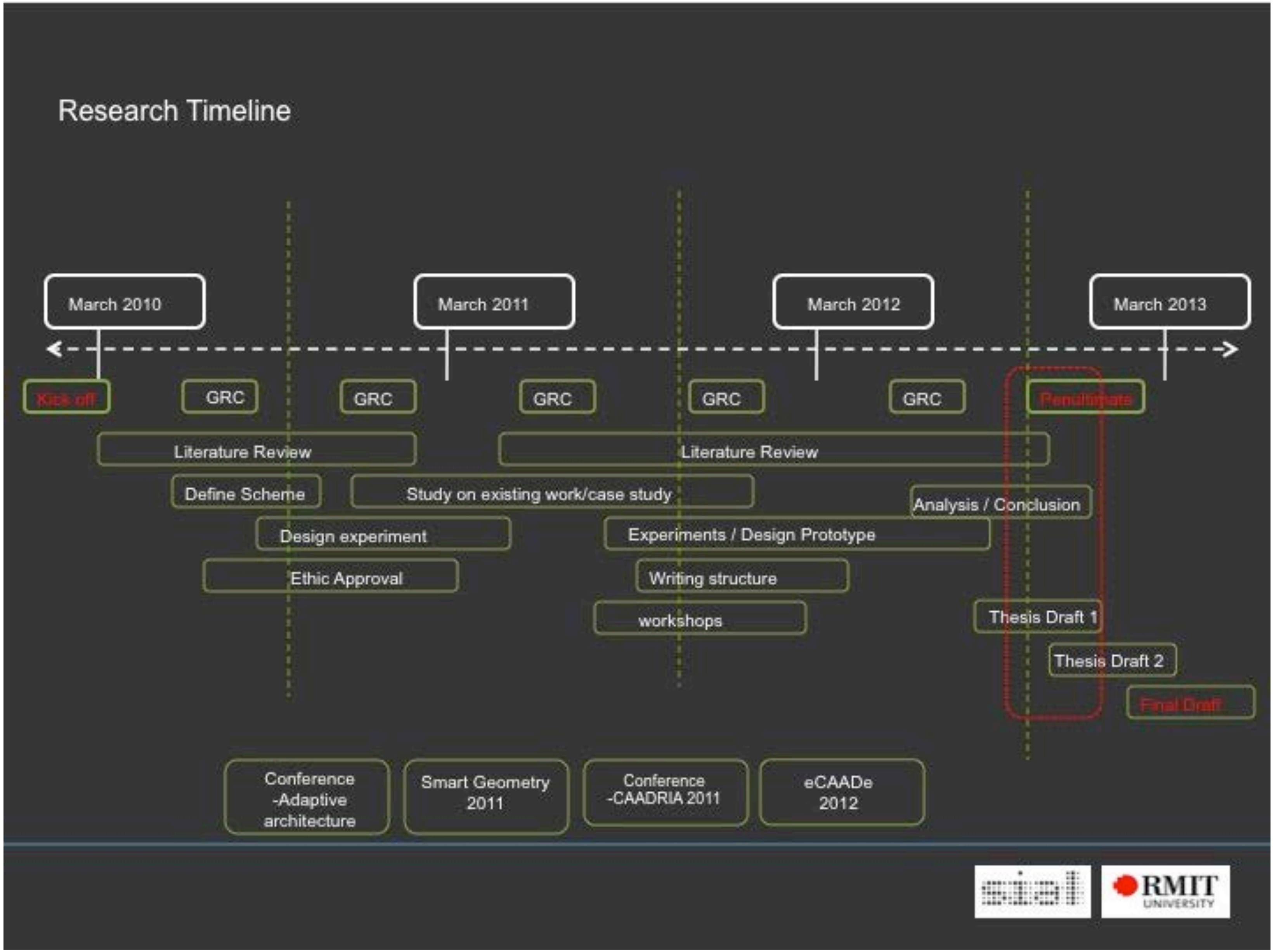








A5.Research Timeline



Research Timeline

March 2010

March 2011

March 2012

March 2013

Kick off

GRC

GRC

GRC

GRC

GRC

Penultimate

Literature Review

Literature Review

Define Scheme

Study on existing work/case study

Analysis / Conclusion

Design experiment

Experiments / Design Prototype

Ethic Approval

Writing structure

workshops

Thesis Draft 1

Thesis Draft 2

Final Draft

Conference -Adaptive architecture

Smart Geometry 2011

Conference -CAADRIA 2011

eCAADe 2012